# THE THERMOMECHANICAL RESPONSE OF STRUCTURAL TIMBER IN REAL FIRE EXPOSURES

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**Abstract**

Timber is commonly found as a building material in both historic structures with significant heritage value, as well as in contemporary structures that are becoming increasingly taller. Although widely used, uncertainty remains regarding timber's fire performance. There is little available information specific to heritage timber, and data is still lacking regarding the degradation of contemporary timber beyond the char layer. Moreover, there is an architectural desire to build more complex timber structures, which often feature open-plan spaces, a configuration for which there exists little information regarding the fire performance of combustible structures as well as very little design guidance. In order to facilitate the conservation of historic timber buildings and the creation of innovative contemporary timber buildings, there needs to be a stronger understanding of the thermomechanical response of structural timber to real fire exposures.

A series of small- and large-scale experiments were performed, to assess the thermomechanical performance of both heritage and contemporary engineered timbers, as well as encapsulation materials meant to improve timbers fire performance. Experimental setups used for assessment considered radiant panels in the Cone Calorimeter and Lateral Ignition and Flame Spread Apparatuses to evaluate and compare metrics such as flame spread, charring rate, and time to ignition. Further, pool fires were used to create a larger scale thermal exposure in the assessment of characteristics such as charring, adhesive strength loss, and material degradation. Lastly, finite element analysis software LS DYNA was used to create a model of a timber ceiling exposed to a well ventilated, open plan fire, in order to understand experimental data collection needs to facilitate future design methodologies for timber structures.

Contributions to the state-of-the-art include developments into a mechanism that may cause gypsum board encapsulation failure, highlighting relative differences between heritage and contemporary timbers fire performance (including charring rate, flame spread, and ignition time),

and analysing adhesive degradation in contemporary engineered timbers (Glued Laminated Timber and Laminated Veneer Lumber). The thermal model also allowed for identification of experimental data sets were recommended for collection, which may eventually contribute towards developing design methodologies for open plan well ventilated timber structures.

**Acknowledgements**

First, and most importantly, I would like to thank my supervisor Dr. John Gales. He has been an incredible mentor and I have learned so much from him in the past few years. I am very grateful to have had the opportunity to work with him.

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I would like to acknowledge the financial support I have received throughout my degree. Thanks to the Natural Sciences and Engineering Research Council and to York University in helping to support this project financially.

While at York University, I was lucky enough to have one of my best friends join me to continue her own research. Thank you to Georgette, who in addition to having incredibly useful technical conversations and spending countless hours in the lab helping me, has been there with me through all of the ups and downs. Thank you also to Avery, for his endless encouragement, patience, and for always making me laugh. Finally, thank you to my parents, Bruce and Sue, who have always been my biggest supporters.

**Statement of Co-Authorship**

The work presented herein has been influenced by several co-authors through the publication of five original research articles. This dissertation is written in modified manuscript format, where each chapter is based on an article that has been published or submitted for publication, though additions have been made to the chapters since their publication as journal articles (as they were published prior to the finalization of this dissertation). The dissertation author was the primary author of each of the research articles, which were all written while the dissertation author was studying at York University for this PhD degree. Where the dissertation author is not listed as first author (Chapter 6), only portions of the publication that represented the dissertation author's research contributions and sections of the publication that they were responsible for have been adapted for this dissertation. The role of authorship is defined here as participating sufficiently in the conception, design, analysis, writing, and/or revision of the manuscript. First authorship was chosen as the author who participated sufficiently to take ownership of the article.

Chapter 3 is based on:

- Chorlton B, Gales J (2020) Fire performance of heritage and contemporary timber encapsulation materials. Journal of Building Engineering 29. doi.org/10.1016/j.jobe.2020.101181

Chapter 4 is based on:

- Chorlton B, Forrest B, Gales J, Weckman B (2020) Performance of Type X Gypsum Board on Timber to Non Standard Fire Exposure. Fire and Materials. doi.org/10.1002/fam.2822

Chapter 5 is based on:

- Chorlton B, Gales J (2019) Fire Performance of Cultural Heritage and Contemporary Timber. Engineering Structures 201. doi.org/10.1016/j.engstruct.2019.109739

Chapter 6 is based on:

- Quiquero H, Chorlton B, Gales J (2018) Performance of Adhesives in Glulam after Short Term Fire Exposure. International Journal of High-Rise Buildings 7:299–311. doi.org/10.21022/IJHRB.2018.7.4.299

Chapter 7 is based on:

- Chorlton B, Gales J (2020) Mechanical Performance of Laminated Veneer Lumber and Glulam Beams after Short-Term Incident Heat Exposure. Construction and Building Materials 263. doi.org/10.1016/j.conbuildmat.2020.120129

The following articles are also included as appendices. These publications do not directly address the research objectives of this dissertation but were written or co-authored by the dissertation author, during their PhD degree. These publications include topics of engineering education, which are included both because they contribute to providing an overview of the dissertation author's work during their degree, and because the themes of these publications support future research related to the thesis objectives.

The publications (or manuscripts submitted for journal publication) included as appendices are:

(B) Chorlton B, Gales J (2020) Structural Repair of Fire-Damaged Glulam Timber. Journal of Architectural Engineering 27(1). doi.org/10.1061/(ASCE)AE.1943-5568.0000445

(C) Harun G, Chorlton B, Richter F, and Gales J (2021) The Effects of Radial Cracks on the Fire Performance of Heritage Timber. This manuscript is submitted for journal publication.

(D) Chorlton B, Mazur N, Gales J (2019) Incorporating Timber Education into Existing Accredited Engineering Programs. In: 2019 Canadian Engineering Education Association (CEEA-ACEG19) Conference. Ottawa, ON

(E) Mazur N, Chorlton B, Gales J (2019) Comparing the Experiences of Women in Engineering Across Different Schools. In: Canadian Engineering Education Association (CEEA-ACEG19) Conference. Ottawa, ON

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# Chapter 1 : Introduction

## 1.1 General

Timber is one of the oldest construction materials, and it continues to be used today. Timber buildings are renowned for a number of reasons, to name a few; they are often seen as architecturally desirable (especially when the timber is left uncovered by another material), and there are health benefits associated with occupying timber structures [1]. In terms of features as a structural material, building with timber can be advantageous for its relatively light weight. Moreover, timber members are often fabricated off-site, leading to quick on-site assembly which can accelerate construction time. Commonly, timber is used for it's potential to be more environmentally friendly than some other commonly used building materials. For these reasons, timber continues to be a popular material choice.

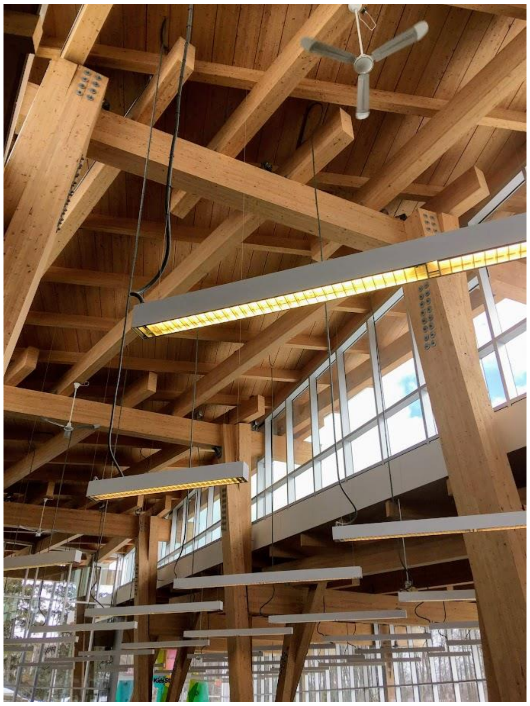


Figure 1.1 Interior of a contemporary timber building in Scarborough, Ontario (author's photo).

One of the challenges in building with timber is addressing its vulnerability to fire. In historic timber structures; these buildings may be neglected and have subsequentially become susceptible to arson, or they may be undergoing preservation work that expose them to additional fire risk. In terms of contemporary structures, timber buildings are continuing to become more complex. As timber buildings become taller, larger, and more intricate than ever before, there is a need to thoroughly understand the structural performance of timber to fire.

## 1.2 Motivation

The ultimate motivation of this research is to better understand the thermomechanical response of structural timber to non-standard fire exposures, in order to better understand the structural fire performance of timber structures, both historic and contemporary.

Heritage timber buildings are exceptional reminders of our history. The timber within these buildings is often well worth conserving, as it may hold architectural or aesthetic importance, or it may represent the structural systems of the time period in which the buildings were constructed. Moreover, heritage timber buildings are often of high interest and importance to their communities. As previously mentioned, these structures are inherently vulnerable to fire. There is also a lack of available guidance regarding fire performance assessment and prevention, that may lead practitioners to either remove the heritage timber or cover it with another material meant to improve its fire performance. In both cases (either the removal or covering of timber with another material), the heritage value of the buildings is obscured.

Today, we continue to see timber as a common building material. While historic buildings typically use solid wood sections, recently engineered timber has been used to create large and tall timber structures. Engineered timber is a product characterized by the union of wood with other fasteners. An example of a tall, engineered timber building is the Brock Commons Building in Vancouver, BC, standing at 18 stories [2]. The Brock Commons Building is primarily comprised of two engineered timber products; Cross Laminated Timber (CLT), Glued Laminated Timber

(Glulam), as well as concrete, however in this building all the wood elements were encapsulated with multiple layers of gypsum board[1]. The use of encapsulation reduces many of the aforementioned advantages of constructing timber buildings, such as aesthetic appeal, and the environmental impact of the project may be increased with the use of additional materials. Furthermore, there is some concern that the gypsum boards may not stay fastened to timber during a fire [3–6]. The use of gypsum boards also raises the question of whether the timber members themselves could have performed adequately in fire without encapsulation.

Previous research has begun to look at the performance of timber in fire, though several areas remain understudied. Some products, such as CLT, have attracted research attention due to behaviours such as fall-off of laminate layers in fire [4]. Meanwhile, several other engineered timber products, such as Glulam and Laminated Veneer Lumber, have received less research attention. Furthermore, to the author's knowledge, experiments on the fire performance of heritage timber have been extremely limited. This lack of information regarding the fire performance of understudied timber products may lead over or under conservative practices, such as encapsulating or removing timber where it may not be necessary.

When timber fire tests are performed, a furnace test that follows a specific temperature-time curve is often used, referred to as the standard temperature-time heating curve (CAN/ULC S101 in Canada) [7]. While standard temperature-time heating curve tests may provide some insight into the fire performance of a material, there is a possibility that the standard temperature-time curve may only characterize the performance of the material in one specific thermal exposure, and even then, the performance is only relative to other materials which have undergone the same exposure. The standard temperature-time heating curve has been criticized for several reasons, such as not

[1] With the exception of one room where the timber is exposed (a study lounge).

considering the cooling phase of a fire, having an initial rate of temperature increase that may not be as severe as a real fire, and that the support conditions of the member tested may not be representative of realistic construction [8]. For these reasons, there is a need to understand the fire performance of materials in fire scenarios beyond the standard temperature-time heating curve.

While there is some understanding of methods that have been used to design timber structures in the past and in the present, recent discussions [9, 10] regarding the appropriateness of using the standard temperature-time heating curve in determining the fire performance of timber elements raises the question of how timber structures will be designed in the future. This has prompted a need to begin identifying information that is needed to develop models to assess the fire performance of timber against non-standard fires in open plan, well ventilated conditions.

The scarcity of available information regarding the thermomechanical performance of several timber types to realistic fires has prompted this thesis, and the research herein. The objective of this thesis is therefore to better understand how understudied timber systems perform in realistic (non-standard) fires.

**1.3 Scope of Project**

Previous work by other researchers (primarily investigating the performance of CLT) have suggested that several aspects of the way in which the fire performance of timber is evaluated may be over or under conservative. This work has included suggestions that encapsulation materials may not remained fastened to CLT panels during a fire [4], however the exact mechanisms causing the panels to become detached during or after a fire have yet to be identified. Furthermore, in assessing the fire performance of the engineered timber itself, the adequacy of current procedures used for quantifying material degradation in fire have been called into question [11, 12], especially with regards to the adhesives. With respect to historic timber, to the authors knowledge there has been little to no contemporary research regarding its fire performance.

All of the aforementioned aspects direct additional research needs regarding the fire performance of several understudied types of timber, as well as systems meant to improve the fire performance of timber. The overarching theme of this thesis is to better understand the thermomechanical response of timber to real fire exposures, which will be addressed through a comprehensive research programme. The research herein therefore explores the themes of;

1. The effectiveness of encapsulation systems at protecting timber from non-standard fires;
2. The thermomechanical response of historic timber to non-standard fires; and,
3. The thermomechanical response (including the degradation of adhesives) of contemporary engineered timber to non-standard fires.

The test programme undertaken to achieve these objectives will be described in the following chapters. In evaluating encapsulation systems, several historic and contemporary encapsulation materials were procured or recreated and tested in controlled laboratory studies at both small scale and realistic scale. Contemporary encapsulation (gypsum board) was further examined in a real building fire. Once the effectiveness and failure mechanisms of encapsulation materials were better understood, the fire performance of timber itself was then evaluated. This began with a test series looking at charring rate, flame spread, and ignition of historic timber, compared to contemporary timber, and continued by examining the failure mechanisms of contemporary engineered timber, including the degradation of the adhesives. Finally, information needed to develop datasets that may be used for the creation of numerical models for assessing timber to nonstandard fire exposures will be explored using computational tools. A comprehensive understanding of each of these themes is essential to understanding the overall structural fire performance of timber buildings.

**1.4 Research Objectives**

The scope of this project explores several central themes, each contributing to the research objectives of this thesis. The novelty of this thesis stems from several aspects, primarily that the timber types and encapsulation systems examined herein have seen little research, especially using non-standard fires. Thus, there is a need to understand the performance of these timbers and encapsulation systems to non-standard fires in order to develop our understanding of how they would perform in a variety of fire scenarios. Furthermore, it is critical to identify the failure mechanisms both in-fire and post-fire in order to facilitate safe timber structures. The research objectives of this thesis therefore include;

1. Developing a better understanding of the effectiveness of historic and contemporary encapsulation materials at protecting timber from fire; as well as improving the understanding of the failure mechanisms of contemporary encapsulation measures (fire rated gypsum board);
2. Investigate the fire performance of heritage timber on a small scale in order to develop a preliminary evaluation of its charring, flame spread, and ignition characteristics;
3. Improve the current understanding of the thermal degradation of engineered timber in fire, including identifying failure modes of fire- damaged structural members; and,
4. Identify and recommend datasets that need to be collected experimentally to facilitate methodology development for assessing the fire performance of timber to nonstandard fires.

### 1.5 Outline of Thesis

This thesis has been written in a modified manuscript style format. Most of the chapters have been adapted from journal papers that have either been submitted or published by the thesis author. Modifications to the manuscripts have been made such that the thesis reads as a whole narrative. The author of this thesis was the first author on the related sections of each of these journal papers meeting said criterion for authorship role. Authorship in this context is defined as sufficiently participating in the conception, design, analysis, writing, and/or revising of the manuscripts. First authors were determined by those who participated sufficiently to take ownership of the article.

The following paragraphs give a brief description of each chapter of this thesis. Figure 1.2 shows the development of topics, and how the chapters feed into one another as a cohesive research programme.

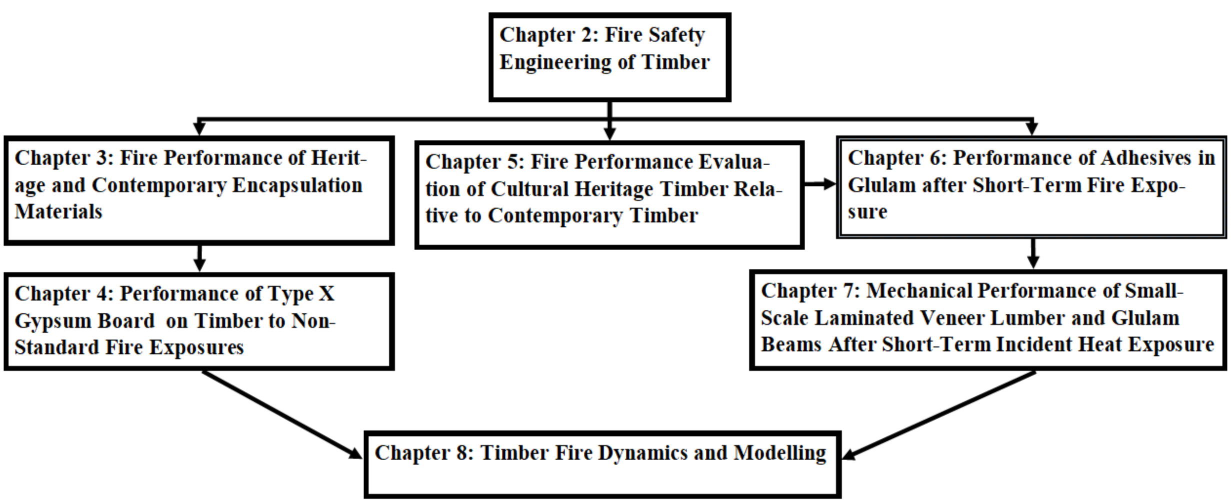



Figure 1.2 Development of topics within this thesis.

**Chapter 2: Fire Safety Engineering of Timber** will provide a background into the current understanding of the thermal degradation of timber, as well as current practices. This chapter has been provided such that a background in timber and fire safety engineering is not necessary to read the following chapters, however, readers who do have such an understanding in these topics will not require this review. Topics covered in this chapter include the material properties of timber, fire testing technologies, fire dynamics, thermal performance and decomposition of timber in fire, current practices for determining structural capacity, and use of encapsulations to improve timber fire performance.

**Chapter 3: Fire Performance of Heritage and Contemporary Encapsulation Materials** examines the history and evolution of encapsulating timber to improve its fire performance through analysis of archival literature dating over 200 years ago, as well as evaluates the fire performance of bench-scale samples of these historic and reproduced encapsulations with controlled and repeatable testing. The purpose of these tests was to understand the successes and failures of these encapsulations and to assist practitioners who may encounter these dated protective measures. Plasters, metal plates, lime-based paints, and gypsum boards were all tested using a Cone Calorimeter apparatus (a coiled radiant heater which can produce a controlled heat flux) and the heat release rates, material decomposition, charring and ignition of timber were analyzed.

**Chapter 4: Performance of Type X Gypsum Board on Timber to Non-Standard Fire Exposures** extends the results of Chapter 3 to larger scale experiments but focuses only on contemporary encapsulation (Type X fire rated gypsum board). In recent studies where non-standard fire exposures have been utilized, there have been concerns as to whether encapsulation successfully can improve the fire performance of the assembly due to board fall off or heat penetration between layers throughout the duration of a non-standard fire scenario (which includes cooling phases and auto-extinction). A two-stage experiment studying multi-layered and fire-rated gypsum clad stand-alone columns is addressed in this chapter. In the field study, a stand-alone timber column within a large, open farm structure was encapsulated in three layers fire rated gypsum board. The second stage of the research involved four, encapsulated timber columns with localized non-standard fires (methanol pool fires exposing one face only) in controlled laboratory conditions. These tests used novel narrow-band spectrum illumination to document the underlying breakdown of the gypsum board with non-standard fire exposure and cooling phases.

**Chapter 5: Fire Performance Evaluation of Cultural Heritage Timber Relative to Contemporary Timber** addresses if historic timber performs significantly different to contemporary timber in fire. The chapter begins by outlining available guidance for practitioners who encounter heritage timber buildings and describes historic fire tests of timber. Contemporary fire tests of historic timber by the author are then described. Controlled and repeatable fire tests have been performed on four different types of timber, two contemporary Glued Laminated Timbers (Glulam) and two historic timbers from buildings constructed in 1898 and 1839. The timber was tested using Lateral Ignition and Flame Spread Test and Cone Calorimeter apparatuses, following ASTM E1321 and ASTM E1354 standards, to compare the relative performance of the timber types in their char depth, time to ignition, and flame spread.

**Chapter 6: Performance of Adhesives in Glulam after Short-Term Fire Exposure** considers the extent of the adhesive degradation and the validity of the zero-strength layer guidance with respect to short duration fire exposure on thin glulam members. Realistically scaled Glulam beams were heated locally using a controlled pool fire in controlled locations along the length of the beam.  Reduced cross section samples were created by mechanically carving a way an area of cross section equal to the area lost to char on the heated beams. The mechanically carved samples were created in order to observe any strength loss of material degradation beyond the char layer, as theoretically the carved and charred samples would have the same effective cross-sectional area. All of the samples were then loaded to failure in four-point (laterally restrained) bending tests.

**Chapter 7: Mechanical Performance of Laminated Veneer Lumber and Glulam Beams After Short-Term Incident Heat Exposure** was prompted by the research needs outlined in Chapter 6; namely the need to study additional types of engineered timber (beyond CLT) and the need for a large number of tests to reduce variability. This chapter therefore explores the performance of timber elements exposed to well defined thermal boundary conditions and examines the extend of adhesive degradation after heating. 28 small scale beams are considered, consisting of Glulam and LVL. A subset of beams was exposed to radiant heat using a Lateral Ignition and Flame Spread Test apparatus, to reach a defined damage state. An additional subset of beams also had an area of their cross-section carved away, equivalent to the char depth of the heated beams. The carved beams allow for the identification of degradation beyond the char layer, as theoretically both the carved and charred beams would have the same effective cross-sectional area. All beams were mechanically loaded using a four-point loading setup. The current zero-strength allowance for degradation effects beyond the char layer is discussed in the context of the results of this chapter.

**Chapter 8: Timber Fire Dynamics and Modelling** ultimately aims to highlight experimental data collection needs required for finite element modelling, which could eventually be used in the creation of design methods for open plan, well ventilated timber structures. This chapter provides an overview of current design procedures being used by practitioners in Canada and internationally, which include analyses of risk and underscore the importance of finite element modelling of timber in design. A model was created using LS DYNA, simulating a fire incident on the soffit of a Cross Laminated Timber (CLT) ceiling, which was used to highlight missing data sets needed for input parameters or model calibration.

**Chapter 9: Conclusion and Recommendations** will outline some of the main findings of the previous chapters, as well as highlight the usefulness and novelty of these results. Recommendations will also be made for future research needs to further develop our understanding of the fire performance of these timber members and systems, contributing to the overall safety of historic and contemporary timber structures.

In addition to the main text, five appendices are included with this thesis. Four of these are publications (or manuscripts submitted for publication) that represent studies completed throughout the author's degree, but do not directly address the research objectives. These include publications related to engineering education, which are included both to give a comprehensive overview of the author's work during their degree, and because the themes of the appendices support future work related to the thesis objectives.

**Appendix A: Supplementary Information to Chapter 8** provides additional information related to the modelling completed in Chapter 8. The intent of this chapter is to give an overview of the modelling process such that it could be adapted in the future. **Appendix B: Structural Repair of Fire Damaged Timber** discusses the possibility of repair of timber members after fire, by carrying out experimental tests where four fire-damaged members are repaired using additional timber panels and structural screws. Members were loaded to failure in four-point bending, and a hypothetical cost analysis is provided as a baseline of what a potential repair might cost in a fire-damaged timber structure. **Appendix C: The Effects of Radial Cracks on the Fire Performance of Heritage Timber** examines how existing radial shrinkage cracks on heritage timber member affect the members fire performance, including if the presence of the crack affects the overall char depth. Members were extracted from a historic building undergoing renovation, exposed to a pool fire, and subsequently loaded to failure. Additional small-scale samples extracted from the same members were tested in a Cone Calorimeter apparatus. Observations regarding char depth and crack expansion were made during and after testing. **Appendix D: Incorporating Timber Education into Existing Accredited Engineering Programs** proposes a method to incorporate timber education into existing Civil Engineering programs across Canada, until full courses can be developed across all institutions. This method of presenting learning modules was implemented in a fourth year Civil Engineering course and students were surveyed to gauge effectiveness at teaching timber design at a high-level, and to gauge student interest. Finally, **Appendix E: Comparing the Experiences of Women in Engineering Across Different Schools** analyses the results of a survey distributed to engineering students across four North American universities. The purpose of this study is to identify factors that may be affecting some genders more than others, so that these causes may eventually be alleviated.

# Chapter 2 : Background of Fire Safety Engineering of Timber

This chapter will provide much of the background information needed to contextualize the following chapters. The content of this chapter is a review of current knowledge and practices regarding fire safety engineering of timber. This will begin by examining the material properties of timber and continue by looking at currently available fire testing technology and some basic fire dynamics principles. The thermal performance and decomposition of timber will be discussed, including factors that may influence the fire performance of a timber sample. Finally, current practices for determining the structural capacity of a fire-damaged timber member will then be presented, as well as the use of encapsulation materials to achieve the desired fire performance will be discussed.

## 2.1 Properties of Timber

In order for the thermomechanical response of timber to be evaluated, the fundamental material properties must first be understood. Timber is a somewhat unique building material in that it is orthotropic due to the orientation of the grain. The three axes directions are relative to the grain direction and growth rings; longitudinal (to the grain), tangential (to the growth rings), and radial (radial to the growth rings and perpendicular to the grain). In structural engineering, timber is typically considered to be either parallel or perpendicular to the grain (longitudinal or radial directions, respectively). In general, timber is stronger when loaded parallel to the grain, and weaker when loaded perpendicular to the grain.

Timber is often categorized as being either a hardwood or a softwood (where softwoods are trees that often have needles year-round, and hardwoods have broad leaves that shed). The use of softwood in contemporary structural applications is common. Hardwood is used very little in structural applications, however, it may still be found in some historic sites.

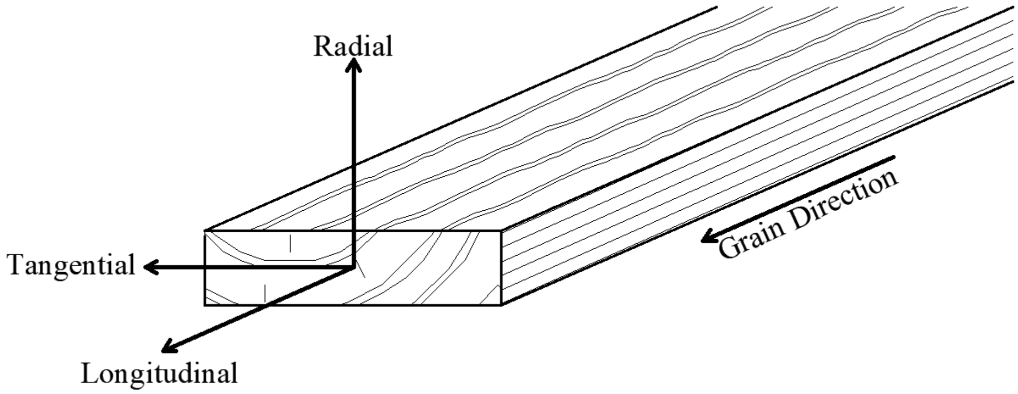


Figure 2.1 Timber axes relative to grain orientation and growth rings (adapted from [13]).

When trees grow, they grow outwards through the development of growth rings. New wood cells are produced on the inside of the bark, producing earlywood and latewood. Earlywood is developed earlier in the season (typically the spring), and usually has cells with large cavities and thin walls, while latewood (which develops later in the season) has smaller cavities and relatively thicker walls [14]. Earlywood is lighter weight and weaker than latewood, attributed to the higher density of latewood [14]. In seasonal climates, earlywood and latewood will be different colours (with the latewood being darker than the earlywood), allowing the approximate age of the tree to be counted as one year per growth ring. Trees may grow more than one growth ring per season if the growth cycle is interrupted (by droughts or other reasons) or may not have any defined growth rings (due to species or climates with indistinct seasons). Factors such as the speed of growth may have an effect on the size of growth rings and density of the wood, however, researchers have not unanimously agreed on this correlation [15].

The microstructure of wood is comprised primarily of elongated cells (fibres or tracheids), as well as a binding matrix [14]. These cells provide mechanical support, and (in some species) are used to transport sap within the tree. Trees also have cells that run radially from the centre of the tree towards the outer bark to move sap across the grain, known as ray cells [14]. With regards to chemical composition, wood is comprised primarily of cellulose, lignin, and hemicellulose. Cellulose makes up the cell walls themselves, with the lignin and hemicellulose making up the matrix which binds the cells together. The percent composition of these materials is largely dependant on the species type.

Figure 2.2 Growth rings as seen on a piece of Pine timber (author's photo).

Since timber is a natural material, it often contains defects that can affect its structural performance. Knots are common in timber, representing the remains of a branch. Other defects include wanes (bark remaining on the timber), checks (separation along the grain due to uneven drying), and shakes (longitudinal separation). The number of defects may be reduced in higher grade timber. Timber can be graded either visually or mechanically. In a visual grade, an inspector would grade the timber based on quality, which would include limits for the size and presence of defects including knots, shakes, and checks, and an allowable angle for the slope of the grain. Machine stress-rated (MSR) graded timber would be assessed visually for many of the same defects mentioned above and would then undergo a bending test from which a computer could determine the modulus of elasticity of the timber.

Engineered timber is created by combining smaller pieces of timber with fasteners such as adhesives or nails. This process can allow for small, highly graded pieces of timber to be combined to create a strong section, allowing it to be used in applications of high loading or long spans. Types of engineered timber include Cross-Laminated Timber (CLT), Glued Laminated Timber (Glulam), and Laminated Veneer Lumber (LVL). CLT is usually used to create surfaces such as walls or floors and uses layers of timber alternating in direction. Glulam is often used for beams or columns and uses small sections of timber all in one direction. Laminated veneer lumber is also used for components such as beams and is built up by multiple very thin laminates of timber, again oriented in the same direction. All of these engineered timber products are adhered together. Examples of these products are shown in Figure 2.3.

a. b. c.

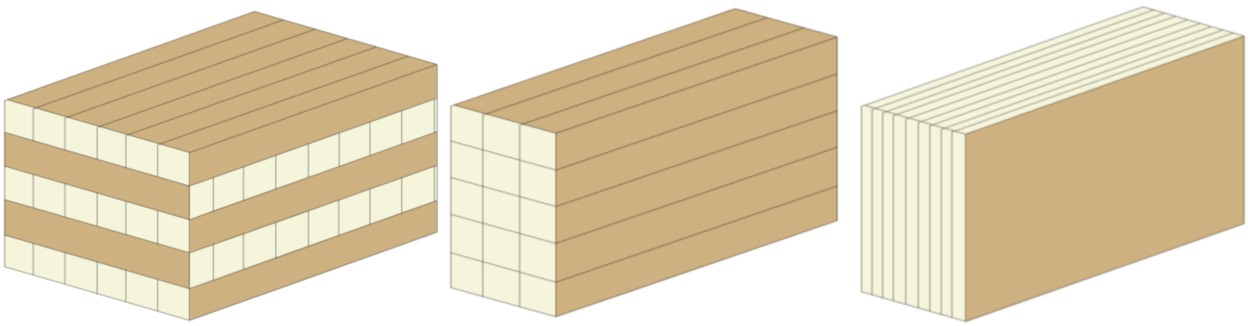


Figure 2.3 Examples of engineered timber, a. CLT, b. Glulam, and c. LVL.

**2.2 Fire Testing Technology**

In fire testing, several test apparatuses and setups can be used to conduct experiments. The first of these is a furnace. Fire testing in a furnace is often associated with the standard temperature-time heating curve. Furnaces in a basic sense are comprised of a large test area, several burners, and an exhaust leading into a flue gas treatment system. The burners use fuel to achieve the desired temperature. The furnace can then be programmed to follow time-temperature curves. The temperature will be read by several thermocouples along the floor, roof, or walls of the apparatus.

Smaller equipment can also be used to characterize fire performance. These include the Lateral Ignition and Flame Spread Test (LIFT) and Cone Calorimeter apparatuses. The LIFT is usually used to measure flame spread (the rate at which flame spreads laterally along a material) and characterize the surface heat flux and temperature needed for the material to ignite. In these contexts, heat flux is the rate of heat energy transferred per unit area (kW/m$^2$), and temperature is the amount of molecular energy of a material compared to a reference. The setup of the LIFT consists of a few key components. The first is a specimen holder, of which a specimen of approximately 155 x 800 mm could fit into. Along the bottom of the specimen holder is a series of pegs, spaced 50 mm apart (the pegs allow for fame spread to be visually tracked along the specimen during testing). Facing the specimen is a radiant heater (where radiation is heat transfer through electromagnetic waves). The radiant heater is placed at an angle to the specimen, such that it is closer to the specimen at one end and further away at another. This introduces a heat flux gradient along the specimen. The final component is the pilot burner, increasing the likelihood of ignition. Above the test specimen, smoke is collected by an exhaust. The LIFT setup is seen in Figure 2.4. The heat flux of the apparatus is calibrated prior to testing the specimen by reading the incident heat flux with a heat fluxmeter (a water-cooled sensor) at 50 mm intervals. The accuracy of the heat fluxmeter of a LIFT apparatus is calibrated to ± 5% [16].

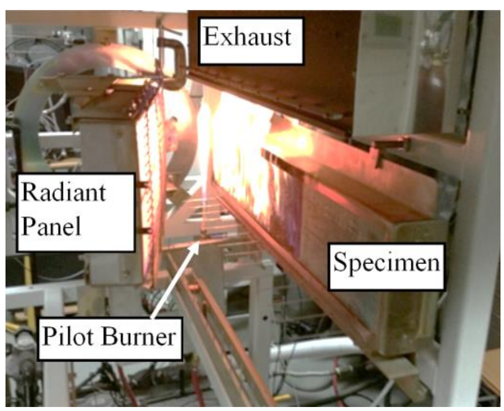


Figure 2.4 LIFT test setup.

Another test apparatus used for small scale experiments is the Cone Calorimeter. The Cone Calorimeter is used to test samples of 100 x 100 mm. In this test setup, the sample is placed in a sample holder below a coiled radiant heater. The radiant heater can then impose a constant, specified heat flux on the specimen. A spark igniter may be used to increase the likelihood of ignition. The Cone Calorimeter can be used to measure several properties, including the time to ignition. The apparatus also collects data such as mass loss and heat release rate (the rate at which heat energy is released). The test setup of the Cone Calorimeter is seen in Figure 2.5. The incident heat flux is read prior to testing by a heat fluxmeter. The accuracy of the load cell of the Cone Calorimeter is within 0.1 g, and the accuracy of the heat fluxmeter within the Cone Calorimeter is within ± 3% [17].

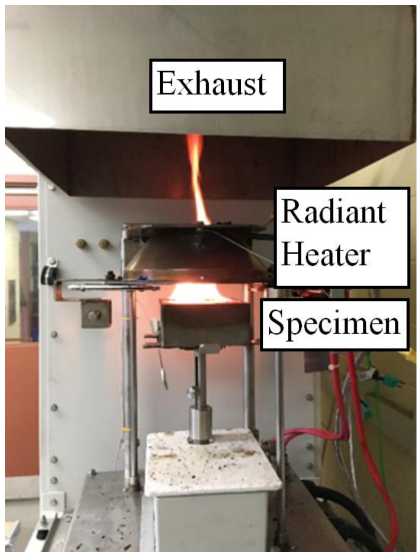


Figure 2.5 Cone Calorimeter test setup.

Fire testing can also be done using pool fires to provide heat exposure. In this test setup, liquid fuel is ignited to create a fire. The thermal exposure created depends on factors such as the distance from the fuel to the specimen, the volume of fuel used, the area of the pan used to contain the fuel, the type of fuel used, and the ventilation conditions of the room used for testing, to name a few. The temperature created on the specimen can be measured using thermocouples.

**2.3 Fire Dynamics**

There are several factors that influence the fire development and thermal exposure of a fire. These include the properties and quantity of the fuel used by the fire, the geometry of the compartment in which the fire is located, the ambient conditions (such as the ambient temperature) of the room, and the ventilation conditions. Each of these aspects impacts fire development.

In fire testing, there are several ways to create heat exposure. Many of these can be done using the equipment described in Section 2.2. The heat exposure could be characterized by the heat flux incident on the specimen, as is the case for the Cone Calorimeter and the LIFT. Alternatively, heat exposure could follow a temperature-time curve. A temperature-time curve is a heat exposure in which the temperature of the compartment changes over time. This can be done using a furnace. A common temperature-time curve that is used for fire testing is known as the standard temperature-time heating curve. The standard temperature-time heating curve follows a similar curve in each of the different standards in which it has been adopted, such as ASTM E119, and ISO 834 [18, 19]. The ASTM E119 curve is seen in Figure 2.6.

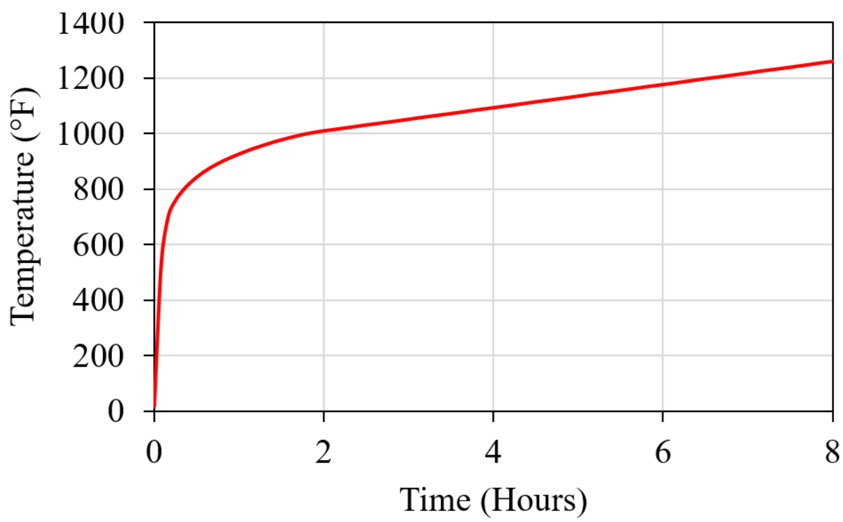


Figure 2.6 Standard temperature-time heating curve (from [18]).

The first edition of the North-American standard temperature-time curve (now known as ASTM E119) was released in 1918 and was reflective of the results of experimental and ad hoc tests [20]. The standard temperature-time heating curve has not significantly changed since this time. As previously mentioned, the standard temperature-time heating curve has been criticized for several reasons. It is often used to assign a Fire Resistance Rating (FRR) to a material, indicating how long (in minutes or hours) the material will withstand this fire exposure. FRRs are often used in structural design to assume the amount of time the material will withstand a real building fire, when in reality, the performance of the material to the standard temperature-time heating curve is only indicative of how it may perform in that one specific exposure. Moreover, the standard temperature-time heating curve may not be as severe as a real fire in some respects, especially the initial rate of temperature increase. In addition, the support conditions needed for furnace testing may not be reflective of what would occur in realistic construction (i.e., in a construction application, a structural member may not have continuous support) [8]. Furthermore, cooling is not considered within the standard temperature-time curve, even though the cooling phase of thermal exposure has been identified as a phase of exposure where members may be vulnerable to failure [21, 22].

Another aspect of furnace tests that has been criticized is that the ventilation and distribution of fuel would all impact the severity of thermal exposure [23]. In fact, ASTM E119 specifies that this test provides a relative measure and is not representative of all fire conditions;

> "The test provides a relative measure of the fire-test-response of comparable building elements under these fire exposure conditions. The exposure is not representative of all fire conditions because conditions vary with changes in the amount, nature and distribution of fire loading, ventilation, compartment size, and configuration, and heat sink characteristics of the compartment." [18].

The appropriateness of using the standard temperature-time heating curve for combustible materials has been the topic of ongoing discussion. Researchers have found that furnace testing of combustible materials requires less external fuel than for non-combustible materials, and that the fire dynamics of the furnace are unique to the specimen being tested [9, 10, 24]. The implications of these differences make it challenging to compare the results of combustible and non-combustible materials that undergo furnace testing.

Compartment fires are also commonly discussed in fire testing. In this context, a compartment is considered to be a confined spaced, with openings or windows. This configuration allows for the flow rate of air through the windows to be more controlled, such that the ventilation of compartment is better defined than tests performed in the open atmosphere [25]. Compartment fire tests may be also be at a larger scale than tests of single members such as beams and columns, and therefore have been used to better understand the fire and smoke that may develop within timber buildings.

One of the challenges in testing timber is that it is a combustible material. When timber is exposed to heat and ignites, it contributes to the fuel load of the fire. When the structure itself contributes its own fuel and heat to the fire severity, it is difficult to assess the actual fire severity that would occur both in experimental research, and in real applications such as timber structures. This is especially concerning for structures where the timber is left exposed. In designing non-combustible structures, the fuel load is better defined. This is what makes it so complicated to design a timber structure for fire; the severity of the fire effects how much of the timber contributes as fuel to the fire and vice versa.

## 2.4 Thermal Performance and Decomposition of Timber in Fire

Under extreme heating, wood begins to undergo a process known as pyrolysis around 100°C as its chemical properties begin to change. The wood strength begins to degrade until 300°C which is recognized as the charring temperature of wood, at which point the pyrolysis process has completed and the wood is completely converted to char. The pyrolysis and char layers can be seen in Figure 2.7. After this point, char may continue to develop as the wood behind the char layer is heated, and the exposed char continues to oxidize until it begins to crack and flake off or is fully consumed. Although the charring rate is realistically a transient property depending on the degree of char that has already formed and the amount of heat exposure, standardized constant charring rates have been developed. This rate is meant to encompass the initial rapid char phase while fresh wood builds up an insulating layer of char which then slows the charring rate to a much lower value.

Accurate evaluations of the char depth are critical in using current procedures for assessing the structural capacity of fire-damaged timber, which will be discussed in Section 2.5. Other considerations in evaluating timber's fire performance include the rate of flame spread and the time to ignition. There are several factors that are largely accepted as influencing the fire performance of timber. To name just a few factors which will be discussed in the following chapters; density has been shown to influence factors such as charring rate, with a higher density generally associated with slower charring [26]. Moisture content is another consideration that can alter the fire performance, as is species (due to variations in chemical composition between timber species) [26, 27]. With regards to test setup, the grain orientation has been known to play a role in fire performance (e.g., whether the heat exposure is parallel or perpendicular to the grain orientation). The heat exposure (such as an incident heat flux) has also been shown to impact the fire performance of timber [28]. Despite all of this, charring rates corresponding to the standard temperature-time heating curve are still used in practice, and are usually dependant only on the duration of exposure and on the type of timber product considered (Equation 2.1, from [29]).

$$x_c = \beta * t \qquad [2.1]$$

Where $x_c$ is the char depth (mm), t is the exposure duration (min), and $\beta$ is the charring rate (mm/min and based on the type of timber considered).

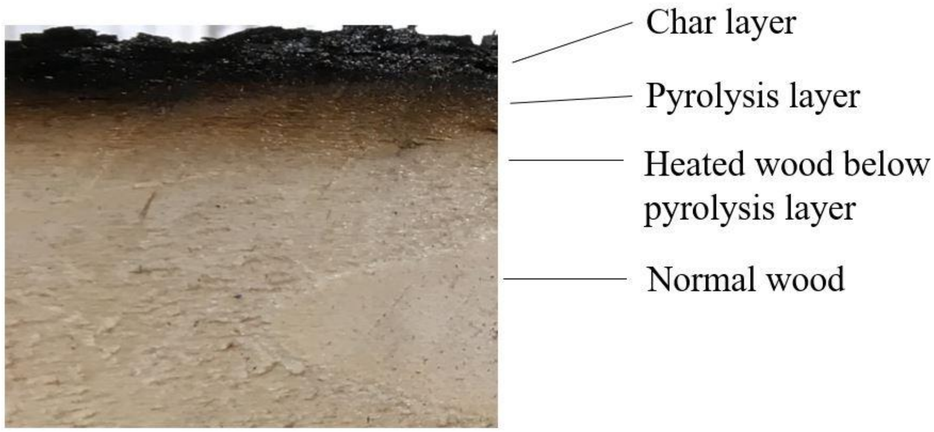



Figure 2.7 Char formation on a piece of Glued Laminated Timber (Glulam).

While the factors mentioned above apply broadly to all types of timber available, there are additional considerations that uniquely impact the fire performance of engineered timber. These considerations largely concern the thermal degradation of the adhesives within timber beyond the char layer. Previous research has shown that the degradation of the adhesives may not be adequately accounted for in practice [30, 31]. Furthermore, the degradation of the adhesives can lead to the fall-off of layers of timber laminates (referred to as delamination herein) [4, 5]. Delamination occurs when thermal penetration into the timber material interacts with an adhesive bond line. The occurrence has been observed most specifically with CLT, due to the comparatively large weight of the lamellae and surface of exposed timber (see [4]).

**2.5 Current Practices for Determining Structural Capacity**

In Canada, CSA O86 Annex B (2014) outlines methods for determining the fire resistance of wood members with large cross-sections. This includes a method for determining char depth (taking a constant char rate and multiplying by the duration of fire exposure) and adding an allowance for degradation beyond the char depth, including the degradation of the adhesives. This procedure allows for the determination of the residual strength of a timber member though the calculation of an effective, reduced cross-section [29]. This method (referred to as the 'reduced cross-section method' herein) begins by taking the original dimensions of the member, subtracting the char depth and an allowance of additional degradation, known as the zero-strength layer, and assuming that remaining area has retained full strength. A visualization of the reduced cross-section method is seen in Figure 2.8.

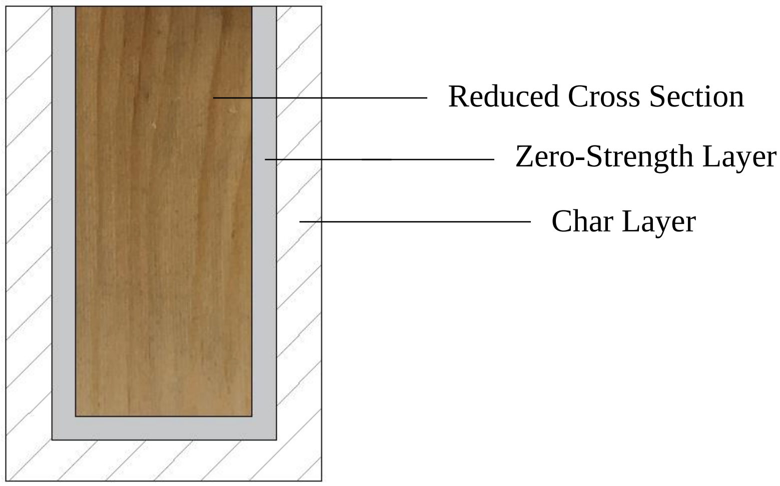



Figure 2.8 Reduced cross-section of a timber beam.

The char depth is determined using a constant charring rate (often taken as 0.7-0.8 mm/min for many types of timber) [29, 32]. The constant charring rate used for these calculations is dependant on the type of timber only and does not account for any other considerations (such as moisture content, thermal exposure, ventilation conditions, etc.). Furthermore, the zero-strength layer is taken as 7 mm for exposure times of 20 minutes or more, and proportionally less for exposure times less than 20 minutes [29, 32]. Equation 2.2 outlines the procedure for calculating zero-strength layer for exposures of less than 20 minutes, and Equation 2.3 outlines the procedure for exposure times greater than 20 minutes (from [29]),

$$x_t = \frac{t}{20} * 7 \text{ for } t < 20 \qquad [2.2]$$

$$x_t = 7 \text{ for } t \geq 20 \qquad [2.3]$$

Where $x_t$ is the zero-strength layer depth (mm), and t is the time (min).

Often, codes may require a specified fire-resistance rating (FRR) for a structural member, which is a rating that has been derived in relation to the standard temperature-time heating curve [29, 33]. Two primary methods of considering the contribution of the timber to the FRR are outlined in CSA O86-14. First, the FRR can be calculated by considering the factored load, the factored member resistance, the dimensions of the member, and the slenderness of the member. Alternatively, members may be oversized such that their 'reduced cross-section' (determined using the method as outlined above) after the fire duration specified by the FRR will still be adequately large to withstand the factored load.

## 2.6 Use of Encapsulations to Improve Fire Performance

Encapsulations have been used to improve the fire performance of timber for centuries. Historically, materials such as plasters, metal plates, and lime-based paints have all been used with the intent of protecting timber from fire, and these historic methods will be discussed in Chapter 3. Encapsulations are still used for a similar purpose today; to improve the fire performance of timber, or they may be used where required by the authorities. CSA O86 Annex B allows the use of fire-rated Type X gypsum board for these purposes, where multiple layers can be used to increase the fire-resistance rating of the member by up to an hour (given the appropriate gypsum board is used, and the required fastening and joint sealing are in place) [29]. This approach is based upon a principle outlined in 1965 by Harmathy, in his publication 'Ten rules of fire endurance rating' [34]. This strategy has been used in structures such as the Brock Commons Building, where, to the author's knowledge, the required fire performance of the timber members is achieved through the encapsulation, and the contributions of the timber are neglected.

As previously mentioned in Chapter 1, the use of gypsum board compromises some of the aforementioned benefits of timber construction (such as the architectural appeal, and the use of additional materials may increase the environmental impact of the project). For the purposes of this thesis, however, of greater interest is the notion that recent tests have provided evidence that gypsum board may not stay securely fastened to timber during a fire [3, 6]. Several of these tests will be discussed in-depth in Chapter 4.

### 2.7 Summary

Even before considerations for fire are accounted for, designing with timber is a complex task. Timber has many mechanical properties that are unique and that do not always need to be considered with other commonly used building materials. The grain structure and its effect on material performance needs to be considered in timber structural and fire designs. Material defects are also difficult to avoid in this natural material. In the creation of engineered timber, adhesives or mechanical fasteners are used to make larger sections from smaller pieces of timber. The presence of adhesives can further complicate the fire design.

The performance of timber in fire is dependant on many factors, including properties of the timber such as density, moisture content, and grain orientation. The degradation of the adhesives in engineered timber also plays a role in its overall fire performance. Currently, code procedures determine the char depth of timber based on a constant charring rate and the duration for which the member was exposed to fire. An allowance for additional degradation beyond the char layer is also added. The remaining area is considered to be undamaged. With this section serving as the basis of the current state of understanding of the performance of timber in fire, the need to continue research on these topics is clear. Several types of timber remain understudied, such as Glulam, LVL, and heritage timber, and the research that is needed extends well beyond standard temperature-time heating curve exposures. This will begin to be addressed in the following chapters.

As this thesis looks at the thermomechanical response of both contemporary and historic timbers, heritage structures will be discussed in the immediately following chapters. Heritage buildings are important to keep safe from fire as they often hold ample heritage value and are very important to the community, so their loss could be catastrophic, with the Notre Dame Cathedral fire of 2019 as a recent example. In assessing the fire performance of heritage buildings, the history of fire protection of timber plays a role in understanding the materials and assemblies that may be found in these structures. Many of the character defining elements of heritage buildings need to be conserved, which can make implementing fire safety measures more challenging. The following chapter of this thesis will begin to discuss the importance of proper conservation of heritage structures and historic fire safety practices for timber and will address some of the intricacies of ensuring fire safety within heritage timber buildings.

# Chapter 3 : Fire Performance of Heritage and Contemporary Timber Encapsulation Materials

The following chapter will begin discussing the heritage timber and historic encapsulation materials. This includes novel experiments performed as a part of this thesis. It also provides insight into the history and developments of using encapsulation materials to protect timber structures from fire. In this sense, this chapter helps to provide some of the background into timber encapsulation materials which will be developed upon in future chapters and sections of this thesis.

## 3.1 Introduction

Cultural heritage buildings can be found worldwide and are often recognized for their heritage value, cultivating a high amount of public interest. Frequently, these buildings serve as excellent exemplars of historic construction methods or may be tied to a historically important person, event, or lifestyle. The Australia International Council on Monuments and Sites (ICOMOS) has provided aspects of a site that may have value in The Burra Charter (2013), and has been a critical influence for many conservation documents to follow (such as the Canadian Standards and Guidelines for the Conservation of Historic Places in Canada) [35, 36]. It indicates that buildings that provide significance may hold "aesthetic, historic, scientific, social, or spiritual value for past, present, or future generations".

Heritage buildings help citizens to understand their own background, and how they developed into the community they are today. They preserve certain aspects of the past, which are often defining elements of a culture, and provide indications of past lifestyles and traditions. Each culture may have its own additional reasons as to why a historic structure may be worth conserving. Many buildings such as churches and places of worship are often conserved for spiritual reasons. A heritage structure may be linked to a particular person or event, or may simply preserve the hardships, triumphs, and everyday life of previous times. In this sense, heritage structures help to commemorate past contributions and adversities. Another benefit of conserving heritage structures is that they often demonstrate a high level of craftsmanship and display construction techniques of the time. Moreover, these buildings are often exemplars of their architectural styles. This reinforces the importance of their conservation, as it is beneficial to have examples from a variety of different architectural time periods, to learn from the past in order to progress forward. A particular structure may have additional value in its uniqueness, for example displaying the oldest, only or a rare instance of a particular style or technique [36].

Beyond these social benefits of conserving heritage structures, there lies an additional environmental advantage. Often conserving an existing structure will be more environmental than demolishing the existing building and constructing a new one [37]. Even replacing existing buildings with new buildings that are considered to be energy efficient have been shown to take decades in order to break even environmentally [37]. For these reasons, it is important to take measures that ensure the conservation of our heritage structures.

These buildings pose a unique challenge to fire safety, as along with the usual considerations (such as life safety and operational resilience), the conservation of the heritage structures themselves is also very important. Historic buildings are often vulnerable to fire as the fire protection system may be reflective of the technologies used at the time of construction. They are also frequently subjected to renovation and conservation projects, which pose an additional fire risk to the building. Occasionally, they are not as well-maintained as they could be, prompting acts of arson. Since 2008, there have been several high-profile losses of heritage structures. A small sample of these are documented in Table 3.1. It can be seen from this compilation of fires that arson and accidental fires are major causes for concern for heritage buildings, with several notable losses of buildings that are hundreds of years old and hold heritage value. It should be noted that while the Notre Dame Cathedral was constructed in the 12th-14th century, significant changes and restoration work occurred in the 19th century to portions of the building that were involved with the 2019 fire.

Table 3.1 Examples of recent fires within heritage buildings.

| **Name** | **Location** | **Construction Year** | **Fire Year** | **Fire Cause** |
|---|---|---|---|---|
| Alma College | St. Thomas, Canada | 1878 | 2008 | Arson |
| Namdaemun gate | Seoul, South Korea | 1398 | 2008 | Arson |
| Quebec City Armoury | Quebec City, Canada | 1887 | 2008 | Accidental |
| Provo Tabernacle | Provo, United States | 1898 | 2010 | Accidental |
| Glasgow School of Art | Glasgow, UK | 1909 | 2014 | Accidental |
| Glasgow School of Art | Glasgow, UK | 1909 | 2018 | Unknown |
| National Museum of Brazil | Rio de Janeiro, Brazil | 1803 | 2018 | Accidental |
| Notre Dame Cathedral | Paris, France | 1163-1345, with significant changes and restoration in the 19th century | 2019 | Under investigation |

Beyond these well-known structures, it is also common for vernacular timber buildings to also experience loss to fire. In these cases, ample heritage value is still lost. Examples of this include a March 2018 fire of a heavy timber Mill building in Pennsylvania, USA. The building dated to the 1870s as an organ and piano manufacturing business, and was under renovation at the time (to adapt it into an apartment building) [38]. The building's sprinkler system was inoperative at the time of the fire, which ultimately ended up killing two firefighters (and injuring others). A couple of years later in downtown Toronto, Canada, two semi-detached late 19th century homes known as the "McLeish-Powell Houses" caught fire in March 2020 [39]. This building was constructed in 1888, and while not formally heritage designated yet, it was in the process of receiving heritage designation for its contribution in understanding the historic development of the neighbourhood, as well as the architecture of the building [40]. The building was vacant at the time of the fire, there had been recent discussions regarding incorporating the structure into a tall condo building. Regardless of the causes of fire in the case studies, buildings under renovation can be prone to accident, and vacant heritage structures can be prone to arson. These vulnerabilities reinforce the need to better understand the performance of heritage timber, so that heritage timber structures can be safeguarded from fire.

From a heritage conservation standpoint, it is advantageous to avoid altering a heritage building in a way that changes elements that define the character of the place (known as character-defining elements). The character-defining elements are unique to each particular heritage building but often includes the structural system. Furthermore, early fire safety strategies may be seen as representing the technology of the time period and may have heritage value in their own right. Heritage guidance suggests against the removal or covering of the character-defining elements and heritage value of a building where ever possible [36].

For centuries, building owners and engineers have been implementing methods meant to make timber buildings more secure from fire. Often these strategies involved covering up (encapsulating) the timber with another material meant to improve its fire performance. While the encapsulation materials may have changed through time, this practice is still done today, examples being gypsum products in North America that are commonly recommended for enhancing the fire performance of a timber assembly [29]. A sample of commonly encountered historic encapsulation materials include plasters, metal plates, and lime-based (whitewash) paints. See Figure 3.1 for example of an 18$^{th}$ century mill plated with metallic plates covering timber. Note that the plates in this building are by heritage designation not to be removed in renovation.

Figure 3.1 A structure with metallic plates installed in the 18th century (by permission).

The purpose of this chapter is to investigate and understand commonly found encapsulation technologies in historic timber buildings. This will be achieved, for the first time, through a comprehensive recovery and analyses of primary literature created during the time period these encapsulation materials were originally developed (majority of articles dating over 200 years ago, and subsequently not transcribed until today). Recognizing that fire testing was in its infancy in terms of scientific quality when these coatings were installed, for those that encounter these protection systems, this chapter seeks to introduce how these historic and contemporary encapsulations perform in high temperature conditions. This will be done with controlled and repeatable experiments of reproduced samples bench marked to common day gypsum encapsulation technologies following the ASTM E1354 standard using a Cone Calorimeter [17]. This chapter concludes with preliminary guidance and research needs forward for the engineering conservationists who encounters these coatings in practice. These findings will help in understanding the progression of the use of timber encapsulations through history, explaining how we have arrived at current practices today, and to assist current architects and engineers who may have to comment on the coatings relative inefficiencies or efficiencies.

## 3.2 Background and History of Timber Encapsulations

Encapsulation materials are meant to improve the fire performance of timber first by creating an incombustible barrier to the timber, but later evolving to perform as a heat transfer barrier. A number of these encapsulation technology methods will be reviewed in the following section; including metal plates, plasters, whitewash paints (chosen as they are found in heritage constructions), and gypsum board (chosen for contemporary bench marking). A timeline of early mentions and descriptions of these encapsulations is seen in Figure 3.2.

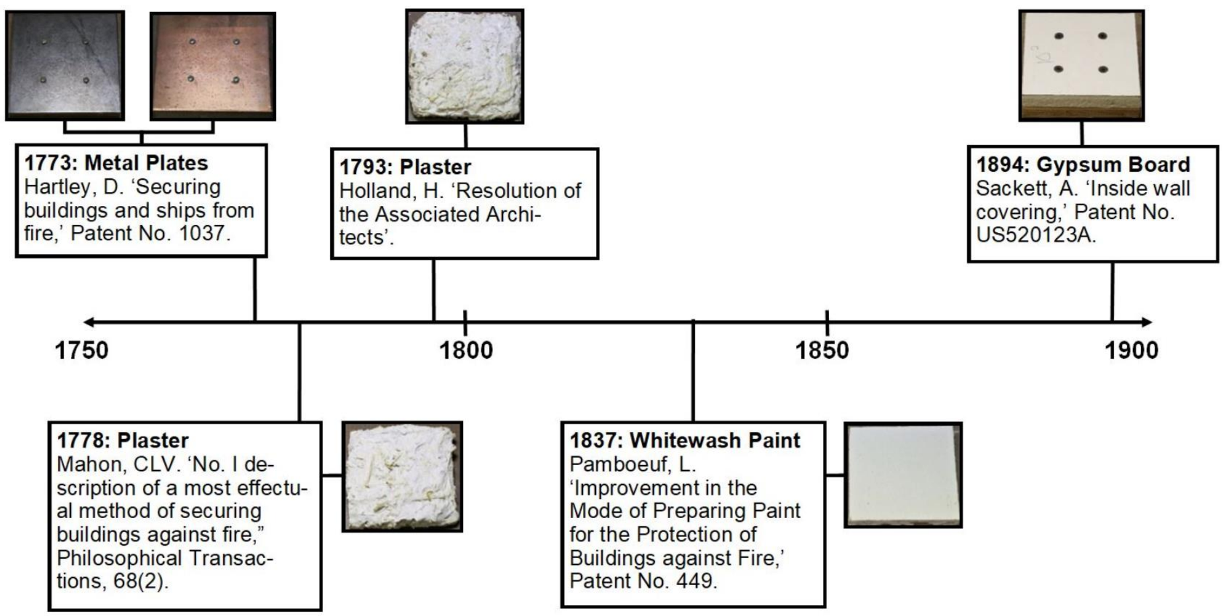



Figure 3.2 A timeline of early mentions of encapsulation methods for improving the fire performance of timber assemblies.

It is of interest to the reader that many other early 18$^{th}$ and 19$^{th}$ century fire protection technologies can be found in early construction (for example the Roebling System, the Barret-Fox floor), however this chapter's scope is to consider technologies that were explicitly used for timber-based systems. It is by no means a full comprehensive listing of all possible coatings; these procedures may be adaptable should the conservationist encounter alternative technologies. The coatings considered herein represent the coatings with the first documented controlled testing in which measurements were taken and recorded in the English language. It is possible that other historical tests of timber encapsulations were documented in other languages, and these should be explored through future research.

Prior to the use of documented encapsulation methods, timber buildings have long been left exposed. An exposed heritage timber building (currently used as a retail store) is seen in Figure 3.3. In the late 18$^{th}$ century, a group of well regarded architects formed a committee (known as the Associated Architects) to deal with the fire problem that they believed was disrupting London, UK, and other cities [41], this committee was formed in response to a recent theatre fire. This association would be later viewed as the precursor to Royal Institute of British Architects (RIBA). Led by Henry Holland, they aimed to identify the causes of the recent conflagrations, as well as methods of preventing similar fires from occurring in the future. The Associated Architects, as they called themselves, described and instructed the use of metal plates and plasters for use as fire protection encapsulations.

Figure 3.3 An exposed timber building, constructed in 1902 as a warehouse in Toronto, Canada (author's photo).

Holland also tested and reported on encapsulation methods such as Hartley's metal fire plates and Mahon's plaster, performing six fire tests on each encapsulation. The tests generally consisted of applying the encapsulation to walls, floors, or staircases, and exposing the setup to a seemingly arbitrary fire severity [41]. Holland then described the post-fire state of the assemblies, mentioning the extent and location of the charring. In the following centuries, other encapsulations were created, including whitewash paints and, more recently, gypsum board.

### 3.2.1 Metal plates

The use of metal plates as an encapsulation for improving fire performance was described by David Hartley in 1773 in his English patent, "Securing buildings and ships from fire" [42]. In his method, Hartley describes the use of metal plates to prevent fire and air currents from reaching the encapsulated material. Hartley's suggesting fire plates of iron, as well as copper as a more expensive option that he believed would not rust [43]. Arguably, Hartley can be credited as receiving the first governmental grant to study fire protection systems as he was awarded as a member of the UK Parliament. Fire testing of the metal plates occurred more pronouncedly by Hartley in 1792, largely consisting of lining timber elements and buildings with the metal fire plates, exposing them to a fire of arbitrary severity, and observing the damage [41, 44]. By 1793 the metal plates are deemed 'effectual' by the Associated Architects [41]. Today, there is a monument (consisting of an obelisk with inscription) commemorating the site where Hartley performed his first fire tests – arguably the first documented fire tests in 1776. This monument is seen today in Figure 3.4 and is a grade 2 heritage structure. The structure in which he tested his plates is no longer in existence.

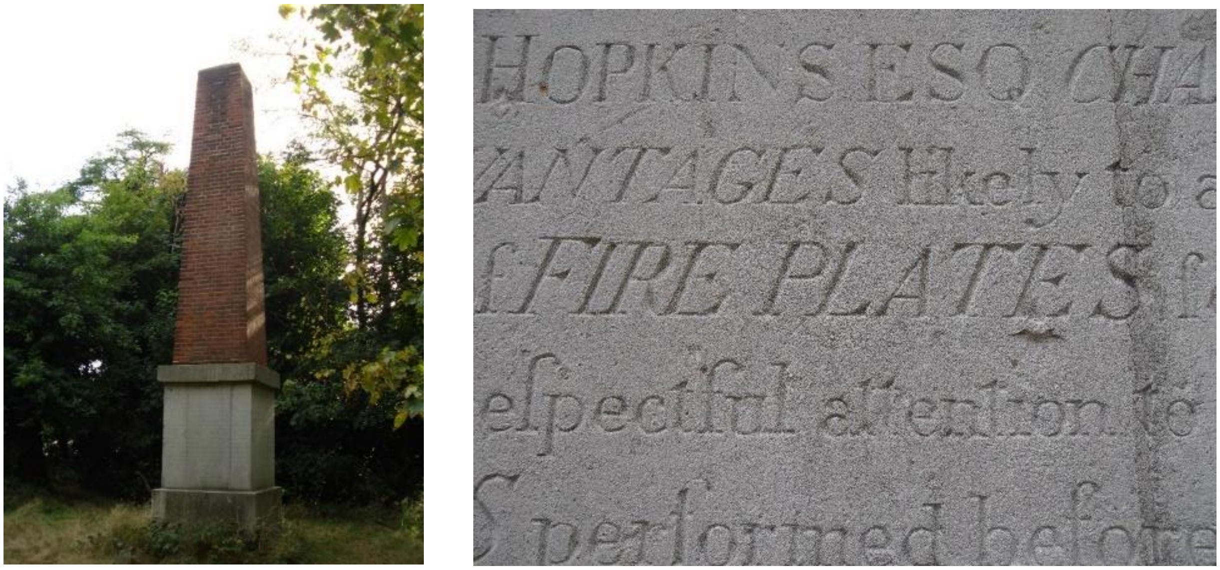



Figure 3.4 Monument on the site of Hartley's fire plate tests at Putney Heath (by permission).

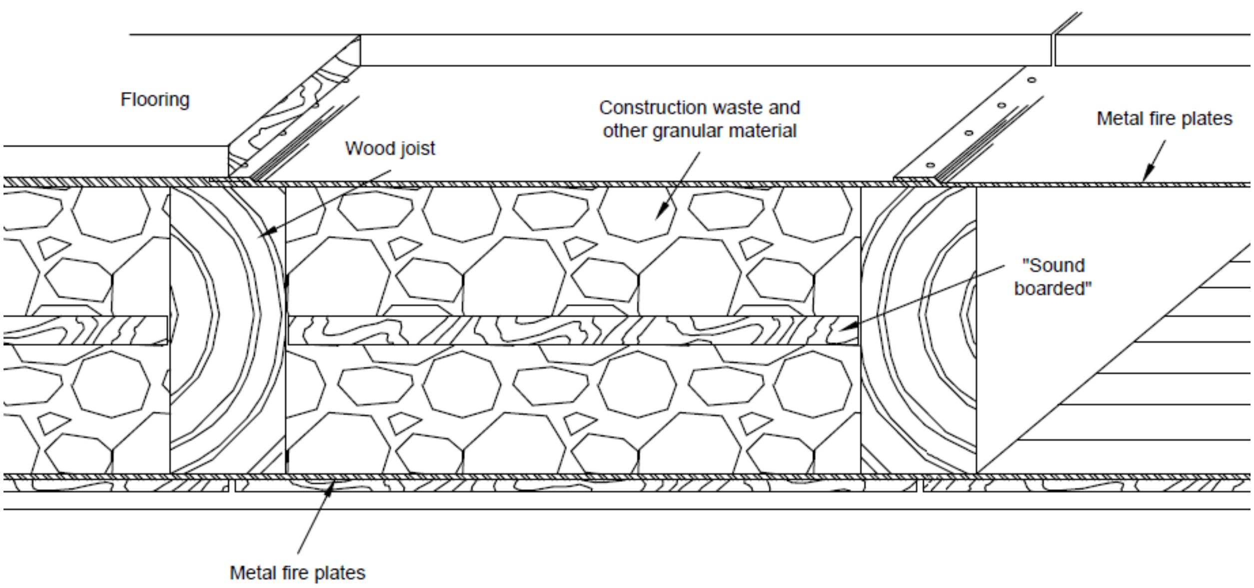
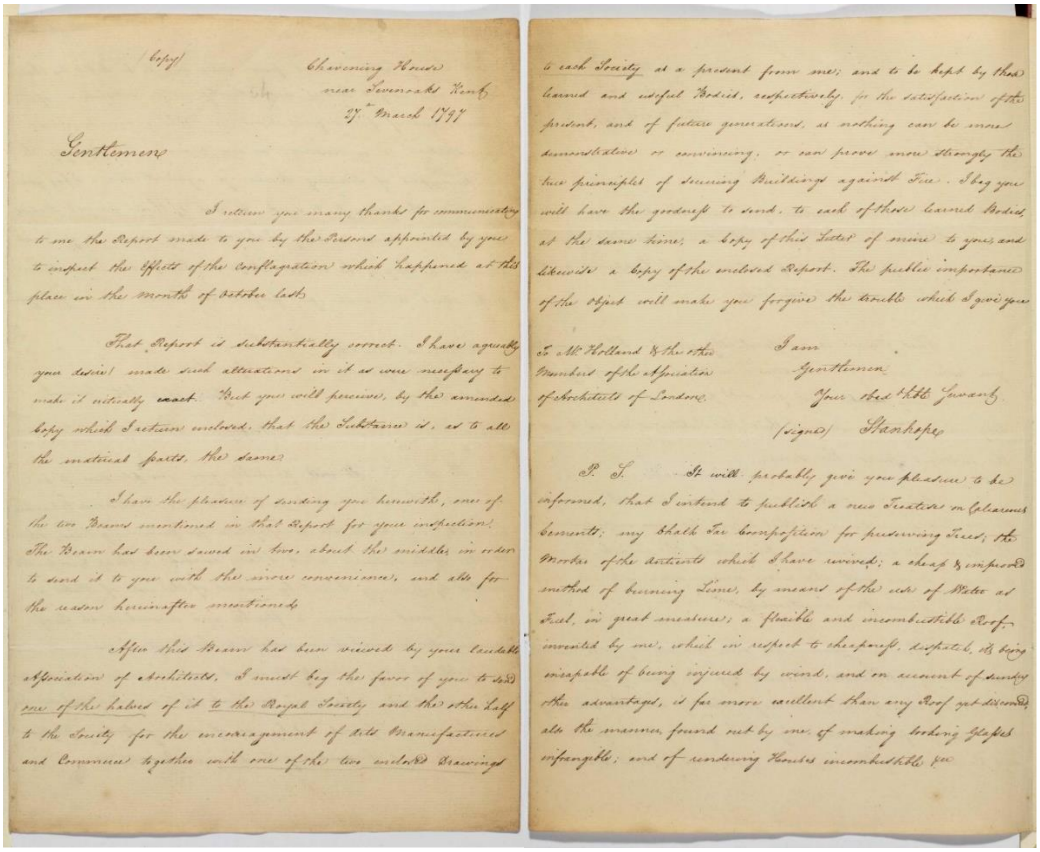



Figure 3.5 An alternative configuration of installing metal plates on wooden joists (as adapted from [45]).

### 3.2.2 Plasters

The use of plaster as an encapsulation material was also discussed by the Associated Architects [41]. The use of plaster was originally proposed by Charles Mahon (3rd Earl Stanhope) and was later recreated and modified by Henry Holland. The plaster by Mahon was first published in the Philosophical Transactions Journal in 1778 [46]. Mahon carefully outlines the proportions and ingredients of the plaster, as well as the proper method of application in a house, by “underflooring, extra lathing, and inter-securing” [46]. Mahon also performed fire tests of his plaster, and the results of the experiments were also published in 1778. Similar to Hartley’s tests, they mostly comprised of using the encapsulation to cover timber members and exposing the assembly to an arbitrary fire [46]. Henry Holland and the Associated Architects deemed Mahon’s plaster to also be ‘effectual’, but believed there was more liability for injury than Hartley’s metal plates as it seemed to fall off in most tests performed [41].

After the release of Holland’s report in 1793, Mahon forwarded a letter to the Royal Society via the Associated Architects in 1796. This letter can be seen in Figure 3.6. The letter was in response to a fire at Mahon’s residence, Chevening House where Mahon’s plaster was used (which still stands today). Charles Mahon was prompted to forward a beam with attached plaster from Chevening House fire for their inspection. The letter and beam were sought to be lost, indeed the beam has since been discarded; however, the letter was found for digitization and contemporary analysis.



(Copy)

Chevening House
near Sevenoaks Kent
27th March 1797

Gentlemen

I return you many thanks for communicating to me the Report made to you by the Persons appointed by you to inspect the Effects of the Conflagration which happened at this place in the month of October last.

That Report is substantially correct. I have agreeably to your desire made such alterations in it as were necessary to make it critically exact. But you will perceive, by the amended Copy which I return enclosed, that the Substance is, as to all the material parts, the same.

I have the pleasure of sending you herewith, one of the two Beams mentioned in that Report for your inspection. The Beam has been sawed in two, about the middle, in order to send it to you with the more convenience, and also for the reason hereinafter mentioned.

After this Beam has been viewed by your laudable Association of Architects, I must beg the favor of you to send one of the halves of it to the Royal Society and the other half to the Society for the encouragement of Arts Manufactures and Commerce together with one of the two enclosed Drawings to each Society as a present from me; and to be kept by those learned and useful Bodies, respectively, for the satisfaction of the present, and of future generations, as nothing can be more demonstrative or convincing, or can prove more strongly the true principles of securing Buildings against Fire. I beg you will have the goodness to send, to each of those learned Bodies, at the same time, a Copy of this Letter of mine to you, and likewise a Copy of the enclosed Report. The public importance of the Object will make you forgive the trouble which I give you.

To Mr. Holland & the other Members of the Association of Architects of London.

I am
Gentlemen
Your obed.t h'ble Servant
(signed) Stanhope

P. S. It will probably give you pleasure to be informed, that I intend to publish a new Treatise on Calcareous Cements; my Chalk Tar Composition for preserving Trees; the Mortar of the Antients which I have revived; a cheap & improved method of burning Lime, by means of the use of Water as Fuel, in great measure; a flexible and incombustible Roof, invented by me, which in respect to cheapness, dispatch, its being incapable of being injured by wind, and on account of sundry other advantages, is far more excellent than any Roof yet discovered; also the manner found out by me of making looking Glasses infrangible; and of rendering Houses incombustible &c.

Figure 3.6 Letter from Mahon dated 1796, to the Royal Society and Associated Architects, in response to a fire at Chevening House.

The letter explains that Mahon forwarded with his letter a beam from Chevening house that had been cut in two, about the center. He asked the Association of Architects to forward half of the beam to the Royal Society and the other half to the Society for the Encouragement of the Arts, Manufactures and Commerce. Mahon hoped that these societies would keep these beams for the education of the society members, present and future, to prove his method of securing buildings from fire.

Henry Holland, in the report of the Associated Architects, expands upon the Mahon's plaster through the suggestion of several additives in 1793. The possible additives suggested include "plaster of Paris, brick rubbish, coal ashes, or any other materials that will form a cement when mixed with hair or chopped hay" [41].

Following Holland's study of these technologies, in 1794, both Mahon and Hartley's technologies were used in the construction of the floors and stairs in the mostly timber-framed Drury Lane Theatre (Theatre Royal) in London, UK designed by Henry Holland as architect [47]. The Drury Lane Theatre was considered the most advanced fire-proofed building of the time. Four water reservoirs were also installed on the roof in order to suppress fire should it occur (akin to a sprinkler system). However, during theatrical performances, these reservoirs served another purpose: the tanks were used to produce real waterfalls and lakes on stage – at the expense of fire-fighting. In 1809, the theatre caught fire while its water tanks were empty and the installed technologies were insufficient to protect the building. The building collapsed before 30 minutes – there was no reported life loss (Figure 3.7). Following this fire, there is limited evidence that these technologies were used in buildings following 1810.

Figure 3.7 Drury Lane Theatre Fire (Prints from 1825).

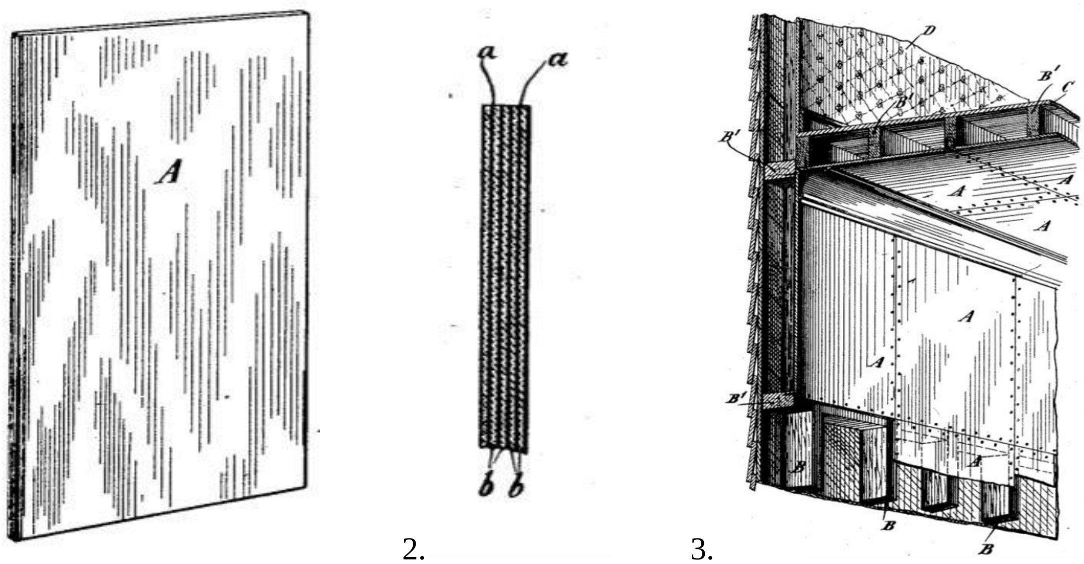
### 3.2.3 Whitewash (lime-based) paints

Lime based paints, which will herein be referred to as whitewash paints, were another encapsulation technique used to enhance fire performance. Whitewash paint, which in its most basic form is the mixture of water and lime, was widely used in the 18$^{th}$ century, though there is little evidence that it was used for fire purposes at that time [48]. To the author's knowledge, the first documented use of whitewash paint for fire performance purposes appears in the 19$^{th}$ century. In 1837, Louis Paimboeuf filed a United States patent titled, "Improvement in the Mode of

Preparing Paint for the Protection of Buildings Against Fire" [49]. In this patent, Paimboeuf describes a mixture primarily of water and slaked (hydrated) lime, with other possible additives such as alum, potash, and salt, as well as plaster of Paris if the whitewash is desired to be white, to help render wood incombustible [49].

### 3.2.4 Gypsum board

The precursor to gypsum board was first documented in the late 19$^{th}$ century and was then known as Sackett Board. In 1894, Augustine Sackett patented his inside wall covering [50]. In his patent, Sackett describes a board which is to be applied to the interior walls of rooms, made up of multiple layers of paper and calcined gypsum, which makes a firm and durable wall surface. Sackett also claims his invention to be fire-proof and discourages the use of any materials that soften when heated in the creation of the boards (such as ozocerite and bitumen) [50]. The images included in Sackett's patent are seen in Figure 3.8. In Figure 3.8, 'A' denotes Sackett Board, 'B' and 'B' denote vertical and horizontal framing respectively, 'C' is the floor, 'D' is a decorated wall, 'a' is layers of paper and 'b' is layers of plaster [50]. Gypsum board is still used for fire purposes today, usually considered as a board with a non-combustible core (usually primarily of gypsum), with paper on the outer surfaces [51]. Today, current code provisions in Canada (the thesis author's jurisdiction) allow for the use of multiple layers of Type X gypsum board to provide a fire resistance rating of 15-60 minutes to timber elements (provided that requirements for joints fastening are adhered to) [29]. In the 1917-1919 column test series led by Simon Ingberg, gypsum board technologies were assessed for the first time to the standard temperature-time heating curve (these tests will be discussed further in Chapter 5) [52]. While the academic community is still studying this technology with respect to installation and fall off in fire, it is relatively understood to its performance, and therefore this technology is utilized as a bench mark for evaluation of the previous technologies.




1. 2. 3.

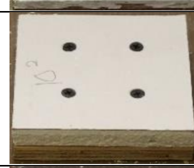
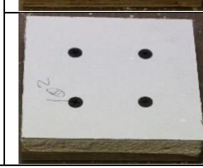
Figure 3.8 Images from Sackett's patent for an interior wall covering, 1. plan view, 2. cross-section view, showing built up layers of paper and calcined gypsum, and 3. possible applications of the boards (from [50]).

**3.3 Experimental Methodology**

The experimental portion of this chapter will begin to look at how these encapsulation materials perform in fire using contemporary test methods. As mentioned in the previous sections, many of the historic encapsulations were not tested using any type of standardized method during their creation and have had dubious performance when considered in real installation and real fires. Six encapsulations were created or obtained and tested herein. Each of these encapsulations was applied to a 12 mm piece of plywood of dimensions of 100 x 100 mm as required by the test apparatus in the ASTM E1354 standard. Plywood was chosen as a substrate for the encapsulations, as it is a contemporary material used today in wall and ceiling constructions. Solid wood could have alternatively been used as a substrate. The evaluation of the encapsulation systems is relative to the performance of the control, so the important element is that the substrate is kept common between all samples. All materials were allowed to acclimatize to laboratory conditions, and all plywood substrates had a moisture content of near 10% at the time of testing. For the metal plates and the gypsum board, the encapsulations were screwed into the plywood using one screw at each of the four corners, 30 mm from each side. An additional unencapsulated piece of plywood was also tested for comparison. The encapsulation compositions and original measurements are summarized in Table 3.2.

Table 3.2 Encapsulation compositions, photographs, and original measurements.

| **Sample ID** | **Encapsulation Name** | **Photo** | **Thickness (mm)** | **Mass (g)** |
|---|---|---|---|---|
| 1A | Control |  | 12.2 | 61.9 |
| 1B | |  | 12.0 | 61.9 |
| 2A | Mahon Plaster |  | 23.9 | 202.2 |
| 2B | |  | 28.9 | 212.2 |
| 3A | Holland Plaster |  | 27.4 | 219.9 |
| 3B | |  | 29.6 | 219.9 |
| 4A | Iron Plate |  | 15.0 | 320.0 |

| Sample ID | Encapsulation Name | Photo | Thickness (mm) | Mass (g) |
|---|---|---|---|---|
| 4B | |  | 15.0 | 320.0 |
| 5A | Copper Plate |  | 15.0 | 364.8 |
| 5B | |  | 15.0 | 364.6 |
| 6A | Whitewash Paint |  | 12.0 | 67.0 |
| 6B | |  | 12.0 | 70.0 |
| 7A | Gypsum Board |  | 28.8 | 178.3 |
| 7B | |  | 27.8 | 164.0 |

Assumptions needed to be made in creating and procuring materials since the original inventors did not always provide all of the required information necessary to reproduce their materials and technologies. In creating the plasters, ratios of some of the materials were stated but it was not clarified whether the ratios were by volume or by mass. It was decided to assume the ratios were by volume, as hay had the largest ratio but was the lightest material, and therefore it seemed unreasonable that the compositions would be by mass. Other materials included in the plasters were not assigned a ratio (particularly in the Holland plaster). It was decided to arbitrarily add half of one measure of each of the ingredients that was not assigned a ratio. Furthermore, the Hartley fire plates were described as being thin without an exact specified thickness. The thickness of the metal plates was therefore taken as 3 mm, correlating to the plate thickness found in a heritage building which used this method.

The whitewash paint was created by soaking the (hydrated) lime in 500 ml of water. The salt was also dissolved in 415 ml of water. The two mixtures were then combined. As previously mentioned, the gypsum board tested represents a modern gypsum board used today, rather than attempting to the replication of an original. The gypsum board can therefore be considered a contemporary encapsulation method (hence benchmark). The original descriptions of the encapsulation materials as compared to the materials tested is seen in Table 3.3.

A Cone Calorimeter apparatus was used for testing, following the ASTM E1354 standard. This test setup can be seen in Figure 2.5. The Cone Calorimeter apparatus is useful in allowing for controlled and repeatable tests. Each of the test specimens was exposed to heat for 5 minutes, at a heat flux of 50 $kW/m^2$. The test severity was determined through trial and error, as an upper limit of what an unencapsulated piece of plywood can withstand before charring completely though its depth. After testing, the char depth was measured under the encapsulations. It is of note, that for practicality the testing was not extended beyond 5 minutes or at more severe heat exposures. A material specific test was used to rank performances, further research could be done to explore performance of these materials against more severe testing, however as will be described in Section 4 of this chapter, most heritage material coatings performed poorly in short duration and low heat flux testing.

Table 3.3 Original descriptions of historic materials and the composition of materials tested.

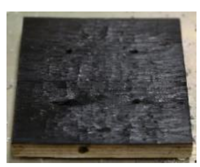
| Encapsulation Method | Documented composition | Experimental composition |
|---|---|---|
| Mahon Plaster | One measure rough sand<br>Two measures slacked lime<br>Three measures chopped hay<br>Well mixed with water | 300 ml Hydrated lime<br>150 ml Sand<br>175 ml Water<br>600 ml Hay |
| Holland Plaster | Mahon Plaster; with possible additions of:<br>Plaster of Paris<br>Brick rubbish<br>Coal ashes<br>Hair or chopped hay<br>Any other materials which form a Cement | 300 ml Hydrated lime<br>150 ml Sand<br>75 ml Brick<br>75 ml Plaster of Paris<br>75 ml Seashell<br>240 ml Water<br>600 ml Hay [a] |
| Iron Plate | Unvarnished or Varnished plates of metal | 3 mm thick iron |
| Copper Plate | Unvarnished or Varnished plates of metal | 3 mm thick copper |
| Whitewash Paint | 1 Gallon Slaked Lime with Water<br>20 Pounds Alum<br>15 Pounds Potash<br>1 Bushel of Salt | 500 g Hydrated Lime<br>965 ml Water<br>150 g Salt |
| Sackett Board/ Gypsum Board | 4-10 Alternating layers of Manila paper or builders sheathing paper, and calcined gypsum or Plaster of Paris | 1 layer 15.9 mm Type X Gypsum Board |

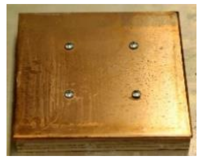
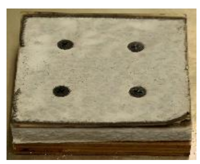
[1] – Measures were taken by volume not by mass to replicate older procedures.

### 3.4 Results

A summary of post-heating photos of all of the specimen is seen in Table 3.4. This table also describes the flaming behaviour, as well as the char depth recorded after testing. The char depth was determined visually by colour, by subtracting the depth of uncharred wood from the original sample depth. The charred portion of the wood was taken to be any portion that was black in colour.

Table 3.4 Post-heating images of each sample.

| **Sample ID** | **Encapsulation Name** | **Post-Burn Photo** | **Char Depth (mm)** | **Flaming Observations** |
|---|---|---|---|---|
| 1A | Control | N/A[1] | N/A[1] | Immediate ignition, through to test completion |
| 1B | |  | 11 | |
| 2A | Mahon Plater |  | 0 | No flaming, some smoke observed |
| 2B | |  | 0 | |
| 3A | Holland Plaster |  | 0 | No flaming, some smoke observed |
| 3B | |  | 0 | |
| 4A | Iron Plate |  | 3 | Flaming though screw holes |
| 4B | |  | 2.5 | |
| 5A | Copper Plate |  | 0 | No flaming or smoke observed |

| Sample ID | Encapsulation Name | Post-Burn Photo | Char Depth (mm) | Flaming Observations |
|---|---|---|---|---|
| 5B | |  | 0 | |
| 6A | Whitewash Paint |  | 10 | Ignition occurs 20 seconds after test begins, through to test end |
| 6B | |  | 9.5 | |
| 7A | Gypsum Board |  | 0 | Flaming initially for 15 seconds, then no additional flaming or smoke |
| 7B | |  | 0 | |

[1]- Sample 1A was used to determine an appropriate exposure time and was heated for 15 minutes, at which point it had burned through. For that reason, char depth and post-burn photo are not provided.

Other properties which were recorded include the heat release rates over time. These heat release rates can be seen in Figure 3.9 (all heat release rates represent the average of two samples). This figure shows the heat release rates of the control sample, gypsum board, and whitewash paint. These three are the only samples that had flaming, and the peak heat release rates of the remaining samples were under 15 $kW/m^2$ and are therefore not included in this figure. The final property which will be discussed is the mass loss of the samples. The mass loss over time for every encapsulation material is seen in Figure 3.10 (all mass losses represent the average of two samples).

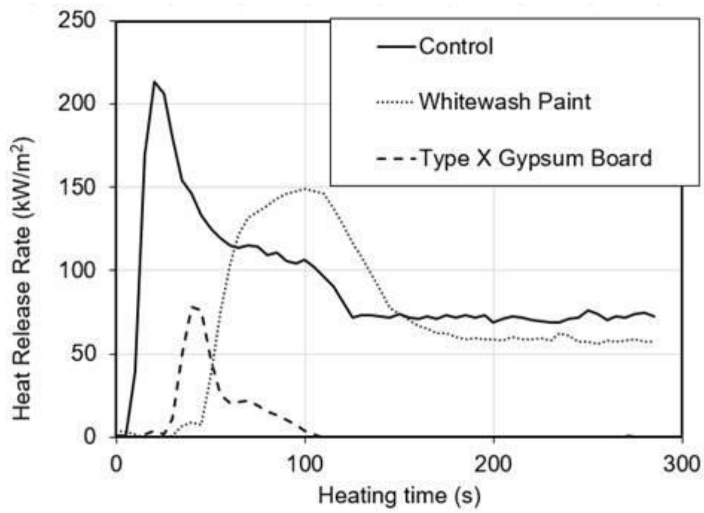



Figure 3.9 Heat release rates over time for the control, whitewash, and gypsum board encapsulations.

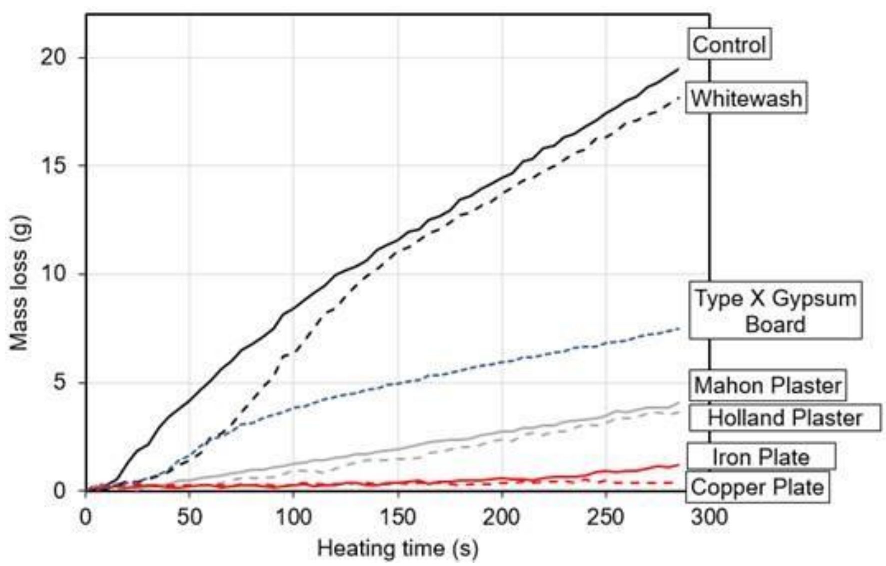



Figure 3.10 Mass loss of the control sample, as well as the historic and contemporary encapsulations.

### 3.5 Discussion

The control sample (unprotected plywood) reported the highest amounts of char, mass loss, and heat release, as expected since it had no encapsulation. The plasters did appear, at first, to improve the fire performance of the timber. No charring occurred on any of the plaster samples, confirming historic fire tests performed by Mahon [46]. Some mass loss was recorded (Figure 3.10), which is attributed to moisture evaporation in the plaster since no flaming or charring occurred on the timber. A major challenge facing the historic plasters was their cohesiveness. Since the plasters were applied to the plywood horizontally, they remained attached during testing, however afterwards they fell off when removed from the testing apparatus, which may be attributed to the dehydration of the plaster. This indicates that the plasters would not be suitable for vertical or upside-down applications, such as walls or ceilings (where they would be installed), as they would be likely to fall off of the surface they are applied to when exposed to fire. Since the plasters do not stay attached to the timber surfaces, they had little to offer with regards to improving fire performance.

The metal plates somewhat improved the fire performance of the timber. While the iron plates had some flaming through the screw hole, a char depth of only 2.5-3 mm was measured after testing (indicating a smouldering fire under the plate), which is still considerably (75%) less than the 11 mm on the control sample. Caution is advised in interpreting this result, as the duration of heating was small, and longer duration testing may not show favourable performance. While away from the screw hole no flaming occurred, heat transfer into the timber still occurred, causing degradation to begin in the depth of the timber. This can be seen in Figure 3.11. As heat transfer was noticeably occurring through the iron plate and into the timber, the effectiveness of the iron plate at protecting the timber was limited.

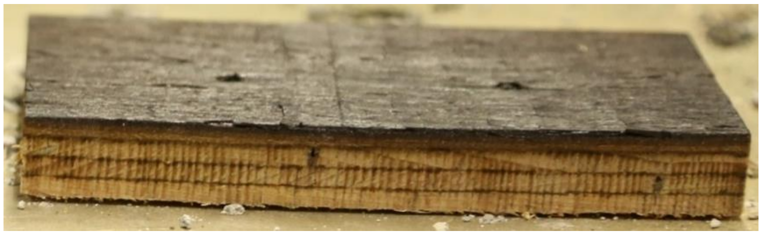


Figure 3.11 Degradation process beginning on the timber, seen after removal of the iron plate.

The copper plate did not have any flaming or charring, and for this reason, it could arguably be said that the copper plate performed superior to the iron plate. The performance of the copper however, is likely due to the reflective surface of the copper. The radiant heat emitted from the Cone Calorimeter would have been reflected by the surface of the copper, and therefore the timber underneath was unharmed. Oxidized copper plates were not tested, and these would be of interest to consider in future studies. Copper is known to oxidize, so while a new copper plate may be reflective, this reflective property will diminish once oxidation occurs [53]. It is likely that the fire performance of copper plates will therefore change throughout their life cycle depending on their reflectiveness at the time of the fire. As heritage building are often hundreds of years old, it is extremely likely that the reflective surface would no longer be present should these plates be found in a heritage building, and therefore their effectiveness at improving the fire performance of timber is likely to be reduced. Another consideration for both of the metal plates, is the possibility of a smouldering fire under the plates, especially as it may be difficult to avoid gaps in the continuity of the plates which would allow oxygen to promote a fire behind the plates. The possibility of metal plates fostering a smouldering fire would need to be considered should they be found in a structure.

Whitewash paint improved the fire performance of the timber only minimally. Ignition of the sample was delayed by about 20 seconds compared to the control sample, as seen in Figure 3.9. The char depth was only slightly reduced, at 9.5-10 mm compared to the 11 mm measured on the control sample, a reduction of about 11%. This indicates that the whitewash paint method only marginally improved the fire performance of the timber, by very slightly delaying the time to ignition.

Finally, the contemporary gypsum board did improve the fire performance of the timber. The layer of paper on top of the gypsum board ignited approximately 35 seconds after beginning the test and flamed for approximately 15 seconds. This is reflected in the heat release rate seen in Figure 3.10. Regardless of the small amount of flaming observed, the wood under the gypsum board was uncharred. Mass loss occurred in the gypsum board, which is attributed to moisture loss of the gypsum. The contemporary gypsum board was the only encapsulation method tested that improved the fire performance of the timber, whilst staying properly fastened.

### 3.6 Limitations and Future Research

Many of the encapsulations were assembled using assumptions (where missing information was not provided by the encapsulation inventor) and using materials available today. While the assumptions made in creating the encapsulations, as well as the materials used, may have altered the fire performance slightly, it is unlikely the results would be significantly different. There is no evidence to suggest that any of the alterations made to the plasters would have improved their cohesion, nor that any of the optional additives to the whitewash paint would remarkedly further delay time to ignition. The metal plates were taken arbitrarily as 3 mm, and in practical applications it is not likely that the plates would be found to be significantly thicker than this (to a point which would delay heat transfer into the wood at low heating durations).

The next limitation that will be discussed is the scale of the samples tested. The small scale of 100 x 100 mm is not representative of a room lined with a particular encapsulation. In addition, the heat exposure of 50 $kW/m^2$ for five minutes is not representative of a realistic fire. For these reasons it cannot be said that the tests performed represent a real fire that may occur in a heritage building. However, despite the small scale of the tests, this study was successful in showing that the historic encapsulations made no real contributions to the fire performance of the timber even at this low severity of exposure. Even the short tests described above were successful in determining that the plasters are limited in their capacity to stay attached to the timber, the whitewash paint only minimally delayed ignition, and the iron plate still allowed for flaming and heat transfer into the timber. A more severe heat exposure is likely to only amplify these effects.

The final limitation that will be mentioned is that in order to successfully conserve heritage buildings, architects and engineers need to understand how the original historic materials will perform in fire. As seen in the previous sections, there are several differences between the historic materials used and manufacturing methods, and the materials and methods used today, all of which may alter the anticipated fire performance of these structures.

### 3.7 Conclusions

Heritage buildings often see immense public support for their conservation and keeping them safe from fire is an important part of this effort. This chapter was useful in examining the history of encapsulating timber to improve its fire performance, and in providing a preliminary indication of how much these encapsulations actually improve the fire performance. Plasters, metal plates, whitewash paints, and gypsum boards were all examined. Experimental testing through the use of a Cone Calorimeter apparatus gave insight to the charring, flaming, mass loss, and heat release rates of these historic and contemporary encapsulations, to understand how much these historic encapsulations improved the fire performance of the assembly.

The results of the experimental tests showed that the plasters performed relatively similar to the contemporary gypsum board, experiencing moisture loss but succeeding in protecting the timber from flaming and char. The improvement to the contemporary gypsum board is that it provides a smooth and flat surface for interior walls and remained attached to the timber better than the plasters (using screws). The plasters however, became detached from the timber quite easily after testing, making them impractical for the purpose of improving the fire performance of timber. Both the copper and iron plates significantly reducing the char on the surface of the timber, however, the iron plate still transferred enough heat into the timber to cause it to begin to degrade, and the performance of the copper plate is attributed to its reflective surface, which will have most likely been lost due to oxidation in most heritage structures. The whitewash paint delayed ignition of the timber by only about 20 seconds; otherwise, the performance of the whitewash was somewhat comparable to that of the unencapsulated control sample.

From these tests, it is seen that none of the historic encapsulations tested made significant contributions to the fire performance of the timber, with only the contemporary gypsum board successfully protecting the timber without any obvious disadvantages. To the author's knowledge, this study is the only source of contemporary testing of these particular historic encapsulations, and the results of these tests suggest that should these encapsulations be found in a heritage building, they cannot be relied upon for fire. With regard to the conservation of the heritage building, it may be necessary to keep them in tact nevertheless (as they would almost certainly offer insight into the technologies of the time period), but even in this case they cannot be assumed to protect the timber against fire. Other strategies may be required in enhancing the fire performance of the heritage structure, which can be implemented without detracting from the heritage value of the building- for instance, there ways to respectfully integrate sprinklers into a heritage building, and regular building maintenance may also be beneficial.

This chapter has also shown that while none of the historic encapsulations were successful at significantly improving the fire performance of timber, the contemporary gypsum board did offer some protection to timber at this very small scale. The results of these Cone Calorimeter tests showed no charring under the gypsum board, and the gypsum board remained fastened to the timber throughout the test. While in this setup the gypsum board performed favorably, there is a need to further explore its performance through a variety of more severe heat exposures before any conclusions about its real scale performance can be made. The following chapter, Chapter 4, will therefore examine the performance of gypsum board at a larger scale using different heat exposures.

Further, this chapter demonstrated that additional research is needed on the fire performance more historic materials and assembly configurations, such as on the timber itself. Many historic structures do not use encapsulations (potentially due to restrictions around heritage designation), and the timber is then left exposed to fire. The fire performance of historic timber itself therefore needs to be investigated due to differences between historic and contemporary versions of similar materials (as has previously been mentioned). Chapter 5 will begin to evaluate the current state of knowledge of the fire performance of historic timber and will extend this understanding through novel experimental tests.

This chapter provided a thorough analysis of the progression of historic encapsulations used for fire through time, as well as an evaluation of the fire performance of these encapsulations. By understanding the history and evolution of encapsulation materials as well as their fire performance, architects and engineers who encounter these encapsulations can better assess the most effective way to conserve a heritage structure. Through further research into the fire performance of historic structures and materials, the successful conservation of cultural heritage buildings becomes possible.

## Chapter 4 : Performance of Type X Gypsum Board on Timber to Non-Standard Fire Exposure

### 4.1 Introduction & Motivation

In the previous chapter, it was seen that while the historic encapsulation measures were not effective at protecting timber from fire, the contemporary gypsum board was able to prevent charring of timber at the small scale considered. This finding indicated to the need for larger scale tests of contemporary gypsum board, that would be more representative of realistic construction. The focus of the fire performance of timber encapsulation materials herein will therefore shift to a predominant contemporary material, fire-rated Type X gypsum board, which is the basis of this chapter.

While the small-scale tests in Chapter 3 showed that in that particular test setup, gypsum board prevented timber from charring at a low heat flux and test duration, previous studies by other researchers have shown that fire-rated gypsum board may not remain fully intact for the entire time needed for auto-extinction within a compartment fire. Recent tests have provided evidence that gypsum board may not effectively remain fastened to timber members during fire exposure in a compartment and fall off is largely attributed to its multiple dehydration reactions [54], screw failure, and/or discrete cracking of the boards (where studies have shown that cracks can act as pathways for heat flow) [55]. For years, research institutions have been noting the fall off of gypsum board in fire experiments [6]. The compartment fire test series performed by NIST and NRCC are a recent example [4]. In those tests, researchers noted that gypsum board fall off occurred in their test configurations, with the severity of fall off ranging from only the face layer of gypsum board falling off, to up to all three layers of gypsum board falling off [4]. Edinburgh-Arup researchers [5] have also noted the fall off of gypsum board during fires in their 2.72 x 2.72 x 2.77 m timber compartments reporting that the dozens of pieces (together weighing over one hundred kilograms) of plasterboard fell off during their experiments. In the literature review conducted by Brandon & Östman [56], several previously reported cases of second flashovers linked to the fall off of multiple layers of gypsum board were identified. These findings reinforce the indication that gypsum board fall off is of concern for timber structures. It should also be noted that for all of these studies, the sizes of the compartments have been approximately the size of a residential room and the bulk of the research has concerned CLT surfaces, which highlights the need for more investigation into larger compartments and various other timber-products and materials.

The present lack of ability to predict the fire performance of protective systems, such as gypsum board, has been identified as a major obstacle in modelling the fire-structure response of timber buildings in non-standard fires [57]. So far, the bulk of the research has focused on compartments the size of smaller rooms and on encapsulation of CLT surfaces rather than structural members such as beams and columns. There will be unique differences in the encapsulation techniques of beams and columns, since the members will need to be encapsulated on multiple sides and will require different methods of overlapping and connection. This has provided the motivation to examine the fire performance of stand-alone timber columns, typical of open space construction, that have been encapsulated with (multi-layered) gypsum board as subjected to non-standard fires in two stages: a field and a controlled laboratory experimental study.

In this chapter, results are presented from a field study and controlled laboratory study in which stand-alone timber columns encapsulated with multi-layered fire rated (Type X) gypsum board are exposed to a steep rise in temperature (initial ramp rate faster than the standard temperature-time heating curve) to a credible high-temperature plateau (greater than 800℃)

possible in a real fire. The duration of heating in the studies lasted no more than half an hour (a time suggested by the extinction time within the field study). These tests will also consider the damage to the timber after the fire is extinguished, as it has been previously reported that gypsum boards have fallen off post-fire [4].

It is important to discuss that this chapter's scope is not to define a realistic fire scenario in a real timber structure nor study its compartmentalized fire dynamic behaviour – indeed the fire scenarios illustrated herein are a few of many possible scenarios that timber structures with gypsum boards may experience. It is acknowledged that other fire scenarios and fire dynamic testing can help verify or advance the fire behaviours reported herein. The value of the study discussed in this chapter is that the research can be built upon by others while illustrating novel encapsulation behaviours not entirely documented before in fire exposures, particularly where the fire exposure is of a non-standard nature with natural cooling (auto-extinction) phase.

**4.2 Experimental Design and Methodology**

As current drivers are being considered for large open architectural spaces in construction, attention is focused on stand-alone columns. The two-stage study was performed sequentially meaning the results of the field study, pilot in nature, had impacted the experimental design and methodology of the second stage of the research project, controlled laboratory tests. The first stage of the project was motivated by the construction of the Canadian Brock Commons building, a 53 m tall hybrid concrete- timber structure where columns were at times installed as stand-alone with multi-layers of gypsum board. Figure 4.1 illustrates an encapsulated column, representative of encapsulation systems used in existing Canadian tall timber structures. In the study herein, care was made to obtain materials representative of actual construction techniques that would be employed in tall timber buildings in Canada i.e., the same manufacturers and specifications of

Type X gypsum board available to the Canadian market. Various other gypsum technologies should be explored through future studies.

Figure 4.1 Encapsulation installation procedure of a stand-alone column (prior to gap sealing/wall finishing), representative of encapsulation used in Canadian tall timber structures (by permission).

### 4.2.1 Field study

A farm structure (a timber barn) with a floor area of 317 $m^2$ was procured for a large-scale burn conducted in Southern Ontario through multiple partners (primarily the security and insurance industry as well as for fire-fighting training). The building dates to as early as 1890 – though it was not categorized as a heritage structure. The field study burn was the last procedure performed on that site that day, and therefore heavily restricted the amount of instrumentation and field preparation which was allowed, requiring certain limitations, and ultimately justifying the need for a controlled study that would follow (detailed in Section 4.2.2).

Although the structure was relatively empty of contents, some mixed hay, as well as small amounts of loose lumbers, books, and plastic tarps remained. The primary fuel source for the fire was, therefore, the exposed timber of the barn. A full structural survey and material condition assessment of the structure were conducted prior to burning. It was determined through this examination that the timber structure was decaying along the exterior frame. This well - ventilated farm structure should not be construed as typical of any new farm or even residential/commercial structure, but its structural components do provide value as well as opportunities for assessing timber construction behaviour in high-temperature exposures. The interior timber column taken under consideration was in good condition, of Oak timber species, with no evidence of rot or decay through analysis (pull out of screws, field tests for rot, etc.). This column was ideal to be encapsulated to study its behaviour under fire exposure (denoted as Column 1 herein). The dimensions of the column were 230 mm x 267 mm, which was similar to the size of columns used in existing tall timber structures in Canada. It was hypothesized (and later confirmed) that the column was also unlikely to be affected by any collapsing debris surrounding it that the structure might impose (i.e., it was expected the column would remain standing without debris impact for most of the duration of the test). It was also assumed that the column chosen had similar loading to surrounding columns due to the rectangular column grid. The column had no additional loading beyond service loads.  Figure 4.2 shows the structure's condition, appearance and dimensional features illustrating the column.

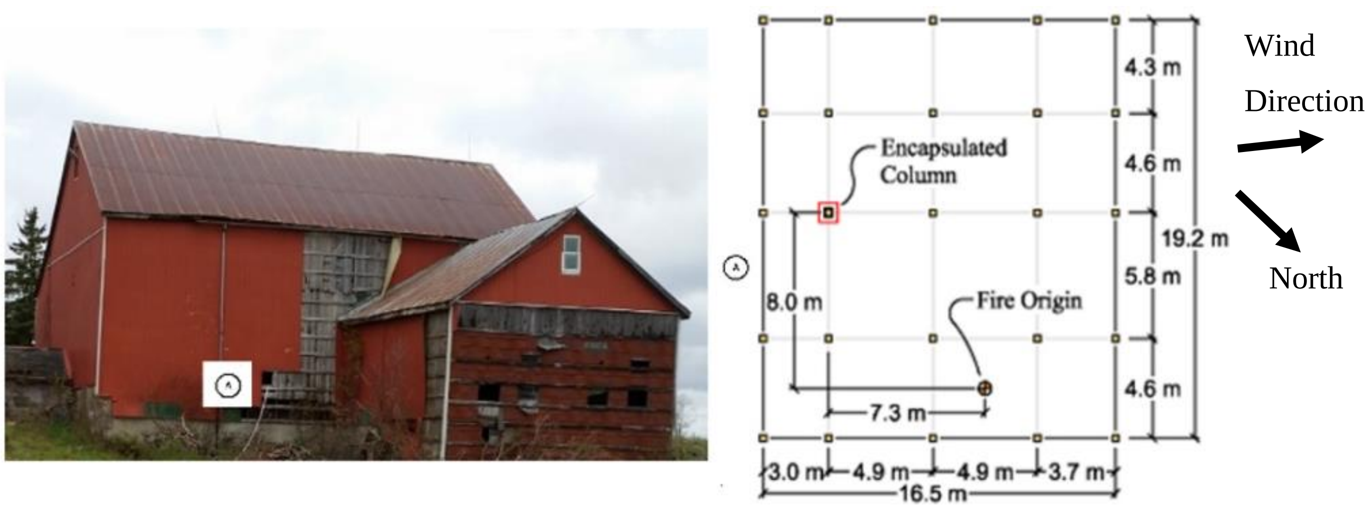



Figure 4.2 Backside of timber farm structure (left), and atrium dimensions (right- annexes not rendered).

Column preparation and testing took place on November 3, 2017. Weather conditions at the time of testing consisted of a temperature of 5°C, a relative humidity of 74% and a wind speed of 22 km/hr in the North-West direction. Due to limited time and access to the site, the research team was strictly limited to six hours of instrumentation time and site preparation (6am to 12pm). Only four of those hours were available in natural daylight conditions. As a result, one load-bearing timber column in the farm structure was encapsulated with three layers of fire-rated 15.9 mm Type X gypsum board. Strict allowances for screw spacing and depth of screws into the timber structure were considered and followed from CSA O86-14 standards precisely. The spacing requirements from CSA O86-14 that were followed included having a maximum screw spacing of 300 mm on centre, having each board fastened by two rows of fasteners (offset by half the row spacing), and ensuring that each fastener penetrates the wood by at least 25 mm [29]. Each layer of gypsum board was installed and screwed separately. The gypsum board installation procedure is illustrated in Figure 4.3 and was meant to be a representative installation of existing tall timber structures. Although the plan was initially to install four layers, there was only time to install three layers and therefore that number of layers would control the amount of gypsum layers seen in laboratory stage for consistency. The remainder of the farm structure was left unprotected (without encapsulation). Figure 4.3 provides instrumentation details of the encapsulated timber column.

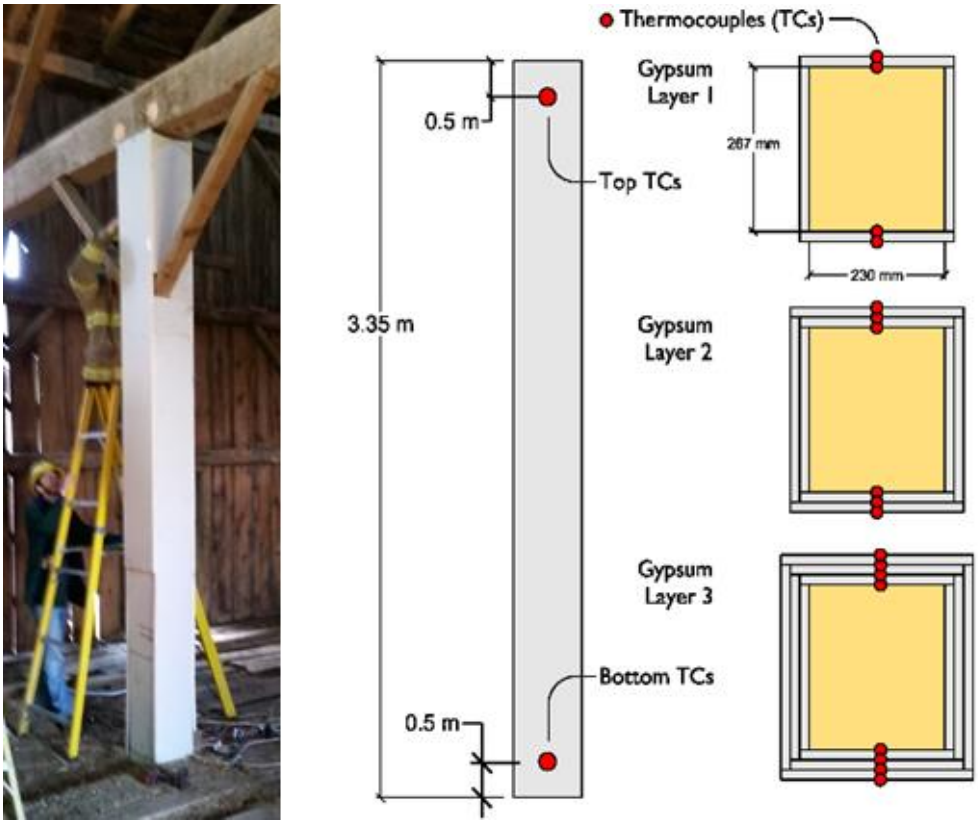



Figure 4.3 Field study encapsulated Column 1 during construction (left), thermocouple placement (right).

As shown in Figure 4.3, the column was instrumented with 16 K-Type thermocouples (as limited by the available data acquisition channels) distributed on the surface of the encapsulation, between layers, and on the surface of the timber (thermocouple error limited to the greater of 2.2 °C or 0.75% of the temperature in ºC). A National Instruments (Model NI-9213) distributed data acquisition unit was used, running Labview software. Thermocouple leads were protected with Rockwool insulation and aluminum wrapping as they extended out of the structure. Thermocouples were not placed inside the timber, as the focus of this experiment was on the performance of the encapsulation system only (not the performance of the timber). The data acquisition unit was left a distance of 10 m from the structure's exterior. Prior to the structure's full collapse, safety and equipment maintenance protocol dictated that once visual indications of structural failure began (noticeable tilt of the back exterior portion of the structure), portable instrumentation was to be disconnected and salvaged – including the Data Logger and associated PC. Data monitoring of the thermocouples would, therefore, discontinue at that indication, though the video would continue until camera failure, the complete collapse of the structure or until auto-extinction. Two interior and three exterior hi-resolution cameras were set up at various locations to obtain qualitative data on the evolution and behaviour of the fire. Ignition occurred in a small sub-compartment of the main farm structure, at a position 8 m by 7.3 m away from the encapsulated column. The location is labelled as the 'fire origin' in Figure 4.2 (approximately 10.8 m away). A member of the fire brigade used a match to ignite hay within a sub-compartment of the barn. The fire was ignited in the sub-compartment to ensure flashover in this region, which would then spread to the main barn. During the fire, strict safety protocols were employed by the attending fire brigade, and material recovery post-fire was prohibited due to safety concerns of smoke contamination of materials. The column's thermocouples were salvaged, and these gave no indication of damage to the thermocouple cables.

### 4.2.2 Laboratory Study

Following the field study, six units of engineered Douglas Fir Glulam fabricated in accordance with CSA O122, 16c-E Stress grade were procured. The timber was chosen as engineered stock as these units formed part of a larger study on adhesive performance in engineered timber underway (with portions of this study discussed in Chapters 6 and 7). As Oak is a hard-wood, and hard-wood species are not representative of modern structural construction in Canada, the species type was therefore not replicated. Dimensioning was chosen for two sizes with units at 175 x 190 x 2532 mm (denoted as Column 2, 5, and 6) and at 175 x 228 x 2532 mm (denoted as Column 3, 4, and 7). Dimensioning was chosen with consideration to the mechanical loading capabilities for later research (Appendix B). These columns were encapsulated in conformance with CSA O86 with single and multiple layers of gypsum board. The encapsulation of Columns 2 and 3, like Column 1, included three layers of fire-rated 15.9 mm Type X gypsum board as defined in Section 4.2.1. Columns 4 and 5 were encapsulated with only one layer of this same gypsum board, in order to directly understand how much a single layer impacts the fire performance of the timber. The installation procedure deviated slightly in application in order to specify a ‘seam’ (two boards side by side) in the fire exposed gypsum layer on the column at mid-span for all Columns 2 to 5. This was in order to study possible heat exposure and impact of seams on the overall performance. The ‘seam’ only appears on the outermost layer and below the board is continuous where applicable. This would be akin to prior wall finishing and a plausible configuration. Columns 6 and 7 were control (unencapsulated) samples. K-type thermocouples were utilized in order to provide temperature measurement at mid-span. Many thermocouples were placed in redundancy (such as the extra thermocouples located on the bottom of every beam) however thermocouples directly exposed to flame temperatures were unreliable in recording board surface temperature exposures as visual indicators illustrated that they detached in testing. Figures 4.4 and 4.5 show the thermocouple configurations for each column (2 to 5). Columns 6 and 7 had thermocouples in the same configuration, on the face of the timber only. The columns and screws were not finished as it was of interest to also observe the possible effects of heat transfer through the screw to the timber (worst case). The column encapsulation process is seen in Figure 4.6.

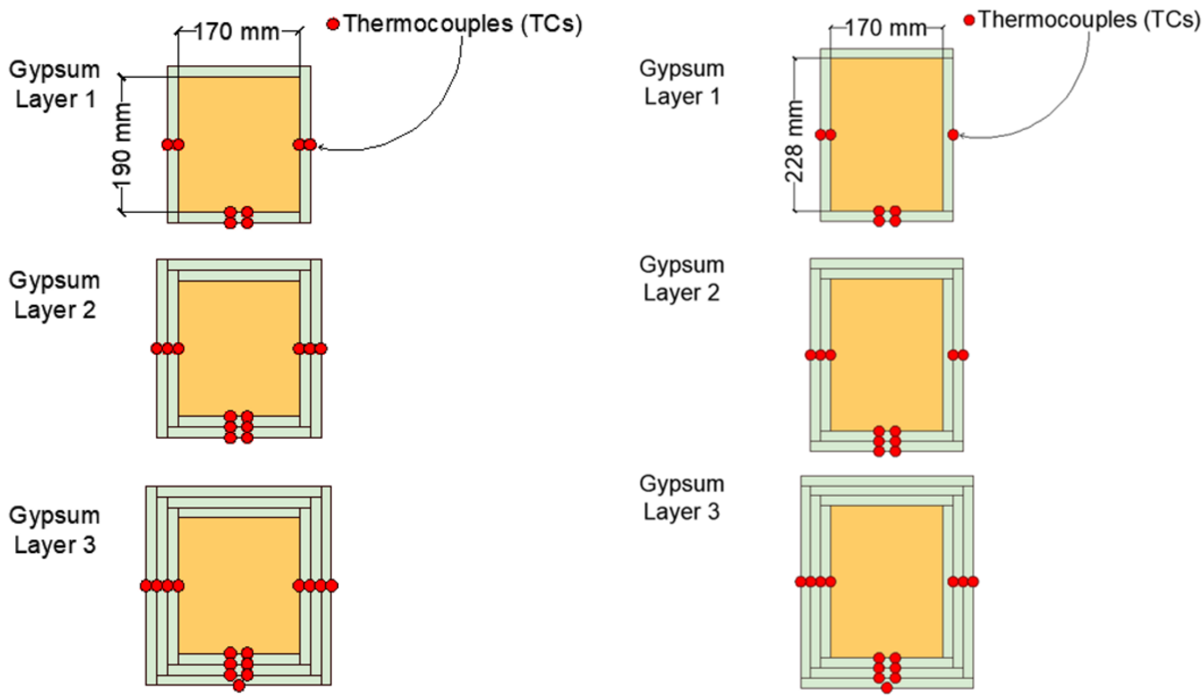



Figure 4.4 Laboratory encapsulated column thermocouple placement Column 2 (left) and Column 3 (right).

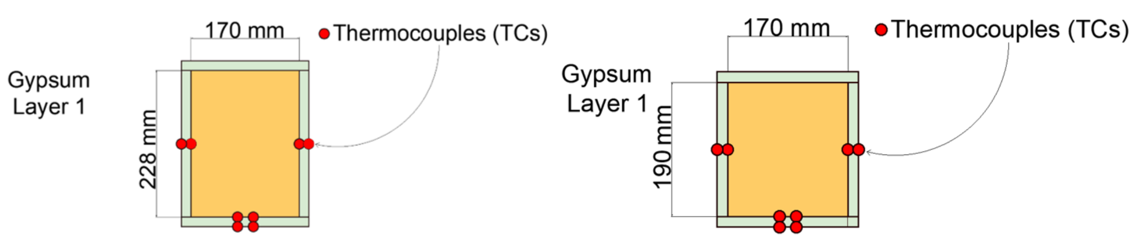



Figure 4.5 Laboratory encapsulated column thermocouple placement Column 4 (left) and Column 5 (right).

Figure 4.6 Encapsulation procedure of a column protected by three layers of gypsum board, clockwise from top right: first layer installation in progress, first layer complete, third layer complete.

Each column was exposed to a non-standard fire, with the fire exposure from one side. Testing was performed at the University of Waterloo Fire Research Burn Hall Laboratory[2]. These tests were performed and planned after the field study and the fire exposure was meant to be at least representative with respect to the fire duration (approximately 30 minutes), with steep initial temperature gradient seen in the field study (see Section 4.3 for justification on the columns heating duration). The columns were not loaded. To enhance visualization through the flames to more clearly observe the gypsum board degradation, a methanol pool fire was used. Other pool fire fuel types were considered and evaluated (such as acetone, kerosene etc.) but ultimately, they were obstructing the view of the specimen through the flames using the novel filming technology (which is discussed below). The 30-minute methanol fire exposure was utilized for the laboratory tests described in this chapter as opposed to previous fire exposures (described in other chapters of this thesis) as in order to visualize performance through the flames, clear views from the camera were needed (necessitating a pool fire) as well as a fuel which created minimal amounts of soot (hence methanol). The methanol fire was observed to create the least amount of soot of the fuels

[2] At the time of testing, York University fire lab was not yet operational, necessitating off-campus testing.

considered [58]. While the choice of methanol may result in different heat exposures in comparison to other fuels, the beam was partially engulfed in, and therefore exposed to, the high-temperature flame gases. Thus, methanol was chosen due to the ability to make clear observations and measurements through the flame. The methanol pool fire heat exposure may be considered as a 'natural fire' due to its dependency on the specific fuel load, ventilation conditions, and materials characteristics [59].

Multiple test fires were performed using various volumes of methanol in different pan shapes to characterize and demonstrate repeatable exposures. For each 30-minute test, 14.3L of fuel in a 0.48 m (width) x 0.6 m (length) stainless steel pan was needed to achieve the desired fire exposure. Stainless steel was chosen as the material for the pan as it was unlikely to melt during testing and was readily available. The size of pan was selected as it was the only pan available that was able to safely contain the quantity of fuel required (it was the largest available). Expected exposure temperatures were measured 200 mm above the initial surface of the fuel. The time-temperature curves for the trial methanol fires, performed to determine the volume of methanol needed (denoted methanol 1 to 3, where the number represents the trial number in determining the quantity of fuel needed for a 30-minute fire), are shown in Figure 4.7.

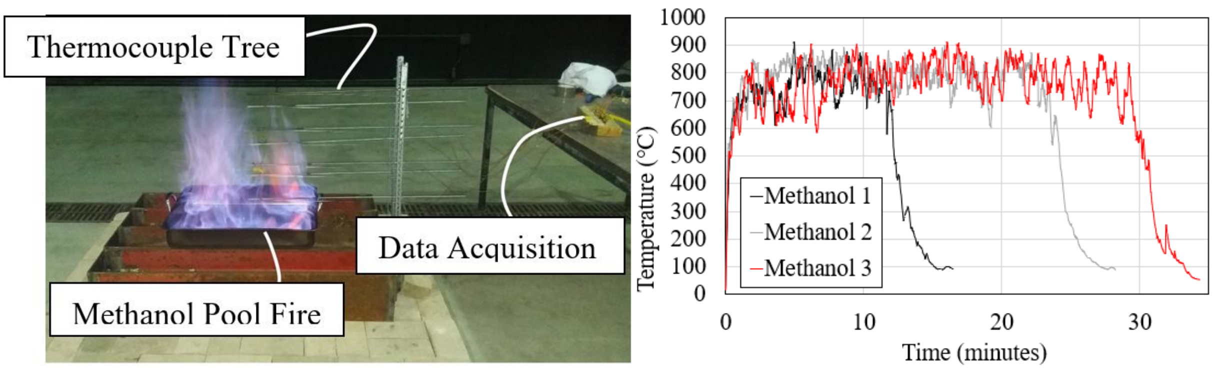



Figure 4.7 Characterization of methanol non-standard fire, where Methanol 1, 2, and 3 represent the trials considered in determining the volume of fuel required (h = 200 mm).

In Figure 4.7, each of the time-temperature curves represents the temperature read by a single thermocouple, however, the maximum difference in peak temperature recorded across the three trials was only 12℃. Localised heating to one-third of the column was considered, opposed to uniform heating, as clear comparisons of undamaged and damaged locations could be made on the column and the possible propagation of flames beneath the board to unheated regions could be considered if applicable. The column was rotated as a beam and was placed so that the bottom face of the member was 200 mm away from the initial surface of the unburnt liquid fuel. This orientation was chosen so that the fire would reach the seam of the gypsum board, and the damage location could be controlled precisely. It is of note that while the steep gradient in temperature was possible at the initial stages of the exposure fire, it was not possible to generate the equivalent peak temperatures observed from the field study (potentially due to supply of oxygen in the very heavily ventilated barn or the large quantity of fuel from the timber of the barn). Therefore, the laboratory tests cannot and should not be considered the same non-standard equivalency as the field test. This was an acceptable deviation, as using the other fuels with higher temperature exposures would have obscured visualization of the gypsum board surface and prohibit qualitative and quantitative observations as will be described in Section 4.3. Once the heating was completed the columns were then monitored during a 30-minute cooling phase in order to assess if damage(s) such as cracking or further delamination of the gypsum board(s) is exaggerated after the fire burns out. 30-minutes was deemed sufficient as a cooling phase duration as at this time, the unencapsulated samples had auto-extinguished, so this cooling duration was kept constant across all test samples. Water was not used for fire suppression in these tests to observe auto-extinction of the timber, and strict environmental protocols were used for testing and wastage disposal of materials.

Following the previous technique validation produced by Gatien et al. [60], qualitative observations and quantitative measurement during testing was performed using narrow-band spectrum illumination and image processing in order to study qualitative changes (cracking/delamination) to the gypsum board at high temperature, as well as approximate deformations and deflection of the columns during testing. The use of narrow-band spectrum illumination and matched optical filters can enhance visibility through clean-burning flames [61]. Such a technique has defensibly been shown applicable in laboratory scales (flame spread testing using a LIFT for example). The technology has not yet been adapted nor defended for use in standard furnace (enclosed) fire testing (but such testing is outside the scope of this research). Verification and modification of the technology should be considered for that application in future research. The exact experimental and camera specifications derived from the Gatien et al. study [60] was used to observe the columns when exposed to the methanol fires. The lab set up included two Spectra Par 100-Watt luminaries with all blue (450 nm wavelength) Light Emitting Diodes (LEDs) to illuminate the sample (see Figure 4.8). A Canon EOS 5Ds Mark III DSLR camera was used to image the column specimens, this was placed 1.5 m away from the column at an angle of 17 degrees. This camera's resolution (images of 5792 x 8688 pixels) allows placement far away from the specimen during testing to maintain high resolution of the specimen while reducing the risk of damage to the camera and lenses due to excessive heating and thermal radiation from the pool fire. The following camera settings were used due to the influence of previous research by Gatien et al. [60]: frame rate of 5 frames per second, ISO 2000, aperture f/13, shutter 1/800. A bandpass optical filter consisting of two stacked filters (HOYA Corporation B440 and Midwest Optical Systems BP470) was attached to the front of the camera's default lens. These two stacked filters provided a low-cost and effective band-pass filter at the desired frequency (450 nm). The camera was shooting at an angle, which was measured in order to translate the downward and upward movement of the column in these tests into a measurable deflection. Geo-PIV RG [62] was utilized for approximating quantifiable deflection and seam deformation measurements. The technique is considered as an approximation and not a definitive calculation as the technique is not fully adaptable to a material undergoing a phase change. Gypsum boards lose their first coating (paper) layer through combustion and the application of tracking paint is therefore prohibitive. The interested reader is encouraged to read about image correlation limitations further [63].

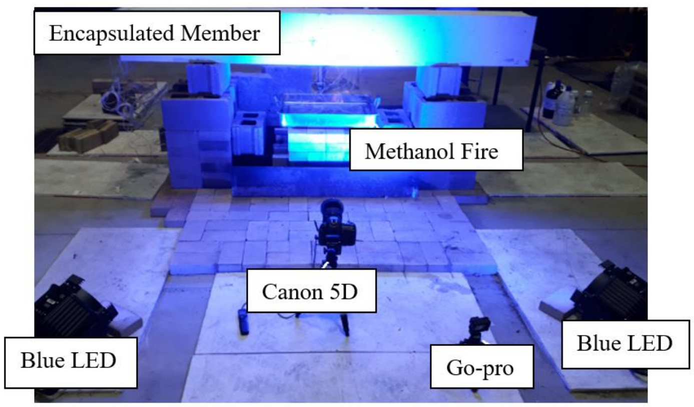


Figure 4.8 Specimen, apparatus, camera and LED light locations.

## 4.3 Results and Discussion

### 4.3.1 Field study

The performance of Column 1 was evaluated primarily through examination of the temperatures reported by the thermocouples and through recorded video footage as plotted and illustrated in Figures 4.9 to 4.12. In the plots shown in Figures 4.9 to 4.11, Gypsum Layer 1 refers to the thermocouple under one layer of gypsum, Gypsum Layer 2 under the second layer, and Gypsum Layer 3 is between the innermost gypsum layer and the timber column itself. Gas temperature refers to the temperature measured by a thermocouple placed on the outer most layer of gypsum board at the top and bottom of the column on both sides. The fire side refers to the side of the column facing the room of fire origin, and the non-fire side refers to the opposite side of the column (not facing the room of fire origin). While cameras were placed throughout the interior and exterior of the farm structure, the thick flames and smoke made it difficult to see the column within the structure and, in particular, the gypsum board encapsulation after the initial period. While it is beyond the scope of this chapter to discuss the resulting fire dynamics, in brevity temperatures were only recorded at the column location, and the thermocouples were manually terminated as structural collapse was considered possible and the data acquisition unit had to be retrieved. The structure eventually collapsed approximately 30 minutes beyond the steep temperature rise. It is not possible to deduce temperatures beyond when the thermocouples were taken offline.

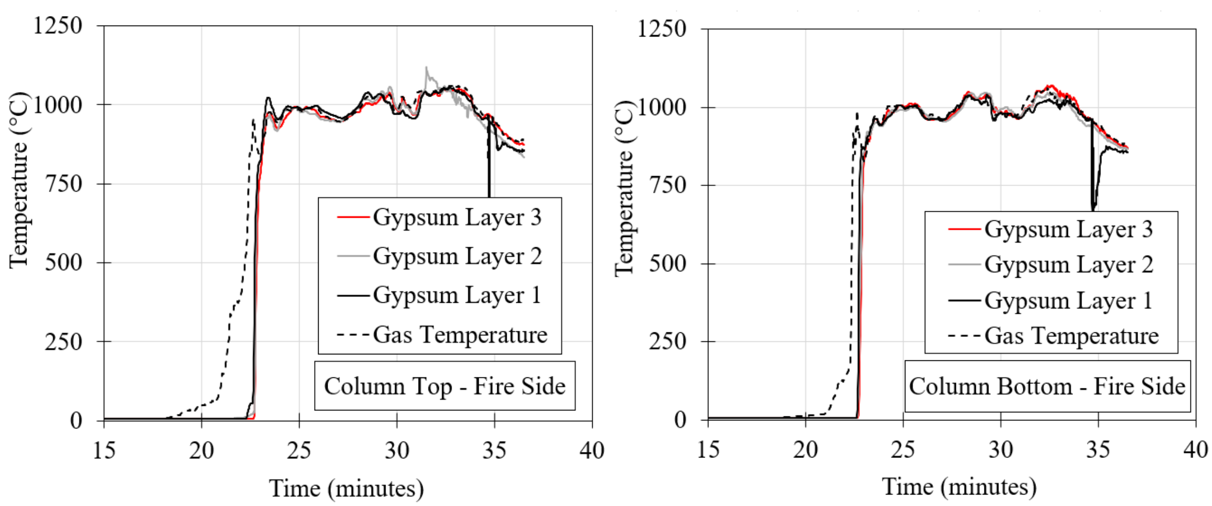


Figure 4.9 Fire side temperatures measured at (left) the top of the Column 1, and (right) the bottom of the Column 1 (t= 0 ignition).

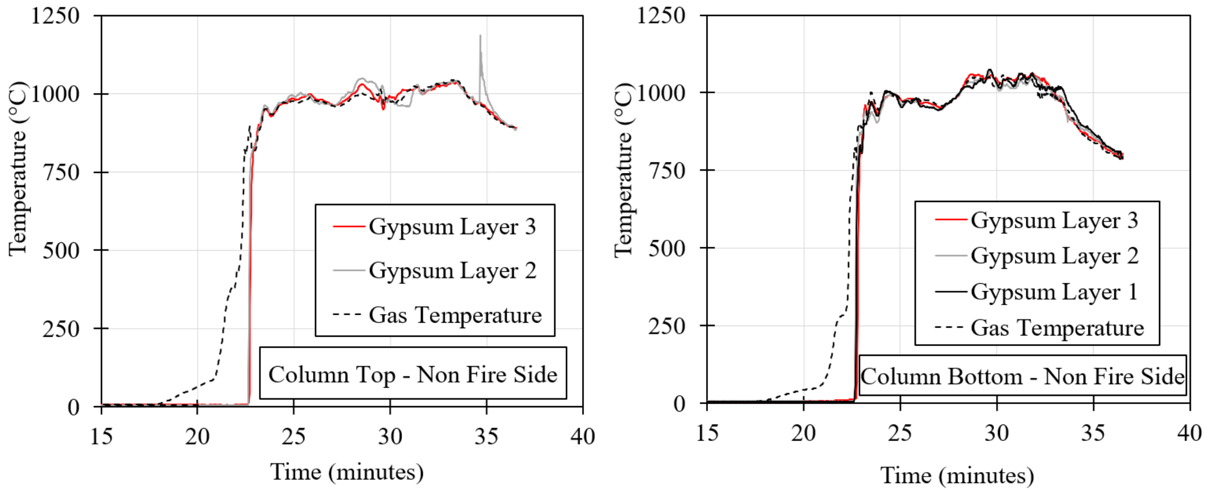



Figure 4.10 Non-Fire Side temperatures measured at (left) the top of the Column 1 and (right) the bottom of Column 1.

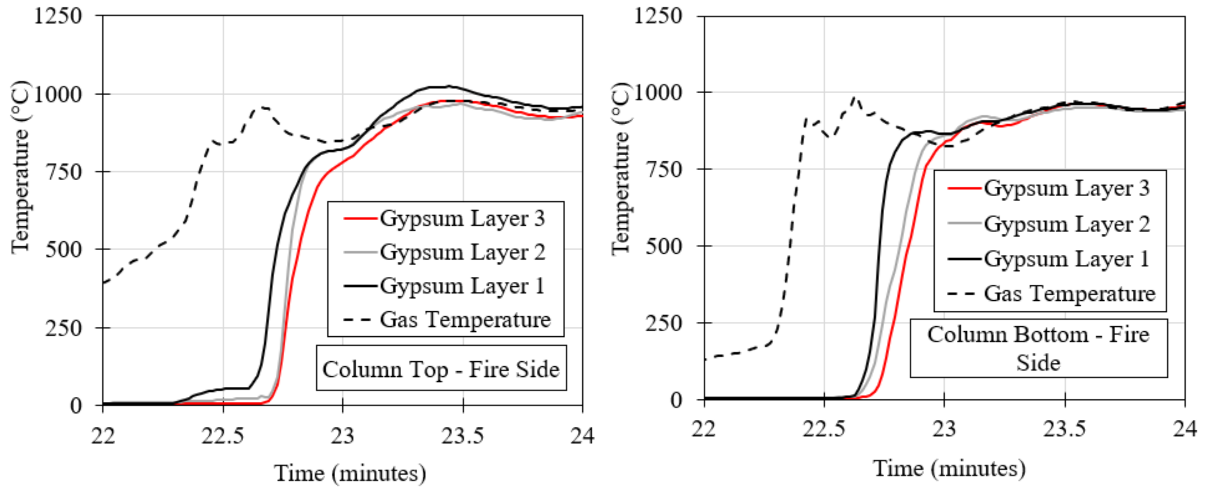



Figure 4.11 Scale magnified of fire side temperatures measured at, (left) the top of the Column 1, and (right) the bottom of the Column 1 (t= 0 ignition).


Figure 4.12 Pre heating view of compartment prior to fire ignition (left), atmosphere of compartment when fire spreads to column (right).

From Figures 4.9 to 4.11, it is seen that the gas temperatures away from the column rise sharply at 20 minutes after ignition when the fire exposure spreads to the column's location (Figure 4.11). Within two minutes, rapid heating occurs, and all of the temperatures beneath each layer of gypsum board rise quickly above 1000℃. This behaviour can suggest several aspects relating to cracking of the board, and sealing effect – where fall off of (all) the gypsum board layers is ruled out, as discussed below.

With respect to cracking of the gypsum board, once the flames had spread to the location of the column, the gypsum board only delayed the rise in temperature by a minute or two where excessive cracking (without fall off) of all of the board could have occurred, thereby allowing heat penetration into the column. Since the temperature at the surface of the timber appeared to be delayed in heating by only a couple of minutes, there is some evidence that the gypsum board may not be performing as desired. A second hypothesis considers that the gypsum may have had a gap in sealing along the length of the column allowing heat penetration between the layers. From Figure 4.10, which focuses only on times around the sudden temperature rise (plotting scales between 22 and 24 minutes), it is seen that the gas temperature rises first, followed by the thermocouple covered by one layer of gypsum, then two layers, and finally the thermocouple at the face of the timber rises in temperature last. These hypotheses suggest that the gypsum board had probably not fallen off at this point as is visually confirmed in Figure 4.13, and instead hot gases were able to penetrate between layers through an unconfirmed mechanism (at this point). It can be clearly shown that at least one layer of the gypsum board seems to be fastened to the column despite the rise in temperature measured in all layers of the field study – it is therefore doubtful that the simultaneous rise in temperature in all layers was observed because all layers fell off. The exact mechanism cannot be determined without examining the column itself in-situ. A post-fire in-situ investigation was prohibited by the fire department in attendance due to concerns for smoke exposure and its contamination with hazardous materials potentially found within the farm structure. In any case, these results suggest that the gypsum board was not successful in functioning fully to extinction of the fire – at least in terms of performance objectives where heat transfer is concerned. This particular field study therefore justifies additional investigations being required to determine the true influences from board cracking, sealing and fall off in controlled tests performed at laboratory scale.

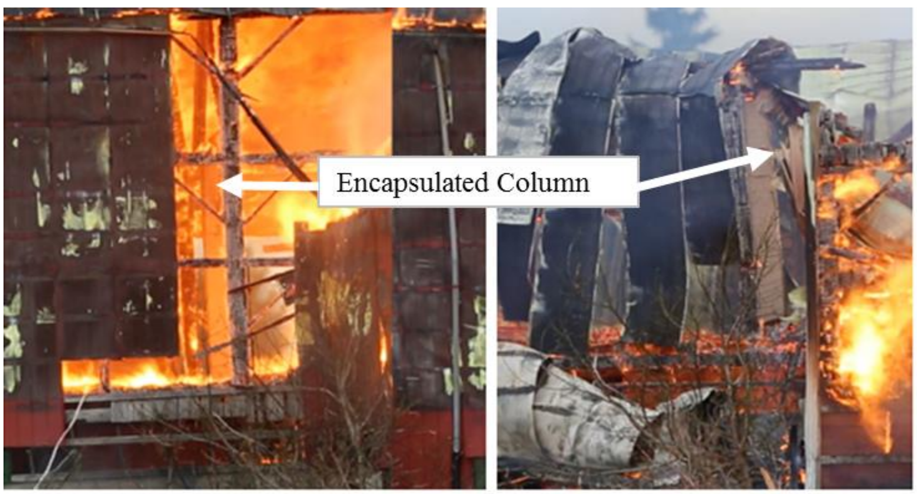



Figure 4.13 Images of Column 1 during field test (left) prior to structural collapse (right) post flashover event.

### 4.3.2 Laboratory Study

#### 4.3.2.1 Thermocouple Results

The performance of the timber columns (2 through 7) within the laboratory study were evaluated first through the examination of the temperatures reported by the thermocouples as plotted in Figures 4.14 to 4.17. In these plots shown, for Columns 2 and 3, Gypsum Layer 1 refers to the thermocouple under one layer of gypsum, Gypsum Layer 2 under the second layer, and Gypsum Layer 3 is between the innermost gypsum layer and the timber columns themselves. Where Columns 4 and 5 have only one layer for consistency it is called Layer 1. Exposed surface and Gas temperatures were unreliable measures in these tests as the thermocouples appeared to delaminate visually from the surface during testing. For the thermocouples underneath at least one layer of gypsum, it could not be entirely verified whether the thermocouple was measuring the gas temperature immediately below the surface of the column, or if the temperature was being measured on the surface of the gypsum which was lower. However, as exact quantities of fuel are given as well as burning rates of the fuel (burn rate of approximately 0.5 L/min) it is possible for the interested practitioner to characterize the exposure if they wish to utilize the results for modelling or replication purposes (which are beyond the scope of this paper). Careful examination of fire dynamics textbook literature provides information on repeatability and quantification of heat exposure from pool fires [23].

The fire side of the columns were installed with two thermocouples mid-span each denoted A and B respectively, where the fire side is the side of the columns facing the pool fire (the bottom of the column). Thermocouples on the vertical sides of the columns (perpendicular to the fire side) are denoted as C and D. On sides C and D the thermocouples were not installed in replicate as channels in the Data Acquisition were limited.

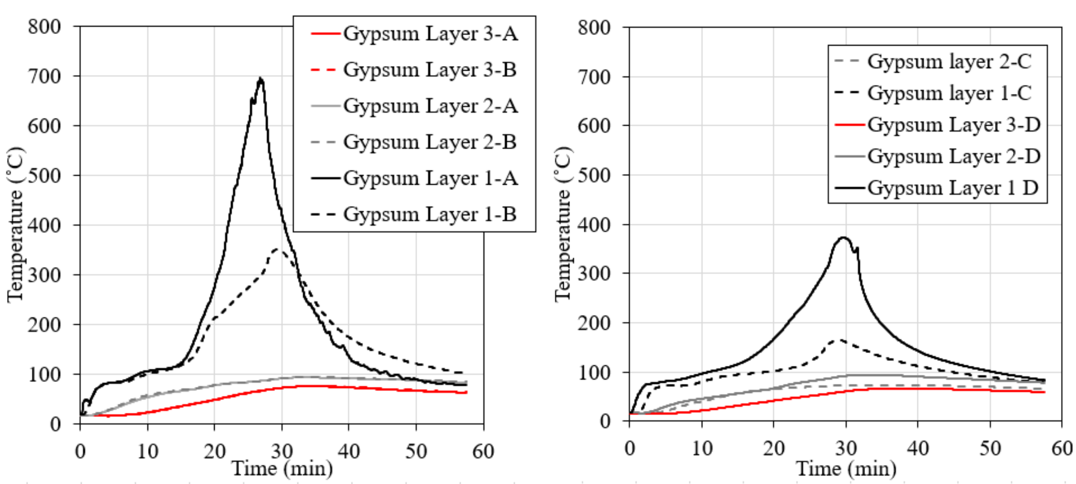



Figure 4.14 Recorded temperatures between the gypsum board layers for Column 2 (175x190x2532) (Note: TC 3C was not installed properly).

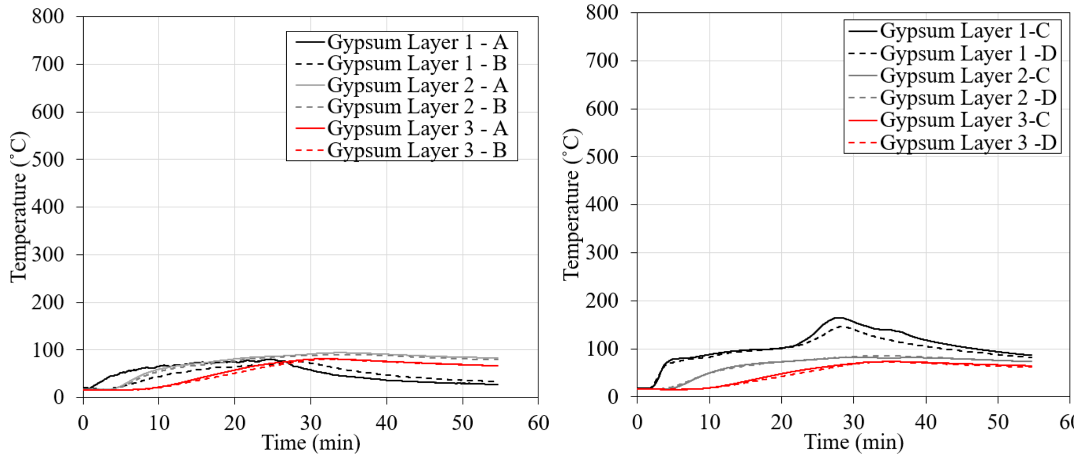



Figure 4.15 Recorded temperatures between the gypsum board layers for Column 3 (175x228x2532).

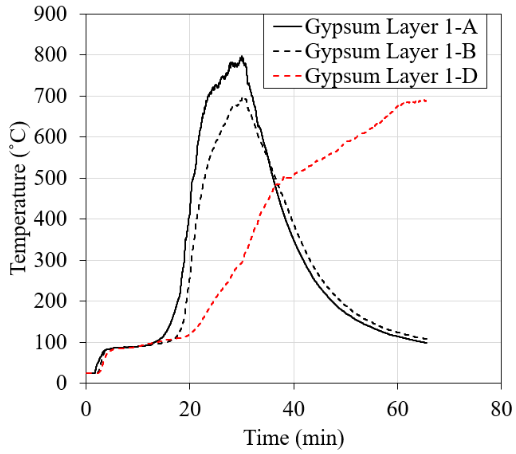



Figure 4.16 Recorded temperatures between the first and second gypsum board layers for Column 4 (175x228x2532) (Note: TC 1C was not installed properly).

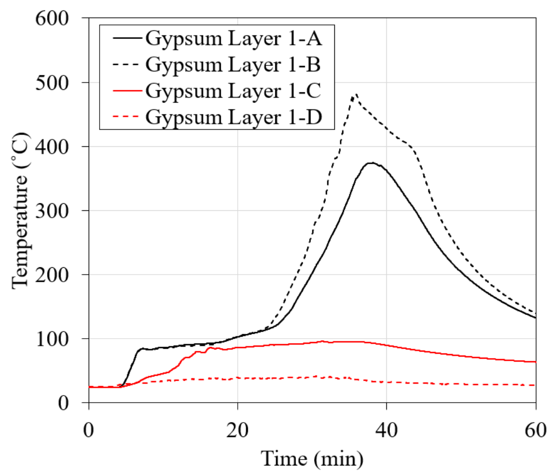



Figure 4.17 Recorded temperatures between the gypsum board layers for Column 5 (175x190x2532).

Figures 4.18 to 4.20 are provided to place the temperature profiles into context. Column 2 has a noticeable increase in temperature during the heating portion of the test, increasing to temperatures of 700°C and 350°C between the $1^{st}$ and $2^{nd}$ gypsum board layers. It is not unexpected that the temperatures do not measure the same between them, on forensic post-fire examination it was observed that these thermocouples were located in the region that coincided with the charred zone of the timber.  Whereas in Column 3, which showed no temperature incline in the temperatures recorded by the thermocouples, examination post-fire showed that these thermocouples were installed away from this charred zone on the second gypsum layer as observed in Figures 4.18 and 19.  This behaviour gives credence that the fire exposure between the first and second boards likely occurred at an isolated location near the seam, resulting in a localized charred area and not along the full length of the column, as it was only a localized fire exposure. The results seem to verify the temperature measurement trends and hypothesis observed in the field study that indicated temperature rise through penetration between the gypsum layers. In the controlled case, however, the temperatures measured beyond the second layer of gypsum board did not exhibit a spike increase in temperature.  Temperatures do discretely rise as expected with duration. The penetration of heating in these tests is likely due to the larger seam opening in the first gypsum layer which correlates to partial delamination of the gypsum board as tracked through narrow spectrum and image filtration technologies (sometimes called blue light technology).

Figure 4.18 Post-fire ‘seam’ opening in Column 3.

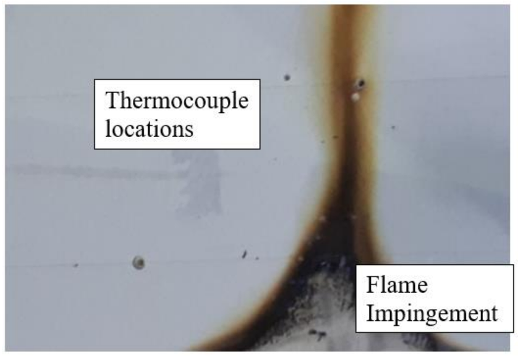


Figure 4.19 Flame impingement after fire of Column 3.

Column 2 illustrates a potential fall off (peel away) of the board in progress as the heating duration halted seen in Figure 4.20. The post-test examination of Columns 4 and 5 reveals the extent of char damage below the board. Figure 4.16 reveals that the ignition of the Column 4 had occurred during the cooling phase of the tests manifesting as a smouldering fire under the side boards away from the fire. Once the boards were removed after 30 minutes of cooling, the fire was damped out with light amounts of water. Excessive smoking also occurred for these columns post heating phase confirming a small self-sustaining (without additional application of heat) fire. Figure 4.21 illustrates that Column 4 developed a 25mm deep crack running along the entirety of the heated zone beyond the charred zone which was not present during the installation of the gypsum boards pre-testing (note Columns 2 and 3 showed no signs of char damage). Figure 4.17 does not show evidence of a fire event on the side boards of the column, though analysis after the test revealed thermocouples C and D for Column 5 were not in the charred region of the column.

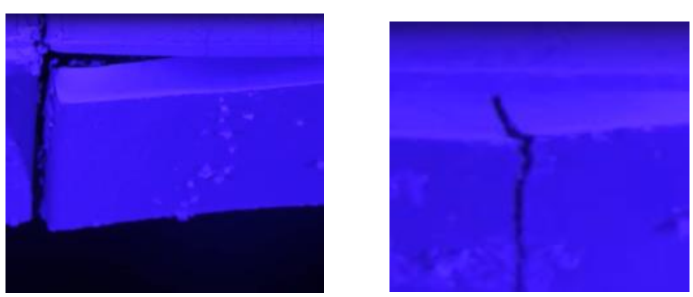


Figure 4.20 Delamination and cracking action of Gypsum Board at seam Column 2 during heating.


Figure 4.21 (left) Post-test condition of Columns 4 and 5 (right) post-fire cracking of Column 4.

#### 4.3.2.2 Qualitative Results using Narrow Spectrum and Image Filtration

The innovative use of narrow-spectrum and image filtration technologies allows for qualitative observation of the surface deformation behaviour, such as that described above of the exposed first layer of gypsum board in Column 2 and 3 tests. Tables 4.1 and 4.2 illustrate an arbitrarily chosen surface feature taken on the fire exposed side near a screw on the first layer of gypsum board for each laboratory test.

Table 4.1 Surface texture during heating and cooling.

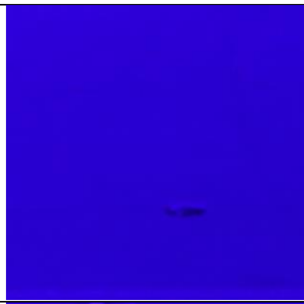
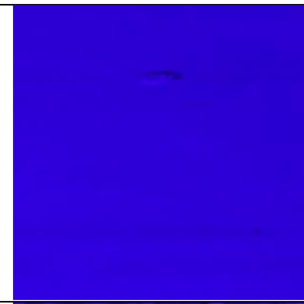
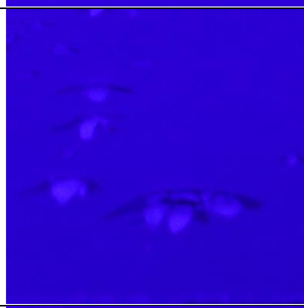
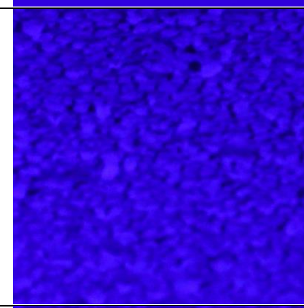
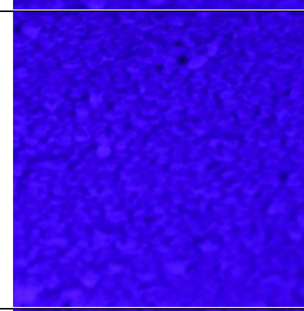
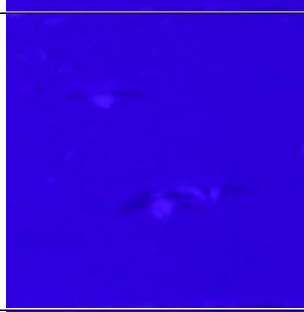
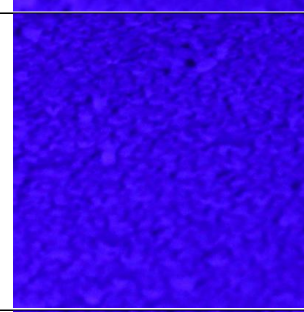
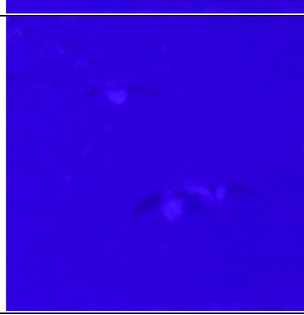
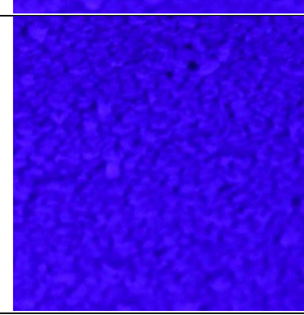
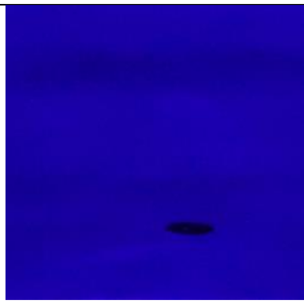
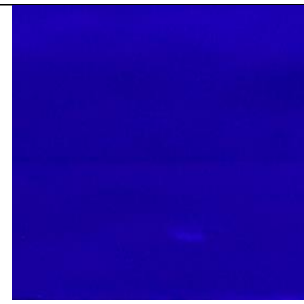
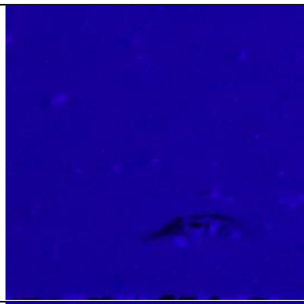
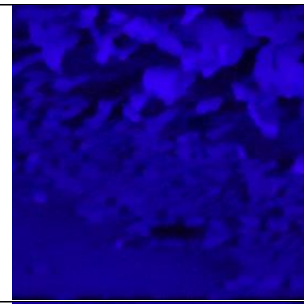
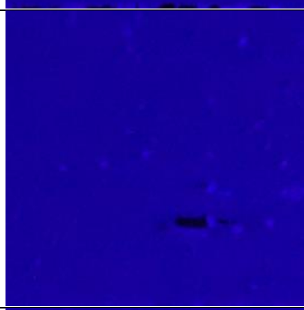
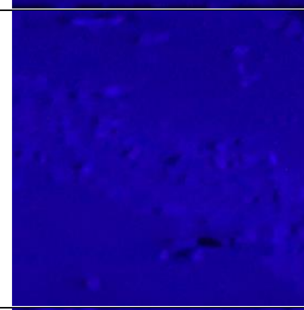
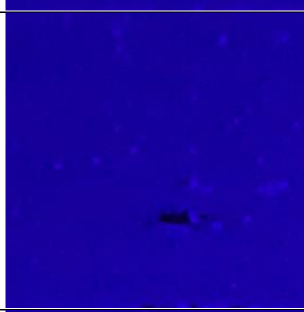
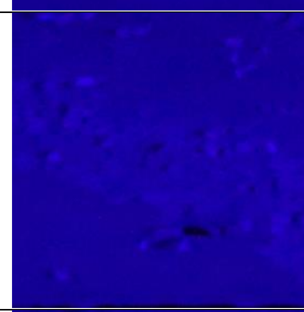
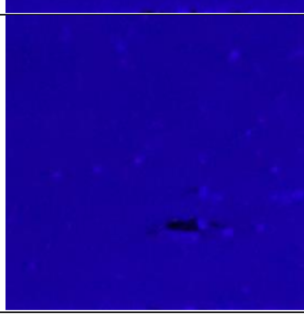
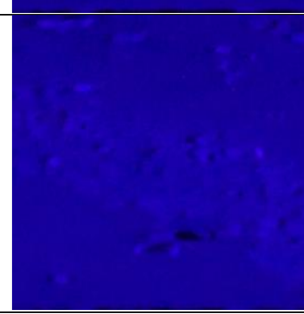
| Column 2 | Test Time (min) | Column 3 |
|---|---|---|
|  | 0<br>(heating) |  |
|  | 10<br>(heating) |  |
|  | 30<br>(transition from heating to cooling) |  |
|  | 40<br>(cooling) |  |
|  | 60<br>(cooling) |  |

Table 4.2 Surface texture during heating and cooling.

| Column 4 | Test Time (min) | Column 5 |
|---|---|---|
|  | 0<br>(heating) |  |
|  | 10<br>(heating) |  |
|  | 30<br>(transition from heating to cooling) |  |
|  | 40<br>(cooling) |  |
|  | 60<br>(cooling) |  |

As the gypsum board heats up, a web of discrete fine cracks forms on the board on Column 3 immediately after the rapid temperature rise. This does not seem to affect heat transfer at the location of measurement. Note that in Column 2, this phenomenon appears absent along the surface; instead, Column 2 demonstrates a larger crack opening along the surface and partial delamination as previously discussed. Figure 4.22 illustrates that cracking patterns tend to exaggerate during the cooling process, a phenomenon that seemed apparent with any large gypsum board crack opening for all columns.

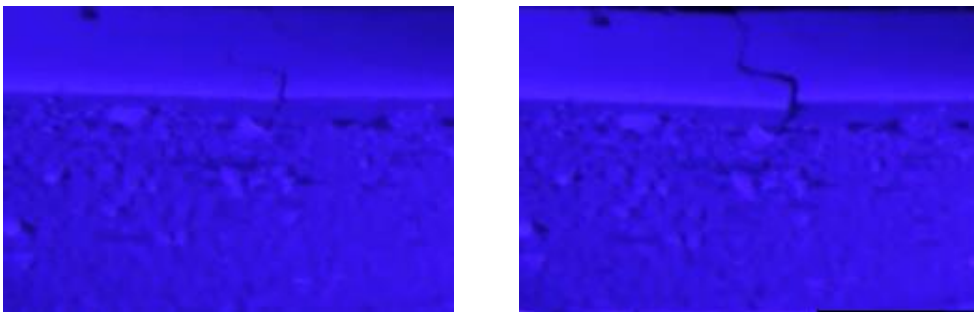


Figure 4.22 Crack opening after heating in Column 3 (left at end of heating, right at end of cooling).

While visually these features appear to be detrimental to the performance of the column, it should be noted that the second and third layers of gypsum upon removal during post-heating assessment illustrate no visible damage. However, Columns 4 and 5 with only 1 layer of board illustrate maximum charring depths of 25 and 15 mm respectively spanning a length of 41 and 29 cm respectively for a maximum 1 cm seam opening during the test. The unencapsulated columns, Columns 6 and 7, had a maximum char depth of 16 and 17 mm respectively. Column 4 notably has the most amount of char depth of all columns. In this case, the larger char depth indicate that a smouldering fire was likely occurring under the layer of gypsum board (which is further supported by Figure 4.16 where the temperature continued to increase on side D even during the cooling phase).  Char depths are tabulated in Table 4.3. Digital image correlation was used to track the peeling of the gypsum board away from the timber. This is seen in Figure 4.23 for Columns 2 to 5.

Table 4.3 Char measurements.

| Column | Dimensions (mm) | Number of gypsum layers | Maximum char depth (mm) | Average char rate (calculated over 30 minutes) (mm/min) |
|---|---|---|---|---|
| Column 2 | 175 x 190 | 3 | 0 | 0 |
| Column 3 | 175 x 228 | 3 | 0 | 0 |
| Column 4 | 175 x 228 | 1 | 25 | 0.83 |
| Column 5 | 175 x 190 | 1 | 15 | 0.50 |
| Column 6 | 175 x 190 | 0 | 16 | 0.53 |
| Column 7 | 175 x 228 | 0 | 17 | 0.57 |

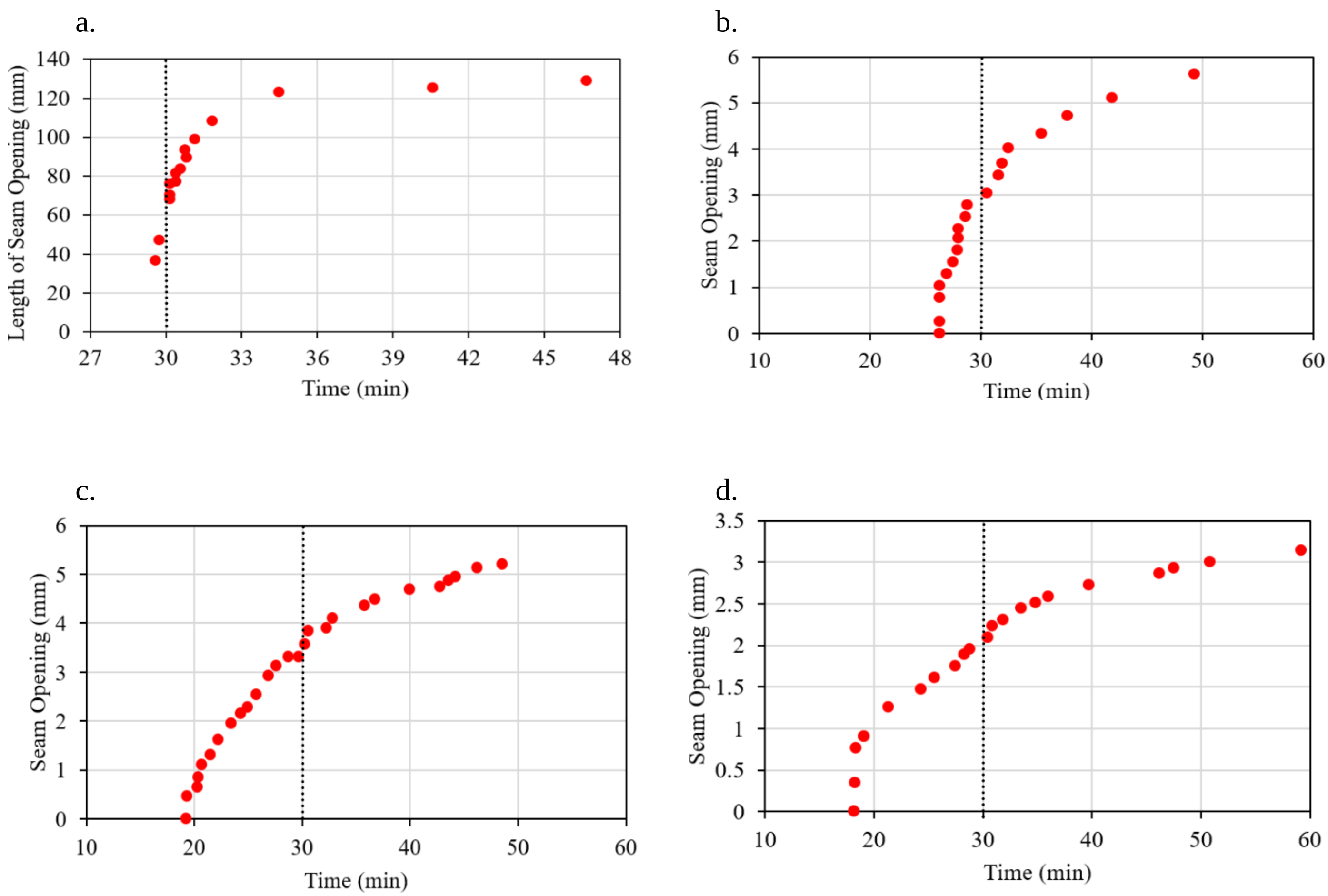



Figure 4.23 Seam opening in the heating and cooling phases (left and right of the dashed lines) for a. Column 2, b. Column 3, c. Column 4, and; d. Column 5.

While the metallic screws utilized were hypothesized to have the potential to transmit heat to the timber below the board, it was observed upon extraction of the screws outside central charred locations that no evidence of localized charring was present in the timber screw holes for post-test evaluation for all tests. A longer heating duration should be explored to test the amount of potential heat penetration into the timber column through the screws. But overall, these remained fixed for the duration of all Column 2 to 5 tests.

In addition to the gypsum degradation, it was very apparent during the tests that Columns 2 and 3 began to bow toward the fire, and upon cooling restored away from the fire. A timber beam unencapsulated tends to bow away from the fire due to dehydration effects. As the timber is protected from the heat it is not dehydrating in these tests, and dehydration is not the driver for the reaction. The bowing behaviour is likely due to a fibre expansion mechanism on the column, as a result of expansion that all layers of the gypsum board are experiencing prior to dehydration dominating the board and timber behaviour (a sign of a short duration fire). Columns 4 and 5 illustrated negligible bowing behaviour but an expected upward camber at test conclusion. The columns in consideration were not loaded at the time of testing. The addition of an applied load may cause the columns to bow further towards the fire than was observed in this study- this effect could be explored in future research, and particularly in model validation.

Table 4.4 quantifies the exact deflections and seam opening measurements taken from the image analysis. Figure 4.24 illustrates the measured fall off behaviour with respect to the temperature of Column 2. It is supported by the narrow band spectrum illumination technology that fall-off/delamination behaviour is driven predominately by the dehydration of the board (100◦C) to when fall off of the board will initiate and is not linked to a specific temperature. Seam openings exaggerated in size during the cooling phase and were substantially large for penetration of air to the surface of the timber, particularly if the board began to peel away from the columns as seen in these tests.

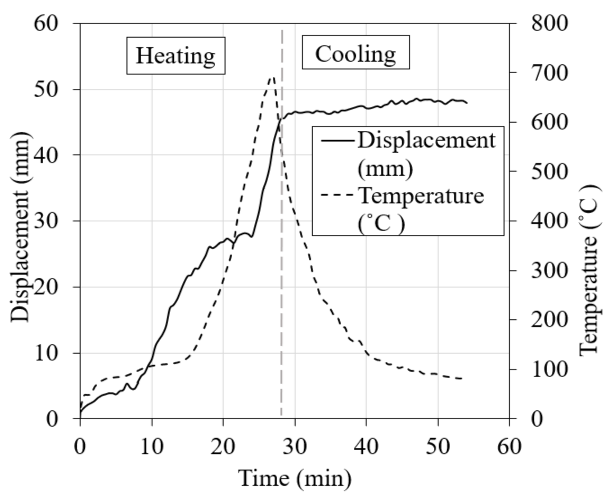
Table 4.4 Deflection and seam opening measurements. [a]

| Column | Max deflection - heating (mm) | Max seam opening - heating (mm) | Max deflection - cooling (mm) | Max seam opening- cooling (mm) |
|---|---|---|---|---|
| Column 2 | - [b] | 47 [b] | - [b] | 129 [b] |
| Column 3 | 12 | 3 | 6 | 6 |
| Column 4 | 4 | 3 | -4 [c] | 5 |
| Column 5 | 6 | 2 | -1 [c] | 3 |

[a] – Values for seam opening have changed from journal publication [64] as enhanced analysis was performed to give more precise values

[b] – Seam includes opening that developed from peel away of gypsum board, it was not possible to take a total deflection with the peel away present on the column

[c] - Upward camber of the beam



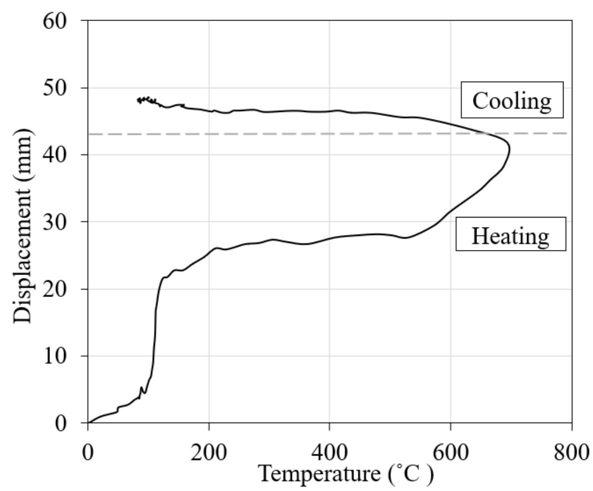




Figure 4.24 Peel away of soffit gypsum board in Column 2 with respect to time and temperature (temperatures are those recorded by Gypsum Layer 1-A).

### 4.4 Conclusions and Future Work

The performance of the five encapsulated columns (relative to two unencapsulated columns) has raised several important design considerations and insights into future studies. On the basis of all tests, it appears that the presence of multiple layers of Type X gypsum boards alone cannot always be successful at significantly delaying a rise in temperature at the surface of the timber column. One layer of gypsum board seemed ineffective where charring depths were near 25 mm for 30 minutes of direct non-standard fire exposure with a maximum charred region of over 40 cm in length. The reasoning for these temperature rises and charring behaviours appears to be caused by the junctions of the gypsum boards, causing a seam on the column. Each seam grew upwards of 1 cm during the tests allowing heat to penetrate below the layers, where one layer is used, prompting ignition of the timber beneath the board lasting well into the cooling phase.

From laboratory experiments, it seems evident that by installing three layers, redundancy can be provided, implying that timber elements can be adequately protected from fire exposure providing that screw spacing is strictly adhered to and redundant layers are utilized. In the field study, there is potential that even if the gypsum board is installed in accordance with current standards, all layers may still not survive cooling and extinction in a realistic fire scenario. In the laboratory study, which innovatively applied narrow-spectrum illumination technology, discrete and large quantifiable cracking patterns in the gypsum board may exaggerate in the cooling process. Cracking mechanisms appeared not responsible for heat penetration within the column. Delamination is possible at low heating times. Testing confirmed that cracking that occurs during heating exaggerates during cooling, and this behaviour gives credence to the fall off of gypsum boards during the cooling and extinction phases of testing.

In both the field study and the laboratory study, the rise in temperatures occurs at a rate higher than the standard temperature-time heating curve, indicating that the time-varying heat fluxes that the columns were exposed to in this study were higher than those considered by standard temperature-time heating curve testing – at least in initial heating phases. Furthermore, in this study, the gypsum boards began to fail (by peeling away from the timber) at lower temperatures than would be anticipated if the assembly were exposed to the standard time-temperature heating curve. This result may support the notion that the temperature may have less of an impact on the fall off of gypsum board, than the dehydration (or rate of dehydration) of the board from high incident heat flux. Further testing is needed for verification, which may potentially consider heating timber encapsulated with gypsum board at varying heat fluxes, but these preliminary results align with previous studies on other materials (such as intumescent paints) which have shown differences in material degradation and failure mechanisms to be tied to the rate of heating [65]. Moreover, significant opening of the seams of the gypsum board layers was occurring throughout the cooling phases of testing (Figure 4.24). This effect may not have been observed if only the heating phase of a fire was monitored, reinforcing the need for non-standard fire testing.

The results of the laboratory study closely looked at both the heating and cooling phases of fire exposure. While many cracks were initially formed in the heating phase of the test, many of these cracks became larger as the gypsum board cooled. This could potentially indicate that gypsum board encapsulation continues to be susceptible to fall off, even after the heating of the gypsum boards has stopped.

While it can be argued that seams will be finished after the construction process completes, there is still a reliance on these boards for the construction process at times, and the gap opening that is developing in these tests supports that such a sealant may not remain in place. This will require further study. For the purposes of this study, the seams are used to explain potential behaviours. Based on the testing and evaluation of this chapter, the following areas of research are advised:

- Equivalent tests of two-layered gypsum are conducted to understand both seaming and deflection mechanisms;

- Other manufacturer's gypsum boards are studied for their performance in non-standard fires;
- Narrow spectrum technology be adapted for standard temperature-time heating curve testing for comparison;
- Narrow spectrum technology be enhanced for use with furnace testing, such that furnace tests of encapsulation assemblies following nonstandard curves may eventually be observed;
- Longer duration tests to the point where all layers undergo dehydration and the dehydration processes are more closely studied;
- Study of the use of realistic fires in realistic compartments of timber structures to understand the realistic fire exposure on a timber assembly;
- Digital image correlation for strain and deflection should be further validated with narrow band spectrum (blue light) technology; and
- Investigating coupled fire strategies where the boards may be pre-wetted with a sprinkler system before fire exposure.

While the tests of Chapter 3 indicated that the gypsum board was the most successful of all the encapsulations tested at a small scale, the laboratory and field study discussed above seem to indicate that gypsum board also has the potential to not protect timber as well as intended. In particular, seams between pieces of gypsum board were not present in the Cone Calorimeter tests of Chapter 3, though these larger scale tests show that these seams may play an important role in the fall off of gypsum board (reinforcing the need and benefit for full scale testing).

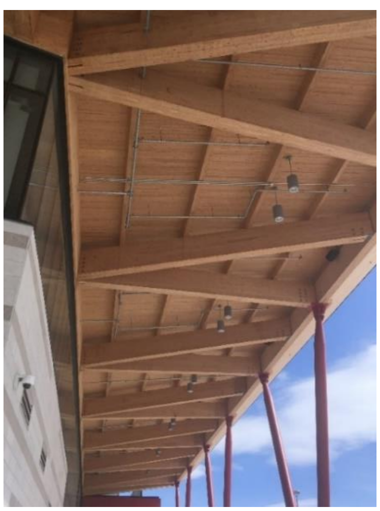
The fire damage that was created on the timber columns in this chapter was very localized in one section of the member, and the charring was limited to 25 mm or less. This raises the question of whether these members, which have been damaged in only one section, could be repaired and continue to be used, should this type of fire occur in a timber structure. While beyond the scope of this thesis, Appendix B begins to look possible repair of the fire damaged areas of these members.

## Chapter 5 : Fire Performance Evaluation of Cultural Heritage Timber Relative to Contemporary Timber

### 5.1 Introduction

The previous chapters of this thesis have examined primarily timber encapsulation materials, however it is equally as important to understand the performance of timber itself in fire. The following chapters of this thesis will focus on the thermomechanical performance of timber, beginning with heritage timber. Globally, we are seeing a growing number of timber buildings being constructed in large and tall applications. These contemporary timber buildings are commonly requested to be left exposed (unencapsulated) [66]. One of these structures can be seen in Figure 5.1 in contrast to a historic timber assembly (both structures in Toronto, Canada). There has been significant research progress around the performance of contemporary timber in fire, and we continue to be able to create more complex buildings with contemporary timber [56].

a.



b.

Figure 5.1 a. A contemporary timber structure; b. a historic timber assembly (author's photos).

As the level of knowledge regarding contemporary timber proceeds to grow, and more intricate contemporary timber buildings are constructed, historic timber continues to be removed or altered within heritage buildings. This may in part be due to the lack of knowledge and guidance regarding how to assess and improve the fire performance of a historic timber structure, however to the author’s knowledge, there is limited evidence to show that historic timber performs significantly differently than contemporary timber or that the fire risk within a heritage timber building is notably different than within a contemporary timber building.

An example where a fire in a historic timber building did not cause the complete destruction of a structure was presented by Otto et al. (2017) [67]. In this case study, an 1898 mill type building in Ontario experienced a fire. A schematic of a similar building is seen in Figure 5.2. Of particular interest is the basement, which utilizes closely spaced wooden columns and beams with cast iron caps, a non-combustible flooring system, and a wooden ceiling above. One of the basement columns was intentionally ignited as an act of arson. The column was exposed to a flame for approximately 40 minutes prior to its ignition. The fire auto-extinguished. The char depth was calculated by removing the char from the column and comparing its post-fire dimensions to the dimensions of the adjacent columns. From this analysis, it was found that the column charred less than 25 mm per side. The fire did not extensively spread along the beams or ceiling to other structural members and was isolated to only the column where the initial fire began.

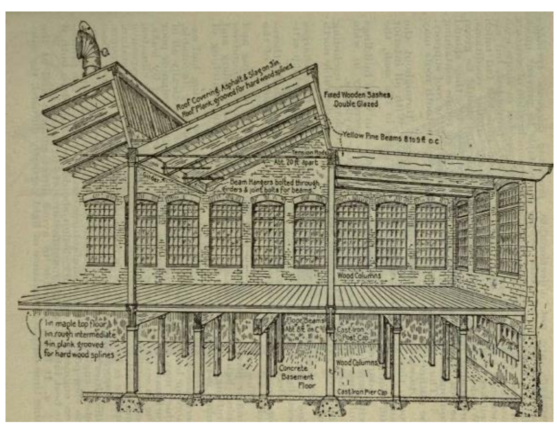


Figure 5.2 Depiction of a building similar to the 1898 mill (image  from [68]).

Although the column still held some residual structural capacity, it was decided to remove the damaged column from the structure on the basis that the non-uniform char damage gave the column an “unsightly” appearance and that the removal of the one column would not significantly impact the strength of the entire structure. This was possible due to redundancy within the design of this specific building. This example details a fire of a historic building that did not cause the destruction of the entire structure. The flame did not spread significantly to other members, and due to the ample amount of redundancy within the structural system, the building as a whole did not experience a significant amount of damage or losses. This case study motivates the research within this chapter, investigating whether historic timber performs significantly different than contemporary timber, so that practitioners can make informed decisions prior to removing or altering timber members within a heritage building. As one of the challenges in ensuring heritage conservation as well as fire safety in heritage buildings is that there is limited guidance available, this chapter will provide a review of guidance documents that direct practitioners how to address heritage timber structures, as well as present information regarding historic fire tests. Contemporary tests of historic timber are then described to help determine if historic timber performs substantially differently than contemporary timber in fire. Contributions to the state of the art included in this chapter involve experiments which begin to quantify the fire performance of timber by looking at flame spread, char depth, and time to ignition, and using these characteristics to compare the fire performance of timber products that are used today with those used hundreds of years ago.

The contemporary experimental research herein focuses on North American softwood timber, as a starting point in evaluating the fire performance of historic timber. Consequentially, North American standards and guidelines are primarily referred to within this study. The results of this study could potentially extend to other regions where additional timber species have been used, though this would require verification by future testing.

## 5.2 Available Guidance and Current State of Practice

The following subsections will review reference and guidance documents available in North American and European practices. Other jurisdictions may have additional documents, but these jurisdictions were chosen to limit the scope. Specific guidance is explained in detail below.

### 5.2.1 North American Guidance

NFPA 914: Code for Fire Protection of Historic Structures is able to offer prescriptive and performance-based design methods of balancing heritage value with fire safety, with an emphasis on understanding the fire safety of the structure [69]. The text references the importance of limited combustibility. This is an important aspect of fire protection for historic structures, especially when it can be implemented in areas that do not alter the heritage value of the space. In many instances, however, a wood frame structure will inevitably be part of the building's character-defining elements. NFPA 914 advises that in these cases, spray-applied coatings or membrane-applied protection are viable options to improve the fire resistance of the members. It goes on to detail that the fire resistance of the structural systems should be determined, and where necessary, new materials such as gypsum wallboard and plaster may be added to improve the fire resistance of the members. NFPA 914 acknowledges that large timber members have some inherent fire resistance, and the more severe challenge lies with the smaller members.

While the method of adding new materials to the structural members may be beneficial in enhancing their fire resistance to meet contemporary compliance, it is possible that it is done at the cost of losing significant historic value. From a heritage perspective, if these elements are found to contribute to the heritage value of the space, it may be desirable to alter them as minimally as possible. It may be worthwhile to find alternatives that are more suited to the principle of minimal intervention. This may be done through understanding the inherent properties of the historic materials and structural systems.

NFPA 914 details the fire properties of a variety of historic materials, on the basis that these characteristics will fall within the known values. The guidance provided by NFPA 914 appears to indicate that historic timber will perform extremely similarly to contemporary timber. It would be useful to comprehensively understand if these values have been proven for heritage materials, or if they have been assumed to be the same as the contemporary materials. Differences exist between contemporary and historic materials, which is largely what prompted this thesis chapter.

In Canada, significant heritage timber stock falls under the jurisdiction of Parks Canada. Subsequently, there is a need to tailor guidance for these structures. The Parks Canada document, Protecting our Heritage: Fire Risk Management Manual for Historic Places in Canada, builds upon a number of the principles introduced by NFPA 914 [70]. Protecting our Heritage provides significant guidance on how to apply many of the recommendations made by NFPA 914, with an emphasis on how to do so while preserving heritage value by offering many practical methods of fire prevention, detection and suppression. Parks Canada echoes the NFPA 914 in offering the ability to increase fire performance through adding materials such as gypsum wallboard and intumescent coatings to areas that may be lacking in fire protection, though this may not be possible to do while achieving heritage conservation goals.  Again, Protecting our Heritage also acknowledges that heavy timber members offer some degree of fire resistance.

### 5.2.2 European Guidance

In Europe, COST Action C17, Built Heritage: Fire Loss to Historic Buildings, was meant to develop the understanding of the problem of heritage losses to fire, and expand techniques to minimize these losses [71]. This action sparked numerous publications and was successful in its goal of sharing information to improve the fire protection of historic structures. Moving forward, there is still a need to be able to clearly assess the fire safety of a particular structure, and how its capacity can be assessed and repaired post-fire.

The Institution of Structural Engineers has also created a guidance document regarding the fire safety of existing buildings, entitled Appraisal of Existing Structures (3rd Edition), which extends to all existing structures, not just those with heritage designation or historic significance, though many of the same methods and principles could apply [72]. Appraisal of Existing Structures advises on many ways to evaluate a building structurally and provides some guidance with regards to fire performance and post-fire repair. This document advises on which species were historically used in different regions and provides guidance on ways to identify and determine the properties of timber used in a particular building. Since Appraisal of Existing Structures is not directly addressing historic buildings, it suggests referencing Eurocode 5 to determine the fire properties of timber [32]. This again raises the question of how historic timber will perform in comparison to modern timber.

One novel aspect of the Appraisal of Existing Structures document is its guidance provided on post-fire repair, offering advice on how to classify the severity of the damage, and how to determine if the member has been harmed structurally. Appraisal of Existing Structures indicates that any uncharred timber can be assumed to have no significant loss in strength and that the charred portion has entirely lost its strength. After the assessment of strength, repair strategies suggested include using mechanical fasteners or steel plates. From this guidance regarding repair of the structures, there are some aspects that could benefit from additional information. For instance, it is unclear whether the notion that the uncharred portion of timber is assumed to have no significant loss of strength, has been confirmed. As well, it would be useful to have detailed examples of how timber may be repaired, especially when applying these techniques to structures with heritage value. The repair of fire-damaged timber is further discussed in Appendix B.

**5.3 Background on Historic Timber Structural Systems**

Timber structural systems are common in historic buildings. Heavy Timber Framing in Late-Nineteenth-Century Commercial and Industrial Buildings provides an overview of the primary differences between historic timber structural systems, including slow-burning and warehouse construction [73]. Slow-burning construction, as the name suggests, was designed to provide some inherent fire resistance to the structure. This type of system, also known as mill construction, was commonly used in the 19$^{th}$ century in buildings that necessitated some level of fire resistance, and often included mills and factories. Slow-burning construction typically uses a masonry wall with large timber beams and columns on the interior. Other features of slow-burning construction meant to improve fire safety include some degree of compartmentalization and fire extinguishing apparatuses. Beyond the inherent fire resistance of the timber itself, slow-burning construction employed several other measures meant to improve the fire safety of the building. Vertical openings were closed with trap doors and stairways were enclosed with brick and featured metal fire doors. Fire suppression measures were also present. These features included water mains, hydrants, standpipes, manual sprinklers, and automatic sprinklers (once they were developed in the late 1870s).

Warehouse construction varied from slow-burning construction in a number of ways. Warehouse construction developed as a means of providing commercial buildings some degree of fire protection. The occupancies that were frequently used in warehouse construction had higher loads than the mills that utilized slow-burning construction. This caused differences in the structure, such as differences in the spacing of the timber members. The mills of slow-burning construction allowed for closely spaced columns, which did not interfere with the function of the space, but this is less desirable for stores, offices, and warehouses. Warehouse construction lacked the other fire protection measures of slow-burning construction, such as the protection of vertical openings and fire suppression measures. Warehouse construction often utilized girders, with beams running transversely. The connections of these timber members included having the beams rest atop the girders, or the use of joist hangers to support the beams. Warehouse construction was often un-sprinklered, as the high number of beams and girders would have interfered.

### 5.4 Historic Timber Fire Tests and Guidance

Researchers have been working to better understand the performance of timber in fire for centuries. While some of the historic test methods may be called into question, these tests can still offer some insight into the performance of the historic materials of their time. This section will outline some of these historic fire tests and advice that has been provided in order to gain an understanding of fire protection features that may be seen in heritage buildings.

<u>1899 – A Treatise on Architecture and Building Construction (Colliery Engineering Company)</u>

The Colliery Engineering Company's book, A Treatise on Architecture and Building Construction, was published in 1899 [74]. This book instructs on the implementation of slow-burning construction, essentially advising to improve the features of braced framing and balloon framing that are susceptible to fire. A detail of a slow-burning construction building is seen in Figure 5.3. It recommends oversizing members by one third to account for loss to char and to build the floors so tight that any water used for extinguishment will not damage the floor below. The text instructs on many of the construction techniques outlined by Wermiel (2004) [73].

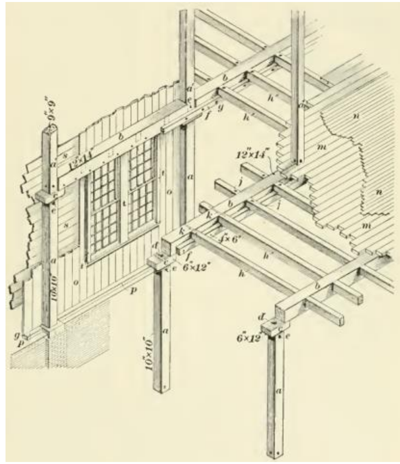


Figure 5.3 Detail of a slow-burning construction building (from A Treatise on Architecture and Building Construction) [74].

A Treatise on Architecture and Engineering goes into detail regarding the state of knowledge of timber at the time it was written. Configurations and techniques for sawing and seasoning are also suggested, so as to optimize the amount of material collected from the trees. General properties of different types of wood species are also outlined, and a number of carpentry techniques are also detailed. This information may be useful in understanding the types of wood and the construction methods used at the time, in order to better assess the current state of a historic building.

<u>1912- Fire Prevention and Fire Protection as Applied to Building Construction: A Handbook of Theory and Practice (J.K. Freitag)</u>

The Fire Prevention and Fire Protection textbook outlines a number of topics relating to both the early theory of fire safety, as well as detailing results of specific fire tests and how these may be incorporated in design [68]. The textbook provides an overview of the severity of the fire problem in the United States, discussing factors such as fire losses and typical hazards. Permanent fire testing stations and committees are then discussed, highlighting some of their research contributions. A series of case study fires are also described, providing insight as to how the older structures performed in fire, as the construction of the building is detailed as well as the severity of the damage.  Fire Prevention and Fire Protection goes on to advise about the materials used in 'fire-resisting' construction. "Fireproof wood" is discussed, including the manufacturing process as well as results of previous tests, providing some general strength properties. The fire properties are described at a high level. Fire resisting design is addressed, both generally for planning a building as well as detailing specific assemblies. Fire Prevention and Fire Protection gives a useful overview of many of the theories of the time, as well as details into how historic buildings were constructed.

1921 – Fire Tests of Building Columns (Bureau of Standards)

The test program, conducted by the Bureau of Standards in 1919 and published later as No. 184, Fire Tests of Building Columns, was meant to understand the fire resistance of a series of columns of a variety of materials, including timber [52]. The columns were loaded for the duration of the tests. They were evaluated on their ability to sustain this load while exposed to fire. The columns were heated using a furnace. The timber columns featured in this test included four pine columns and two Douglas fir columns. The columns were meant to be select structural. One of the columns was encapsulated using gypsum board, and another was protected using a plaster mixture.

The time to failure of these columns was reported in the results and ranged from 35-50 minutes for the exposed columns and up to 2 hours and 15 minutes for the encapsulated columns. The failure mode of these columns was due to deformation at the steel or cast-iron caps. One of these columns may be seen, before and after testing, in Figure 5.4. The study outlines a number of limitations on its findings, including that the moisture content of the timber species was not comparable (and as a result, a comparison could not be made between the tests of the two timber species). Typically, the columns with the cast iron caps withstood longer than those with the steel caps. From these tests, the Bureau of Standards has offered a Fire Resistance duration for each of the materials. These values only require the columns to have a minimum cross-sectional area and have a minimum amount of protection. No additional guidance is offered for larger members or additional layers of encapsulation.

Figure 5.4 Qualitative results of the fire testing of one of the specimen, an unprotected longleaf pine column with a cap and pintle bearing (from [75]).

This test series provides an understanding of fire resistances used in the time period. While the accuracy of the equipment used in this test program is not of the same caliber used today, for instance historically furnace control was done manually in this time period making it difficult to follow time-temperature curves, there are still some findings from this study that are relevant. Some insight is provided as to the failure mode of the columns, which could prove useful if similar columns are found in a heritage building. Moreover, information is also provided regarding the proficiency of historic encapsulation materials. This is also useful in understanding the benefit provided by these coverings.

1928 – Fire Tests of Brick Joisted Buildings (Bureau of Standards)

The test series entitled Fire Test of Brick Joisted Buildings examined the performance of two adjoining multi-storey buildings, with brick exteriors and timber beams and columns [75]. This test occurred in Washington DC in 1928. Prior to the tests, the buildings were loaded with additional lumber to act as fuel, representative of a typical occupancy such as an office.

Thermocouples were placed around the buildings. Kerosene was placed inside the buildings to aid with ignition. The buildings were deemed to be entirely burned down between one and a half, and two hours. The results show that the rise in temperature was quicker than the standard temperature-time heating curve test, and one of their primary conclusions was that the fire spread very rapidly. While some conditions of the test, including the quantity of fuel used, may have not been entirely representative of a real building fire, this example is interesting in that it was performed at full scale and may provide some insight as to the overall performance of similar historic buildings.

1939 – Fire Exposure of Loaded Timber Columns (Underwriters Laboratory)

Following up on the 1921 Fire Tests of Building Columns, Underwriters Laboratory released a paper entitled Fire Exposure of Loaded Timber Columns [76]. It discusses the previous tests from 1921 and then expands to include a new test series. The tests conducted for this paper involved investigating ways to avoid failure at the cap that was previously observed. This was done by adding insulating materials between the cap and the wood and using reinforced concrete caps. This was meant to provide a better understanding of the fire resistance of the timber.

The insulating material used between the steel or cast iron caps and the timber columns were asbestos boards and papers, and floor tiles. The assembly was heated in a furnace while the load was applied. The results of these tests showed that crushing occurred near the steel cap and buckling of the columns. The results of these tests showed failures between 78-112 minutes. The columns failed towards the centre of the members, away from the caps. The conclusions outlined in Fire Exposure of Loaded Timber Columns include that the concrete caps were successful at prolonging failure, while the insulating materials were not. The Fire Exposure of Loaded Timber Columns test series is likely more representative of the fire performance of the timber itself than the tests performed by the Bureau of Standards in 1921. This data may be useful in understanding the fire performance of the assemblies featured in these tests. It may also help to assess the inherent fire resistance of these historic timber types.

### 5.5 Differences between Contemporary and Historic Timber

Historic timber differs from contemporary timber for several reasons. Timber is a polymer, and it cannot be assumed that all polymers within a group (including wood) will act identically in fire [77]. Historic timber was produced from trees that were grown hundreds of years ago. Ancient timber growing practices may be different than contemporary growing practices, which may affect properties inherent to the timber such as density and growth ring width [78, 79]. An example of this is seen in Figure 5.5. For the particular samples shown in Figure 5.5, the contemporary timber shows more uniformity in its growth rings, whereas the historic sample has more variation. Furthermore, contemporary timber often frequently uses adhesives and other additives which may also impact the fire performance of the timber. Adhesive lines in the contemporary Glulam are seen as vertical lines holding together the wood laminates in Figure 5.5a.

a.

b.

Figure 5.5 Cross sections of showing the growth ring width of, a. contemporary Glulam and b. historic timber, from a building constructed in the 1840s (author's photos).

While there is a need to better understand the fire performance of historic timber, there are many challenges around obtaining relevant samples that are useful for testing. First, historic timber must be located, and second, it must be in acceptable condition. As the historic timber is likely to be significant from a heritage standpoint, it is not easy to remove this timber from a heritage building for destructive testing. Therefore, finding timber samples for testing necessitates procuring timber samples that have already been removed from a historic building, or will need to be removed for another reason. When historic timber samples are located, their condition must be assessed. If the timber has been left outside, it may have moisture damage or may be affected by pests. In this case, the timber would not be representative of the timber that would be found in a heritage building and is not useful for the purpose of fire testing. Additionally, should the timber be removed from the building and quickly placed in a new environment, quick acclimatization to a new moisture content can adversely affect the member. The procurement of historic timber in acceptable condition is a significant challenge for the fire testing of these materials. These challenges in procuring materials make the study of historic timber in fire very difficult to study.

As mentioned in Chapter 3, radiant heaters are one method that can be used for fire testing. Fire testing apparatuses such as the Cone Calorimeter and the Lateral Ignition and Flame Spread Test (LIFT) both use radiant heaters. In both cases (for the Cone Calorimeter and the LIFT), 50 $kW/m^2$ is on the upper end (safe operation) of heat fluxes that can feasibly be achieved for long testing durations (exceeding 50 $kW/m^2$ can damage equipment and necessitate replacement of the heating element, which is not sustainable for these tests), though this heat flux of 50 $kW/m^2$ is not as severe as a heat flux that may be expected from a real fire (>100 $kW/m^2$). Advantages of these apparatuses, however, are that they are useful for developing an easily controlled, consistent heat exposure, and are therefore useful for reproducible and comparative tests for research purposes. Furthermore, the heat flux emitted from the radiant heater remains constant regardless of the heat created by the timber itself. In furnace testing (such as the standard temperature-time curve), the temperature follows a specified time temperature curve regardless of the heat emitted by the material being tested. Recent studies have shown that for materials which create their own heat or energy, the amount of fuel provided to the furnace may be lowered in order to compensate [10, 24], as the combustion of the materials inside the furnace provides an additional source of heat [9]. The following sections of this chapter will begin to look at the fire performance of historic timber from several sources, through examining properties such as char depth and flame spread. Assessing the fire metrics of historic timber will help to better understand how it performs in fire relative to contemporary timber, to evaluate if it is conservative to use contemporary procedures in the evaluation of historic timber, and if significantly more fire risk is presented by the historic timber versus the contemporary timber. This analysis will be useful in the assessment of heritage timber buildings, by understanding if the fire performance of the building is acceptable in its current state (mitigating unnecessary interventions), or if the building requires further fire safety strategies. In either case, avoiding unnecessary interventions and ensuring that the building is protected from fire are both steps towards successful conservation.

## 5.6 Methodology – Contemporary Tests of Historic Timber

### 5.6.1 Obtaining and Preparing Samples

Four different types of timber were procured for testing; two historic timbers and two contemporary Glulam. The first type of Glulam tested used a polyurethane-based adhesive, and this timber will be denoted as ‘Glulam – PUR’ herein. The second type of Glulam used a phenol-resorcinol-formaldehyde based adhesive and will be denoted as ‘Glulam – PRF’. The historic timber was obtained from two different sources, both located in Ontario, Canada. The first location is the industrial ‘mill’ type building constructed in 1898 described in the introduction, with a layout similar to Figure 5.2.

The structure used large timber beams and columns connected by a cast iron cap, which is seen in Figure 5.6. Several timber members were (carefully) removed from the structure by the building owner to accommodate an adaptive reuse project, and the timber samples used in this research were sourced from one of these columns (originally located in the basement). The dimensions of the column were 240 x 290 mm. All timber described as ‘Column’ indicates that it is timber from one of the columns within the industrial mill building. The materials were wrapped in plastic to allow slow acclimatization to new laboratory conditions.

Figure 5.6 The timber column in the basement of the structure before removal.

The second source of historic timber was from a commercial building, constructed in 1839. The interior of the structure was demolished to accommodate a new construction project, though the façade of the building was preserved and will be integrated into the new construction. The original structure was listed on the municipal heritage registry. Figure 5.7 shows a photograph of the building dating to 1856. Wooden joists were obtained from this structure for fire testing. The original dimensions of the joists were 350 x 70 mm. As per the procedure used for the previous building, these materials were carefully wrapped and acclimatized to new laboratory conditions.


Figure 5.7 (left) An 1856 photograph of the commercial street from the building where the joist (right) was obtained (5th building from the bottom of the photo) [80].

Once the historic timber was located, there were continued challenges in preparing the timber for testing. All of the timber was thoroughly inspected for pests, rot, and moisture damage, and none was detected. The moisture content of the timber was then kept relatively constant in order to avoid deformations or cracking. The moisture content of the timber was then slowly acclimatized to the lab where they were stored, eventually reaching a moisture content ranging from 7-8% which is within the acceptable moisture content for in service timber. The moisture content was determined following ASTM D4442 oven-dry procedure using an oven at 103℃ [81]. The timber did have some cracks, which made it challenging to obtain samples of the correct size from the timber. The dimensions of the original members also somewhat limited the shapes and configurations of samples which could be obtained. As a result, the side exposed to the radiant heater was freshly cut for all specimen (as opposed to having been allowed to oxidize over time). This side was chosen, as it allowed the required number of samples to be extracted from the Column and the Joist, in the dimensions required for the Cone Calorimeter.

All of the types of timber are seen in Figure 5.8. The Glulam and the Joist timbers are Spruce, and the Column timber is Pine. The wood species affects the fire performance of timber (for example, Pine is typically considered to char at a faster rate than Spruce) [82], and this should be considered when interpreting the results herein, however variations in species may be representative of what has been used historically for construction versus what is used today (at least in the jurisdiction where the timber was procured).

The density of the timber was measured as 504 kg/m$^3$ for Glulam, 394.8 kg/m$^3$ for the Joist, and 417.6 kg/m$^3$ for the Column. As the Glulam and Joist are of the same species, the difference in densities may suggest differences in contemporary and historic growing practices, reinforcing the need to understand potential difference between the fire performance of historic and contemporary timber. The Glulam (both PUR and PRF adhesives), as well as the column and joist were tested with heat exposure perpendicular to the grain. The historic column was also tested with heat exposure parallel to the grain in the Cone Calorimeter phase of testing (Figure 5.8d). The parallel grain orientation of the test was not possible in the historic joist, as due to the thin nature of the member, the required dimensions could not be obtained in that grain orientation.

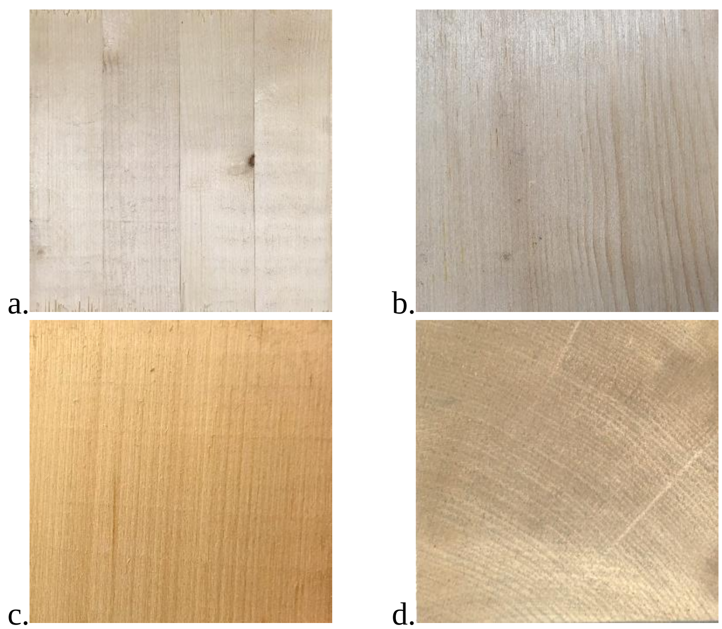


Figure 5.8 Each of the timber samples and the surface exposed to heat, a. Glulam, b. Joist, c. Column – Perpendicular, and d. Column – Parallel.

Timber samples were cut to the size required by the testing apparatus. Two test apparatuses were used, the first a Cone Calorimeter and the second a Lateral Ignition and Flame Spread Test

(LIFT) apparatus. The samples tested in the Cone Calorimeter were 100 x 100 x 45 mm, while the samples tested in the LIFT were 800 x 155 mm x 35 mm.

### 5.6.2 Cone Calorimeter Tests

The Cone Calorimeter tests followed a modified ASTM E1354 procedure [17]. The Cone Calorimeter is an apparatus that uses radiant heating coils wound into a cone [83], and the irradiance of the apparatus can be controlled. Specimens can then be placed under the heater and exposed to the desired heat flux. The Cone Calorimeter test setup is seen in Figure 2.5 (Chapter 2). Modifications to the ASTM E1354 procedure were made in that each sample was removed from the Cone Calorimeter after a specific length of time and extinguished with water (which evaporated upon application to the timber). The use of water to extinguish a fire is representative of what would occur in a real fire scenario. Another modification to the procedure was that the spark igniter of the Cone Calorimeter was not used. The ASTM E1354 standard indicates that the exact irradiance levels or use of external ignition is not prescribed, and that these should be determined separately for each product [17]. The spark igniter was therefore not used in order to be most representative of a realistic fire, as if ignition were to occur, the timber would self-ignite.

For the Cone Calorimeter tests, samples were tested at two different heat fluxes, 30 $kW/m^2$ and 50 $kW/m^2$. These were selected as 50 $kW/m^2$ is towards the upper limit of heat fluxes that the Cone Calorimeter can sustain for long durations of time. 30 $kW/m^2$ was chosen as a less severe point of comparison. Heating durations of 3, 6, 10, and 15 minutes were considered, with two samples of each timber type being tested at each heating duration at each heat flux. Two additional samples of Glulam – PUR and Joist were also tested for 30 minutes at 50 $kW/m^2$. Time to ignition was recorded during testing. After the samples had cooled, each one was cut in half and char depth was measured (+/- 1 mm) along the centreline. Char depth was assessed visually, with the author's interpretation of the char layer seen in Figure 2.7 (Chapter 2).

### 5.6.3 Lateral Ignition and Flame Spread Tests

Tests were also conducted using a LIFT apparatus, following a modified ASTM E1321 procedure (Figure 2.4 – Chapter 2) [16]. The LIFT apparatus is useful for exploratory testing, which can then be used to direct larger scale tests [60]. This is adequate for the purposes of the research herein, which is to begin to compare the fire performance of different types of timber. Like the Cone Calorimeter, the LIFT also uses a radiant heater, though in this case the samples were tested vertically facing the heater and the spark igniter was used. The heat flux of the LIFT apparatus ranges from 50 kW/$m^2$ at one end of the radiant panel and decreases to approximately 2 kW/$m^2$ at the other end. The LIFT apparatus can be used for tracking flame spread across the sample. A series of pegs are located along the bottom of the sample holder, and the time at which the flame reaches each peg can manually be tracked. Samples were left in the LIFT for 18 minutes, chosen somewhat arbitrarily as a time which was deemed appropriate for allowing the flame to spread across the samples. Only a subset of timber types were tested in the LIFT, with Glulam – PUR used to represent a contemporary timber, and timber from the Column representing a historic timber. Both timbers were tested with heat exposure perpendicular to the grain. After the samples were removed from the LIFT and had cooled, the char depth and the char front were measured. The char front was measured at the centreline of the beam.

## 5.7 Results and Discussion – Contemporary Tests of Historic Timber

### 5.7.1 Cone Calorimeter Tests

Time to ignition was one of several properties recorded in the Cone Calorimeter tests. These times are presented in Table 5.1. All of the samples ignited at 50 kW/$m^2$. At the lower heat flux of 30 kW/m$^2$, none of the samples ignited, with the exception of Column – Parallel. Six out of the eight Column – Parallel samples ignited at 30 kW/m$^2$, with an average ignition time of 134.8 seconds (standard deviation of 16.1 seconds). The Column - Parallel samples had the longest time to ignition at 50 kW/m$^2$. Both of the Glulam types had very similar average times to ignition, at around 31-32 seconds after heat exposure began. The historic timber which was exposed to timber perpendicular to the grain had the quickest times to ignition, at approximately 17 seconds for the Column and 19 seconds for the Joist.

Table 5.1 Average times to ignition of the Cone Calorimeter tests at 50 kW/m$^2$.

| **Timber Type** | **Average Time to Ignition (s)** | **Standard Deviation (s)** |
|---|---|---|
| Glulam PRF | 31.2 | 5.1 |
| Glulam PUR | 32.2 | 3.6 |
| Column - Perpendicular | 16.9 | 4.1 |
| Column - Parallel | 39.8 | 4.2 |
| Joist - Perpendicular | 19.2 | 2.5 |

The Column – Parallel sample had the longest time to ignition at 50 kW/m$^2$, however it was also the only type of timber to ignite at 30 kW/m$^2$ (with six out of eight samples igniting). Column – Parallel was the only timber type that was tested with the heat exposure parallel to the grain, which may be the cause of the differences in time to ignition. Grain direction is known to impact the fire performance of timber [26]. The notion that timber heated parallel to the grain would take longer to ignite at high heat fluxes aligns with previous studies [84]. The results of the timber tested perpendicular to the grain suggest that in this case, the contemporary Glulam performed somewhat superior to the historic timber.

The times to ignition observed in these tests are generally slower than as reported in previous literature, however, previous literature has largely used spark igniters in Cone Calorimeter testing [85, 86]. Harada (2001) generally reported times to ignition of 8-18 seconds for softwoods at 50 kW/m$^2$, and more recently Xu et al. (2015) observed times to ignition of 16-29 seconds [87]. Slight variations are expected due to differences in species, however as the historic timber tested with heat exposure perpendicular to the grain ignited at times similar to these previously reported values, even without the presence of a spark igniter, the notion that the historic timber may not be performing as well as the contemporary timber is reinforced.

The charring of the timber samples was also recorded. Figure 5.9 presents the char depth results for the 3, 6, 10 and 15 minute tests for all timber types (in Figure 5.9, each data point represents the average of two samples). At 30 kW/m$^2$, the char depth of all of the timbers are relatively close. At 50 kW/m$^2$, there is a bit more deviation. At the longer heat durations, and especially at 15 minutes (which is the most severe heat exposure considered), the historic timbers have charred more than the contemporary timber. On average for 15 minutes at 50 kW/m$^2$ the historic timber had 1.75 mm (13%) more char than the Glulam.

The charring rate of the timber was calculated from the char depths and the heat duration. The charring rate was taken as the total char depth in millimetres, divided by the total heat duration in minutes. The charring rates for the 3, 6, 10, and 15 minute tests are seen in Figure 5.10. Similar to the char depths observed, the charring rates at 30 kW/m$^2$ do not seem to indicate that any type of timber is charring particularly quickly or slowly. At 50 kW/m$^2$, it can be seen that the charring rates begin charring quicker and then level off. While all the timbers seem to be charring at similar rates, it is notable that at the most severe heat exposure of 50 kW/m$^2$ for 15 minutes, all of the historic timbers report a faster charring rate than the contemporary timber, however the charring rates at this heat exposure only range from 0.83 mm/min (Glulam – PRF) to 1.07 mm/min (Column – Perpendicular). These charring rates are slightly above the charring rates previously reported in experimental studies which consider the standard temperature-time heating curve, for example which range from 0.58-0.71 mm/min in wood-wood-wood connections [88].

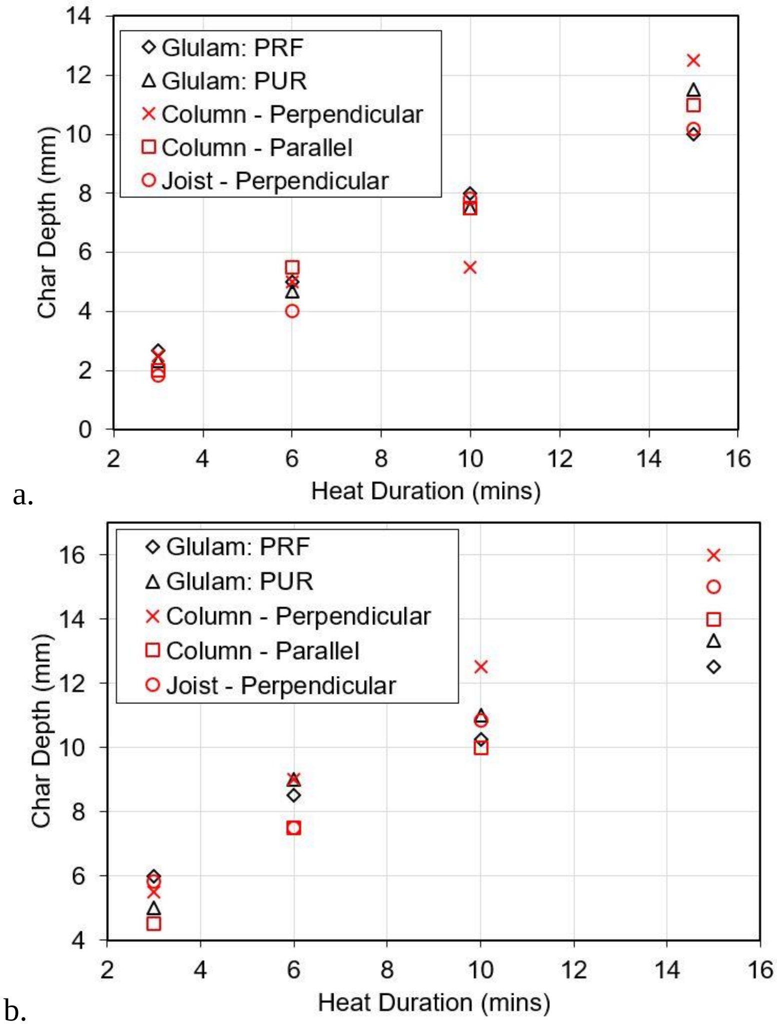
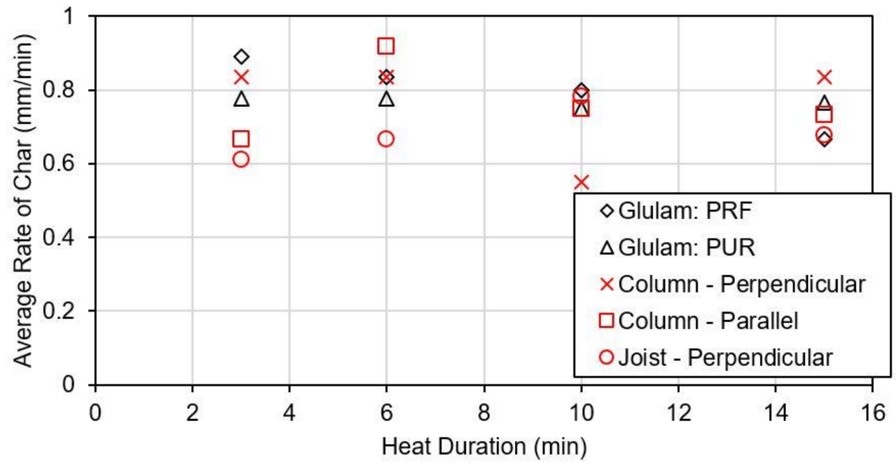
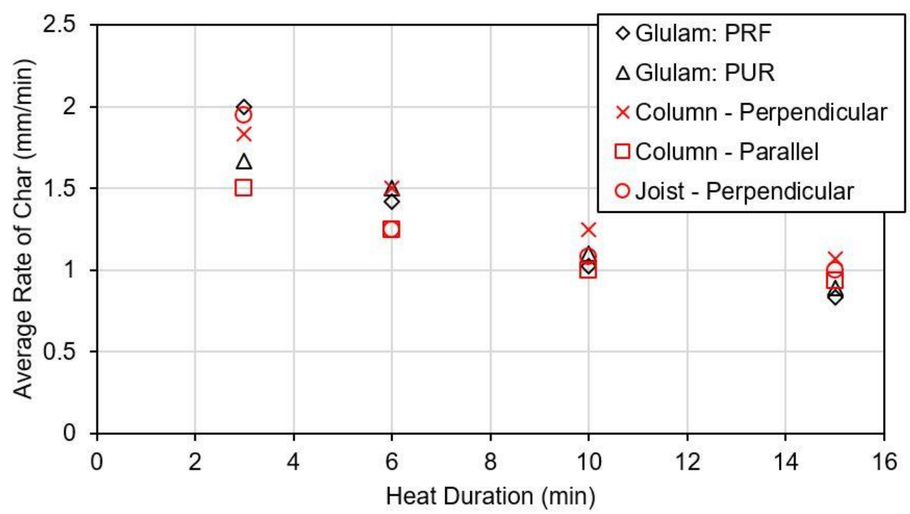



Figure 5.9 Average char depths for each type of timber at a. 30 kW/m$^2$ and b. 50 kW/m$^2$.

The results of the char depths and charring rates showed some discrepancy between the historic and contemporary timber. At 30 kW/m$^2$, all of the timber types charred similarly. At 50 kW/m$^2$, the historic timber had slightly more char depth, especially noticeable at the heat duration of 15 minutes. This may imply that at more severe heat durations the char depth of the historic timber will be slightly greater than the contemporary timber. One of the reasons that may help to explain the difference in char depths and charring rates is the density of the timber. The Glulam was denser than the historic timber, and increasing density has been shown to be tied to a decrease in charring [89, 90]. Many of the other variables known to impact fire performance were constant between each of the types of timber (for example, moisture content, species and sample size).



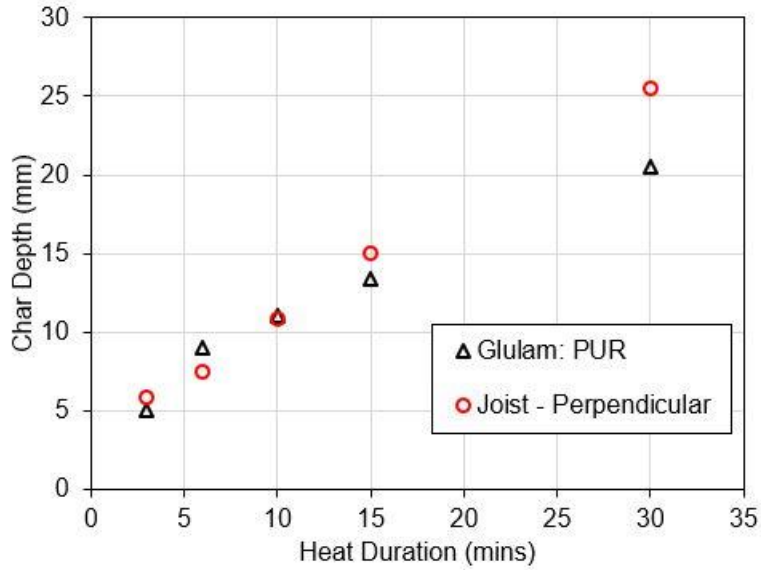

a.



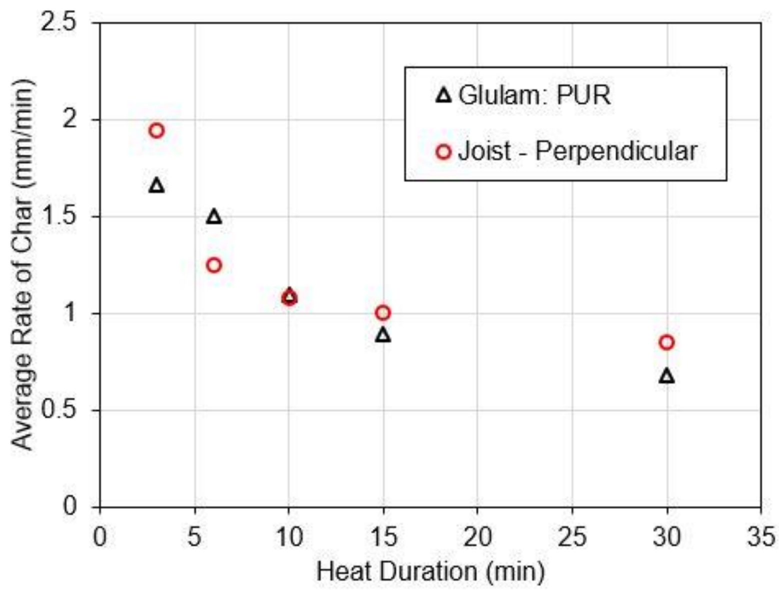

b.

Figure 5.10 The charring rates for the 3, 6, 10 and 15 minute test durations at a. 30 kW/m2 and b. 50 kW/m$^2$.

Apart from the density, additives to the Glulam may also play a part in the differences in performance of the timbers. The contemporary Glulam contains adhesives which may have an effect. Furthermore, it is unknown what the historic timber has come in contact with throughout its life cycle, but it is quite possible the historic timbers were exposed to grease or paints at some point. All of these different additives may contribute to the slower charring of the Glulam, relative to the historic timber.




a.




b.

Figure 5.11 Results for Glulam – PUR and Joist inclusive of the 30 minute tests, a. char depth and b. charring rate.

Two timber types (Glulam – PUR and Joist) were also tested for 30 minutes at 50 kW/m$^2$. The charring depths and charring rates for these timber types for every test duration are seen in Figure 5.11. Some of the trends previously described are exemplified by the 30 minute test. For example, the char depth of the historic Joist is significantly more than the contemporary Glulam, with 5 mm (24%) more char at 30 minutes. The charring rate of the Joist is also clearly higher than the charring rate of the Glulam at 30 minutes.

As seen in Figures 5.10 and 5.11, the charring rates of the timber at 50 $kW/m^2$ are beginning to plateau. Considering only Glulam PUR and the historic joist, the charring rate appears to be plateauing around 0.68 mm/min for the Glulam, and 0.85 mm/min for the joist. The joist was therefore charring at a rate 20% faster than the Glulam.

From Figures 5.9, 5.10, and 5.11, there seems to be relatively similar performance of all timber types at 30 $kW/m^2$, and at 50 $kW/m^2$ up until 15 minutes, at which point the heritage timber begins to char faster. The cause for the initially similar performance that then begins to deviate could potentially be attributed to differenced in growth ring width and cellular structure of the timber. As previously mentioned in this chapter, the Glulam timber tested had very thin growth rings, whereas the historic timber had wider growth rings which could possibly be due to differences between historic and contemporary growing practices. When the timber is heated, the timber converts to char and begins to crack as the timber dehydrates. To the author's awareness, there is little information regarding the effect of timber's properties such as density and cellular structure on the formation and size of cracks developed during a fire, however, one possible factor contributing to the difference in performance between the historic and contemporary timber is that the very thin growth rings seen in the Glulam could be less susceptible to the formation of large cracks. Cracks allow for the ready escape of volatiles [26], which affects the charring performance of timber. At lower heat fluxes and durations, there may not have been an opportunity for sufficient cracks to form causing this effect, though this could potentially be seen at higher heat fluxes and durations. The relationship between cellular structure, cracking, and charring rates could be explored through future research.

### 5.7.2 Lateral Ignition and Flame Spread Tests

The flame spread results of the LIFT tests are seen in Figure 5.12. Recall that in these tests, only Glulam PUR and Column – Perpendicular (heat exposure perpendicular to the grain) were tested. Data ends where the flames auto-extinguished or the flame stopped spreading. The flame spread on the historic Column was faster and spread further than the flaming on the contemporary Glulam. The flames on the historic Column stopped spreading at 141 and 325 seconds (for Test 1 and Test 2, respectively), whereas the flames on the Glulam took longer to stop spreading, at 186 seconds and 388 seconds (for Tests 1 and 2).

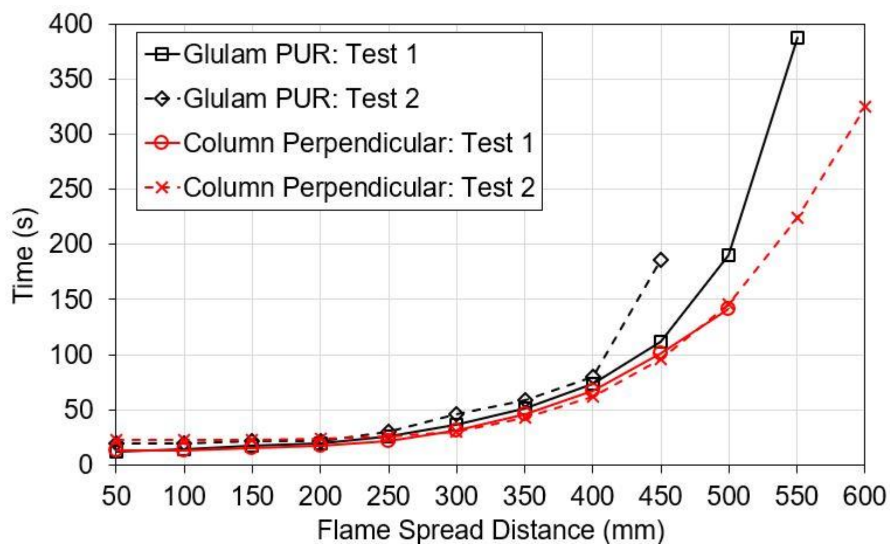


Figure 5.12 Flame spread along Glulam – PUR and the historic Column.

After testing was complete, the char depth and length of the char front were measured. These results are seen in Table 5.2. The timber from the historic column exhibited slightly less char depth than the Glulam, though it had a farther char front.

Table 5.2 Maximum char depth and length of char front of each test.

| Timber Type | Maximum Char Depth (mm) | Char Front (mm) |
|---|---|---|
| Glulam PUR: Test 1 | 12 | 530 |
| Glulam PUR: Test 2 | 14 | 500 |
| Column Perpendicular: Test 1 | 9 | 640 |
| Column Perpendicular: Test 2 | 10 | 560 |

The results of the LIFT tests show that some aspects of the historic timber performed better than the contemporary Glulam. The historic column had less char depth than the contemporary Glulam, and the flames stopped spreading sooner on the historic column. The Glulam performed better in the sense that it had a less extensive char front, as well as a slower rate of flame spread.

**5.8 Limitations and Research Needs**

The tests described above were successful in beginning to compare historic and contemporary timber on a small scale. However, there are some aspects which could be addressed by future research which would broaden the applicability of the results and further progress the current state of knowledge of the fire performance of historic timber.

The scale of testing is relatively small, at only 100 x 100 mm for the Cone Calorimeter tests and 800 x 155 mm for the LIFT tests. Size is one factor that has been shown to have an effect charring rate [91]. Future research is needed on full-scale members. The results described above offer a preliminary indication of the anticipated fire performance of historic timber, but full-scale testing is needed for the results to be extended to full scale structures.

The number of timber types that were tested was limited, mostly due to the challenges in procuring historic timber samples acceptable for testing (as previously discussed). Historic timber from different sources and in different conditions will almost certainly have unique considerations that will alter its fire performance. The timbers tested in this study were North American softwoods, and it would be useful to study other timber species such as hardwoods. Additionally, other regions such as Europe have cultural heritage buildings that are significantly older than the North American cultural heritage buildings tested in this study. Future testing of these older timbers, and different timber species would be beneficial in identifying what trends are occurring, and if the effects previously discussed are exemplified in the older timber due to its age. It is therefore necessary to test historic timber from a wide variety of sources so that the results become more broadly applicable.

Developments in evaluating the fire performance of historic timber through modelling would also be useful in the conservation of cultural heritage buildings. If models are created which can predict the fire performance of historic timber, there is a lessened need to remove historic timber from heritage buildings for fire testing. Models would also help practitioners in the evaluation of the fire performance of the structure, allowing them to understand what modifications to the fire safety system may be required.

Comparisons between different manufacturers of engineered timbers should also be made, as well as comparison to other engineered timber products such as laminated veneer lumber (LVL), cross laminated timber (CLT) etc., as well as solid dimensional lumber. Regional comparisons should also be made outside of Canada.

The heat exposure of a heat flux of up to 50 $kW/m^2$ through use of a radiant heater is sometimes considered to be a limitation, since 50 $kW/m^2$ is not generally considered to be representative of a realistic fire that would occur within a building. However, all of the samples that were tested at a heat flux of 50 $kW/m^2$ ignited, therefore the heat exposure may be more representative of a realistic fire since there was a fire on the surface of each of the samples. Furthermore, at 30 minutes of 50 $kW/m^2$, the charring rates of the Glulam and historic joist were observed to be 0.68 and 0.85 mm/min, respectively. The charring rate derived from the standard temperature-time heating curve for these timbers is 0.65 mm/min, and experimental standard temperature-time heating curve tests have reported similar values [29, 32, 88]. The charring rate appears to be greater or equal to the charring rate corresponding to the standard temperature-time heating curve, however, this is not to say that the heat exposure of this test was equivalent or more severe than the standard temperature-time heating curve. There are several differences such as the incident heat flux, ventilation and oxygen supply, and duration of exposure- and therefore the two experiments cannot be directly compared. In addition, a constant heat flux is used here while the standard temperature-time heating curve follows a transient prescribed temperature time curve. Instead, the results simply suggest that the heat exposure the samples are experiencing is indeed greater than a heat flux of 50 $kW/m^2$ (due to the flaming on their surface) and is therefore an acceptable representation of a real fire. In this sense, the use of a radiant heater for a heat flux of up to 50 $kW/m^2$ allows for a repeatable measure of comparative performance between different timbers.

Another consideration when evaluating the severity of the heat exposure is the notion that the timber also generates heat once it begins burning. The heat fluxes used of 30 $kW/m^2$ and 50 $kW/m^2$ in the Cone Calorimeter represent the heat fluxes generated by the apparatus, but do not necessarily represent the total heat exposure once the heat generated by the timber itself is considered. The heat release rate (HRR) for the 30 minutes Cone Calorimeter tests are seen in Figure 5.13. A higher heat flux will alter the performance of the timber, for example by accelerating chemical reactions which cause ignition at a faster rate [27, 92].

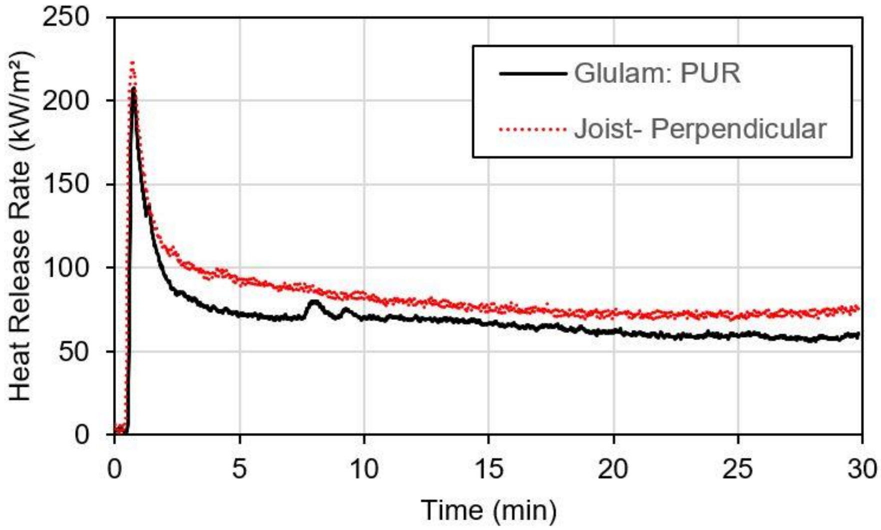


Figure 5.13 Heat release rate of the 30-minute Cone Calorimeter tests.

As seen in Figure 5.13, the heritage timber and contemporary timber have different heat release rates. In these tests which use radiant heaters, the heat flux emitted by the heater is not dependant on the heat created by the timber itself, as opposed to furnace testing where the quantity of fuel will be adjusted in order to follow a specified time temperature curve. For the tests examined in this test series, all timber was subject to a heat flux of either 30 kW/m$^2$ or 50 kW/m$^2$, though as discussed above the actual severity the samples were exposed to may vary based on composition of the timber and due to ignition of the material. From Figure 5.13, the contemporary Glulam does not have as high of HRR as the historic timber from the joist for the majority of the test duration, even though the heat flux subjected by the radiant heaters was the same.[3] In this sense, the heat conditions created on the surface of the timber are dependant on the performance of the timber, and the external heat flux (from the radiant heater) is not reduced for a higher HRR. These tests therefore give a representative comparison of the relative charring of one type of timber to another, and in this aspect the test procedure used in this study is beneficial for comparative

[3] The thesis author considered expanding this figure to include all timber types considered, however the datasets were unavailable (see [102])

testing of combustible materials. Finally, it should be noted that the tests discussed in this study were fully ventilated and were not controlled by the amount of oxygen available. In a real building fire, the dynamics of the fire would be largely affected by the ventilation conditions, as the ventilation conditions govern the availability of oxygen and therefore the consumption of the fuel [10]. The fully ventilated condition of the tests discussed within this chapter are useful in terms of examining the relative performance and in creating a repeatable test, though future testing could look at a wider range of ventilation conditions.

**5.9 Conclusions**

The purpose of this chapter was to identify available guidance regarding the fire performance of heritage timber, including information about historic structural systems and historic fire tests, as well as to compare the fire performances of historic timber and contemporary timber. Industry trends have shown increasingly larger and taller contemporary buildings being constructed, while at the same time, historic timber is often removed from heritage buildings. By compiling available guidance and information about heritage timber, practitioners will be able to make an informed decision regarding whether the heritage timber needs to be removed. Several research areas requiring more study were also identified. One of these areas is guidance on the repair of fire damaged timber, which is further addressed in Appendix B. The results of the experimental investigation compared the times to ignition, char depth, flame spread, and char front of several types of historic and contemporary timber through the use of the Cone Calorimeter and LIFT apparatuses. In comparing these properties, it cannot conclusively be said that the performance of the historic timber is identical to the performance of the contemporary timber, especially in the time to ignition and char depths of the Cone Calorimeter tests, and the flame spread and length of the char front in the LIFT tests.

Considering the char depths recorded in the Cone Calorimeter tests, at 50 kW/m$^2$ for 15 minutes, where there was a difference of only 3.5 mm between the timber type that charred the most and the one that charred the least. Furthermore, the charring rates of the historic joist and contemporary Glulam at 50 kW/m$^2$ for 30 minutes are 0.85 mm/min and 0.68 mm/min (respectively), which are within 20% of one another. As per the LIFT tests, the results showed that the historic timber outperformed the contemporary Glulam in some respects, such as the final char depth and the time at which the flames stopped spreading. While the current study has shown that historic timber does not perform as well as contemporary timber in fire in terms of its material performance (char rates and time to ignition), it is still not performing substantially worse. Current resources available to practitioners may provide some indication of the fire performance of historic timber structures, though practitioners are cautioned that these results have indicated that it may not be conservative to apply all contemporary procedures and values to historic timber. The historic timber present within each heritage structure may need to be individually assessed in some capacity. Additional research into the fire performance of historic timber will better help to understand its properties with the ultimate goal of being able to quantify its performance and allow exposed timber in heritage structures. An increased understanding of the fire performance of historic timber, coupled with other fire protection strategies which can be respectfully integrated within a heritage structure, will help to ensure the successful conservation of cultural heritage timber buildings.

The following thesis chapters will move from examining historic timber relative to contemporary, to examining contemporary timber in depth. Many of the underlying factors affecting the fire performance of the historic timber will also play a role in the performance of the contemporary timber, but the performance of the contemporary timber will further be complicated by the presence of adhesives. Chapters 6 and 7 will address the complex performance of contemporary engineered timbers.

# Chapter 6 : Performance of Adhesives in Glulam after Short Term Fire Exposure

## 6.1 Introduction

The previous chapters of this thesis discussed the fire performance of timber encapsulations and historic timbers. Next, the focus of Chapters 6 and 7 of this thesis will shift towards examining the thermomechanical performance of contemporary (engineered) timbers. This chapter will build upon the findings of the previous chapters; where the historic timber dealt with the fire performance of timber alone, contemporary timber is further complicated by the presence of engineered adhesives.

Engineered timber products, such as Glulam and Cross Laminated Timber (CLT) are being used increasingly in larger and more complex structures (cross sections of engineered timber types are seen in Chapter 2, Figure 2.3). As previously discussed in Chapter 4, one notable demonstration project is the Brock Commons Building in Vancouver, Canada. It is a demonstration-style engineered timber structure as it exceeded height limitations at the time of construction using an exemption in the British Columbia (regional) building code. In this building nearly all Glulam and CLT elements were encapsulated with multiple layers of fire rated gypsum board, from which the timber elements achieve their required fire resistance [93]. Standing at 18 storeys (53 m) high, the Brock Commons building was the tallest timber building at the time construction was completed in 2017. A few years later however, the Norwegian Mjøstårnet building was completed in 2019, standing at 85 m tall. This structure was constructed of CLT and Glulam, much like the Brock Commons building, however in this case the fire protection strategy considered the performance of the timber itself (in conjunction with other strategies such as fire retardant paints, gypsum board encapsulation in stairwells, sprinklers, etc.) [94]. From these two case studies, a couple of observations are made. First, there has been an increasing desire to build taller structures, as buildings even taller than the Mjøstårnet are now planned. Second, there is also a desire to avoid using gypsum board or encapsulating the timber to achieve the required fire performance, as the addition of gypsum board can drive up the construction cost and time, as well as cover up the appearance of the timber members, which is one of the drivers to use timber in the first place.

Canadian practitioner interest in engineered timber has been encouraged by new guidance regarding timber structures by the 2020 National Building Code of Canada [95] (which at the time of writing are subject to final approval by the Canadian Commission of Building and Fire Codes). These changes enable 12-storey tall timber construction of up to 42 m in height (given that certain requirements are met, such minimum levels of encapsulation). The expansion of CSA O86 and Eurocode 5 timber guidance for engineered timber construction has followed [29, 32]. As demonstration projects, some practitioners have begun to build these high-rise timber structures in Canada. However, with the new code changes, there remains peaked interest from various Canadian practitioners in methods and sufficient background knowledge to design these buildings with confidence.

One approach that has been suggested towards enabling tall timber structures is to design the structures such that each compartment can survive auto-extinction of the fuel load [96]. This method relies on the notion that all of the exposed timber will be converted to char and will eventually auto-extinguish. This method also relies heavily on compartmentation. While in principle charred areas of timber may no longer be contributing to a fire, there are several other aspects to consider as have been raised by previous fire tests. These findings (described below) all impact the key notion that the timber compartment will extinguish and retain sufficient structural capacity.

First, previous compartment tests have observed gypsum board fall off. Gypsum board is often applied to timber surfaces to improve fire performance or achieve a desired fire resistance rating, however previous studies suggest that the gypsum board does not stay fastened during a fire. Many of these previous tests were described in Chapter 4 regarding the fire performance of Type X gypsum board. In summary, gypsum board fall off has been identified by several researchers, including NIST/NRCC researchers [4], and Edinburgh/ARUP researchers [5]. The compartment fire test series performed by NIST and NRCC considered six large compartments were constructed and lined with CLT. Each test had varying configurations of exposed versus encapsulated timber, as well as varying ventilation. The researchers noted gypsum board fall off in their tests, ranging from only the face layer, to all three layers of gypsum falling off [4]. Edinburgh/ARUP researchers conducted compartment fires in which they also noted gypsum board fall off, which exposed fresh timber surfaces to fire (in some tests, upwards of 100 kg of gypsum board was observed to have fallen off) [5]. The detachment of gypsum board from timber during heat exposures was examined in Chapter 4, where the deterioration mechanism was examined, and found that fire may be able to reach the timber elements through the opening of the gypsum board seams (especially if redundant layers of gypsum board are not used). These findings of the previous studies regarding gypsum board fall-off are significant in that if gypsum board is detaching, it is possible that fresh timber will be exposed to the fire, therefore providing more fuel and delaying extinction.

Next, delamination has also been shown to alter the fire dynamics of a timber compartment. Researchers at Carleton University performed three compartment fire tests in which they observed delamination indicative of interlayer adhesive failure, allowing fresh timber to be exposed to the fire (similar to the consequence of gypsum board fall off) [97]. They deduced that the delamination was the cause of a second flashover in two of their tests; where their third test- which had the least amount of exposed timber- was the only one of their tests did not have any delamination and was the only to auto-extinguish [97]. Similarly, the researchers of the aforementioned NIST/NRCC led tests, noted that in one of their tests delamination of the CLT laminated was also the cause of a second flashover [4]. United States Forest Products Laboratory (FPL) also performed full scale compartment tests. Those researchers attempted to represent a two-storey apartment, with the location and amount of exposed timber varying between each of their five experiments. Delamination was also reported in these tests by FPL, however FPL attributed the lack of a second flashover in this case to the fact that the delamination had occurred after the compartment had cooled [98]. While delamination was not reported to the same extent as the NIST/NRCC and Carleton University tests, FPL still reported localized delamination of CLT layers causing increased flaming [99]. It can be seen from these tests that heating adhesives can cause delamination, the effects of which can be as extensive as a second flashover. Newer adhesives are being identified which may be non-delaminating [100], which may be a potential method to avoid adhesive delamination, though traditionally used adhesives are still readily available, as they are easy to work with and therefore many manufacturers are still using these traditional adhesives (commonly polyurethane) [98]. This situation raises concern regarding the extent of the adhesive degradation occurring when these timber members are being heated. Even if a member has not delaminated yet, heat degradation may still have occurred within the adhesive causing a reduction in strength to the timber member.

From these previous studies, it is apparent that relying on the notion that a timber compartment may auto-extinguish has several challenges that need to be addressed. Moreover, while delamination in CLT has been clearly identified, what has been less identified is adhesive strength loss due to heating beyond the char front prior to delamination. Engineered timber products are often primary structural members, and therefore adhesive strength loss is of high interest. Should a compartment in a high-rise timber building experience a fire, the structural members within the compartment need to retain sufficient strength to support the structure above (regardless of whether or not auto-extinction is achieved). In this sense, adhesive strength loss becomes extremely relevant in ensuring that this is the case. In order to enable the increasingly taller timber structures that are being constructed and proposed, there needs to be a comprehensive understanding of the strength loss of the adhesives due to heating.

Glulam is a type of engineered timber similar to CLT in that it comprises of many layers of timber held together by adhesives (often similar adhesives are used in both products), however as Glulam often has smaller laminates than CLT, the adhesive layers may be more readily exposed to elevated temperatures. Moreover, while CLT and Glulam are often used in conjunction in many high-rise timber structures, CLT has been the focus of several large-scale studies listed above, Glulam has yet to see this kind of extensive, large-scale research attention. The purpose of the research herein will therefore be to assess the strength loss of adhesives in Glulam.

While this study explicitly considers Canadian design context, as the materials tested are provided by local manufacturers, its results may be generally applicable to other jurisdictions that are also developing tall timber guidance. The research herein should not be construed as an attempt to establish fire resistance metrics or comparators to standard temperature-time heating curves. This chapter is attempting to consider the fire resilience of Glulam by studying the underlying degradation breakdown of complicated engineered adhesive polymers. This chapter examines the post-fire adhesive performance of large-scale Glulam, where the scale of the tests introduces effects such as material defects which may influence the failure of the specimens. Next steps that are required for renewed guidance for tall timber structures in fire concludes this chapter.

## 6.2 Background on Adhesive Degradation

In general, the behaviour of wood in fire is relatively well known based on decades of experiments on the subject, including further contributions in Chapter 5. However, the introduction of adhesive introduces highly complex mechanisms that are still in need of study. In particular, the way the adhesive interacts with the char layer and the adhesive degradation itself (prior to delamination) has scarcely been investigated in realistic building fire configurations.

### 6.2.1 Charring Behaviour of Engineered Timber

As mentioned in Chapter 2 examining the background of timber fire engineering, the reduced cross section method allows for a portion of the cross section of a fire-damaged timber section to be considered undamaged, by subtracting a calculated char depth and zero-strength layer from the original cross section, where the zero-strength layer is taken as 7 mm for fires of 20 minutes or longer (see Chapter 2, Figure 2.8 for a diagram showing zero-strength and char layers) [29]. However, this guidance is in need of review as the current quantification of the zero-strength layer has been debated in recent literature, ranging from 7 to 23 mm depending on the type of fire and the severity [11, 101, 102].

Engineered timber products are largely believed to char in much the same way that solid timber would. Chapter 2 discussed that charring rate is realistically a transient property depending on the degree of char that has already formed and the amount of heat exposure, though standardized constant charring rates have been developed. For example, a commonly quoted value for Spruce-Pine-Fir (SPF) Glulam is 0.7 mm/min. This rate is meant to encompass the initial rapid char phase while fresh wood builds up an insulating layer of char which then slows the charring rate to a lower value. However, it has also been derived from the standard temperature-time heating curve, so questions regarding the applicability have been raised, given that different fire exposures may result different charring rates based on the heat flux, ventilation, etc. Modified charring rates for Eurocode parametric fires have been proposed [103].

As for the code procedure of taking a zero-strength layer of 7 mm beyond the char depth, an in-depth study was done by Lange et al. (2015) in which numerous engineered timber beams were loaded in furnace tests exposed to standard and parametric temperature-time heating curves [11]. The study be Lange et al. (2015) suggested that this layer may range from 8 mm for a short, intense fire, up to 16 mm for a longer fire or standard temperature-time heating curve exposure.

### 6.2.2 Research on Timber Adhesive Fire Performance

Adhesives in timber are typically tested at temperatures below 300°C as the strength of the material is assumed to be completely lost at this point as the wood chars. However, the performance of the adhesive just beyond a char front has seen limited studied. Notable studies include a study by Frangi et al. (2004) and Clauß et al. (2011) [104, 105]. Frangi et al. (2004) tested small 40 mm bond lines on double lap specimens through compression loading for several different adhesives including one phenol-resorcinol-formaldehyde resin (PRF) and five different polyurethane adhesives (PUR). Hundreds of samples were heated in an oven to various temperatures ranging from ambient to 170°C. It was found that the behaviour of the PUR varied greatly between manufacturer and thus chemical composition. Three PUR and the PRF adhesive performed similarly to that of the wood itself, while two of the PUR performed very poorly and began to lose strength from 50-70°C.

Clauß et al. (2011) similarly performed shear tests on several different adhesives but using single lap samples with bond lengths of only 10 mm through tensile loading. The specimens were uniformly heated to various temperatures up to 220°C. The results in this test series were highly variable, but similarly found that the performance of various PUR adhesives were diverse with some losing thermal stability around 70°C while others remained stable until 150-200°C. The most recent testing that specifically referenced to adhesive performance was a two-part test series by Nicolaidis et al. (2016) and Emberley et al. (2016) on glued single lap samples exposed to environmental chamber heating and CLT beams exposed to radiant heating, respectively [30, 106]. Pine and spruce wood were used, respectively, with a one-component PUR. The single lap samples had 600 mm bond lengths and were heated uniformly immediately prior to testing. The exposure on the CLT beams was akin to a realistic fire condition but at a very low heat flux of 6 $kW/m^2$, thus inducing a gradient of in-depth temperature below the pyrolysis temperature of wood. The bond lines were mostly uniformly heated perpendicular to the bond on the tension side of the CLT beam, increasing the temperature of the bond lines to just 60-85°C. Heating perpendicular to the bond line is a common scenario on CLT in realistic compartments, however Glulam members will often experience heating parallel to the exposed adhesive lines. In both parts of that experimental series, changes in the failure mode from primarily timber failures to primarily adhesive failures were seen in the higher temperature range tests. Of particular note, the failure modes in the adhesive were often made more severe by the discontinuity and stress concentrations caused by timber failure propagating into an adhesive joint. This stresses the importance of the size effect in experiments and failure modes changing based on the length of bond line tested.

Quiquero et al. (2016) examined the underlying mechanics of the failure of fire-damaged engineered timber, specifically in timber box sections. The test series included axial compression of Glulam coupons and four-point loading of short Glulam beam sections [107]. A group of the samples were burned in a furnace following a one-hour standard temperature-time heating curve and allowed to cool after fuel supply was halted for an additional hour. Following this the samples were allowed to cool and tested at a later date so that the material could reacclimatize in moisture and so that the mechanics of the beam performance and failure could be closely studied. Of the samples that were not burnt, some were left as control specimens with original dimensions, and a portion of the samples were manually altered to carve off the corresponding char depth to the burnt specimens. Specimens were carved to remove the char depth recorded in order to investigate whether the assumption that the cross-section below the pyrolysis zone had full strength. In all cases in which a corresponding specimen was carved to match a burnt specimen, the manually reduced test always had a significantly higher capacity than the burnt counterpart. This indicated that there was some other factor contributing to the failure of the specimens other than the loss of cross-sectional area. The adhesive in the engineered timber could be affected by the extreme heating and the charring encroaching on glue-lines, causing it to have a reduced strength. Samples in this study however were not of representative length of what would be used in construction.

Quiquero (2018) went on to examine small scale adhesive shear tests on cone calorimeter samples [102]. 50 Glulam samples were heated under various severities, with each of the Glulam samples having an adhesive line exactly along the centreline of the specimen. Glulam using two different types of adhesives were considered, PUR based and PRF based. The specimens were extinguished with water immediately after being heated. A shear test of the heated and control samples was then performed, using a custom apparatus created to ensure shear along the centre adhesive line. Quiquero (2018) found that adhesive beyond the char layer is affected by the heat, by correlating the residual shear capacity of the samples with their remaining shear area. Quiquero (2018) found that a zero-strength layer of 23 mm would be needed to conservatively correlate remaining shear area with remaining strength. Additional observations included studying slip along the adhesive line, where it was found that as heating duration increased, lower loads were reached for the same level of slip, indicating that adhesive stiffness has degraded from the heat exposure. This study is useful in that it considers a large number of samples at varying exposures, however cone calorimeter samples are very small and therefore may not necessarily reflect what may occur in a realistically sized member.

From these previous studies, it is seen that there are multiple research needs with regards to use of the zero-strength layer. Many of the previous studies examined small scale samples only, where tests of a more realistic size are needed to understand how the results would apply to real constructions. The purpose of the research herein is to evaluate the current value of the zero-strength layer (and if necessary, propose an alternative value), reflective of realistically sized Glulam beams exposed to a non-standard fire.

### 6.3 Experimental Methodology

Commercially available Glulam and the performance of adhesive after exposure to fire conditions is considered. The Glulam had 5% moisture content (before heating). It was machine rated as 24f-ES and made of SPF species. The adhesive used in these members was polyurethane based. The Glulam samples were beams of dimensions 4200 by 195 by 45 mm. These dimensions were used as the specimens were in stock and donated in-kind by a local Glulam manufacturer. As such, the timber members considered were thin, and only moderate degrees of charring could be considered.

A custom experimental procedure was designed for the fire response tests conducted. This testing consisted of localised fire exposure (shear and moment regions of the specimens) followed by mechanical testing of the beams afterwards. The first phase test setup, consisting of a single beam locally exposed to a fire is shown in Figure 6.1. The fire for each test was fuelled by 1 litre of kerosene, contained in a one-meter long modified steel (W section) trough.[4] While the fire exposure is dependent on the fuel type considered, in this case the objective was simply to create a quantifiable and repeatable char depth on the specimen. The fire dynamics of this test series was therefore not of interest and only the repeatable damage state was of concern, and it was decided that any fuel type that would generate an easily repeatable damage state would suffice.

The fire burned for approximately 5 minutes, producing a peak surface average temperature of 900°C on the exposed beam. The heating configuration was determined through a series of test burns. The beams were exposed to fire twice; once along each of the depths (sides) of the beams (the beams were flipped). As the purpose of the pool fire procedure was to create a repeatable damage state, the beams were protected outside their fire exposed regions to inhibit flame spread for a more quantifiable damaged area. This was done by wrapping the beams in aluminum foil in the regions where no char was desired (seen in Figure 6.1). Insulation was also used to protect thermocouple wires running from the data acquisition unit to the pool fire (also seen in Figure 6.1). No water was needed for extinguishment as the beams auto-extinguished once the kerosene fuel was consumed. The fire is to be considered a short period of real fire impingement on a structural element. The fire exposure was designed as non–standard to explicitly induce a controlled and quantified amount of charring on the samples from test to test.

Figure 6.1. Test setup of the heating portion of the experiment for the moment region (left) and the shear region (right).

[4] The steel trough that was used was created by welding steel plates to the ends of a W section, creating a customized trough of the desired dimensions.

Five identical Glulam beams were charred at different locations along their length for the full duration of the fire (which was five minutes per side). Four additional beams that were not fire damaged were also considered, consisting of two control samples and two samples that were mechanically carved to simulate charring. The description of all nine beams are summarized in Table 6.1.

Table 6.1. Damage type of each beam.

| **Beam Number** | **Damaged Region** | **Damage Type** |
|---|---|---|
| 1 | Centre (Moment Region) | Charred |
| 2 | Centre (Moment Region) | Charred |
| 3 | Centre (Moment Region) | Carved |
| 4 | Side (Shear Region) | Charred |
| 5 | Side (Shear Region) | Charred |
| 6 | Side (Shear Region) | Charred |
| 7 | Side (Shear Region) | Carved |
| 8 | None – Control | ---- |
| 9 | None – Control | ---- |

Of the charred beams, two beams were charred across a 1 m length directly in the center of the beam, and three were charred across a 1 m length on one end, beginning 270 mm from the edge of the beam (Figure 6.1). The purpose of these locations is that in the next phase of testing (mechanical loading through four-point bending), the centre of the beam would be in the region of highest moment, and the side of the beam would be in the regions of constant (highest) shear. This heating configuration had negligible differences in the amount of char observed, even along the top and bottoms of the beams (5 +/- 1 mm at three locations on each beam equally spaced and across the depth). Aluminum foil was wrapped around the beam immediately adjacent to the intended char zone to limit the radiant heat and flame spread to other parts of the beam. When the pool fire burned out, the beams were left to auto-extinguish. Since this happened immediately, no water was used for extinguishment. This test setup allowed for two-sided heat exposure.

A second set of beams was used to compare strength loss due to degradation beyond the char layer. This set of beams consisted of Beam 3 and Beam 7 (from Table 6.1). Both of these beams had an area of cross section mechanically removed to represent the cross sectional area lost to char in the fire damaged beams. Beam 3 was mechanically carved in the centre, to be compared with the beams damaged in the moment region, while Beam 7 was mechanically carved towards the side, to be compared with the beams damaged in the shear region. The area removed was approximately 5 mm deep on all four exposed sides and 1 m long, consistent with the charred area on the fire damaged beams (see Section 6.4.1 for details). All damaged beams (charred and carved) therefore had the same non-charred cross-sectional area for the mechanical testing. In this manner, any variation in the strength data will be due to factors other than the effective cross section reduction of the damaged beams. The intention on this degree of charring (5 mm) is not to be thought of as information on timber's fire resistance, but rather a controlled set amount of damage that can allow the underlying breakdown mechanisms of timber exposed to fire to be rationally studied. After time for re-acclimatizing to lab moisture conditions (5%) four-point loading was performed to induce constant moment and shear on the specimens. Beams were restrained against lateral torsion at the supports and at the points of load application. The loading setup can be seen in Figure 6.2.

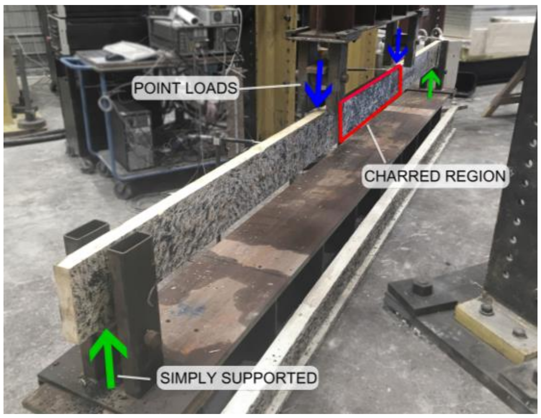



Figure 6.2.Mechanical loading of simply supported beam with four-point loading.

### 6.3.1 Deformation Measurement

Digital Image Correlation (DIC) was used to monitor the deformations of all experiments. This has previously proven accurate for measuring displacements and strain in wood specimens within 0.16 px [108]. The displacement measurement technique uses a pixel-tracking software to locate user-specified locations on a series of high-resolution photographs. A speckled pattern is painted on the surface in order to ensure there is a very unique patch of pixels for the software to track from image to image. The software then records the location of the pixel patch in each photograph, which may be used to compute the displacement and relative deformations. This technology was used to measure deflection at the centre point of the beam. This was complemented using linear potentiometers to record out of plane distortion. The pixel-tracking software that was used to process the test images was GeoPIV RG [109]. A Canon Mark III 5D DSLR camera was used in conjunction at 3 second intervals.

## 6.4. Experimental Results

The results of the fire exposure and subsequent mechanical loading of the Glulam specimens are discussed below. The resulting flaming behaviour and charring of the charred beams was consistent through all five exposed samples. Variability cannot be quantified as a smaller number of beams were tested due to the larger scale. However, the results of the burnt beams are compared herein to the unaltered control beams of original dimensions and two beams with manually reduced cross-sections in critical regions.

### 6.4.1 Post-fire damage state

In order to quantify the amount of char on the fire damaged beams (to ensure char depth was an even 5 mm), the fire-damaged samples were sliced in the charred region after being tested in four-point bending. The char depths were measured across the cross section and were confirmed to be 5 +/- 1 mm. A depth of 5 mm was then taken as the depth to be removed on the carved beams. The mechanical carving of the beams was performed manually by chiseling and sanding.

### 6.4.2 Post-fire mechanical behaviour

As they were mechanically loaded, the beams primarily failed within the moment region, along both adhesive bond lines and finger joints. The failure mode can be seen in Figure 6.3, where the failure originated along the adhesive bond lines within the moment region.

Figure 6.3. Failure mode of a Glulam undamaged control beam.

The average failure loads obtained during the mechanical loading are summarized in Figure 6.4. On an average basis, the control beams failed at the highest applied load, with all of the carved and charred beams failing at lower loads. All failure loads were higher than the hand calculated estimated strength, accounting for only the reduction in cross sectional area (predicted as 10.6 kN for the damaged beams). The displacement of the beams is presented in the plots of load versus vertical displacement in Figure 6.5. Displacements were measured by digital image correlation. In all tests lateral movement measured by linear potentiometers (an indication of torsional failure) was negligible.

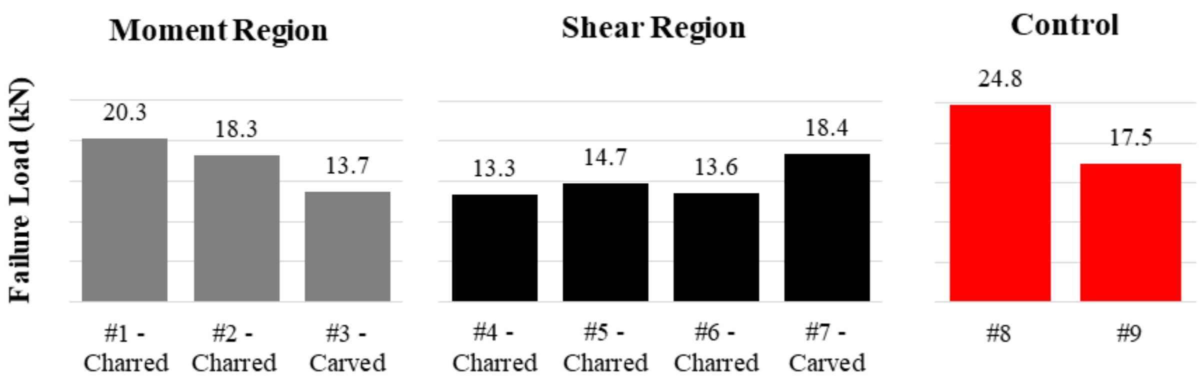



Figure 6.4. Failure load of all beams damaged in the moment region, shear region, as well as the control beams.

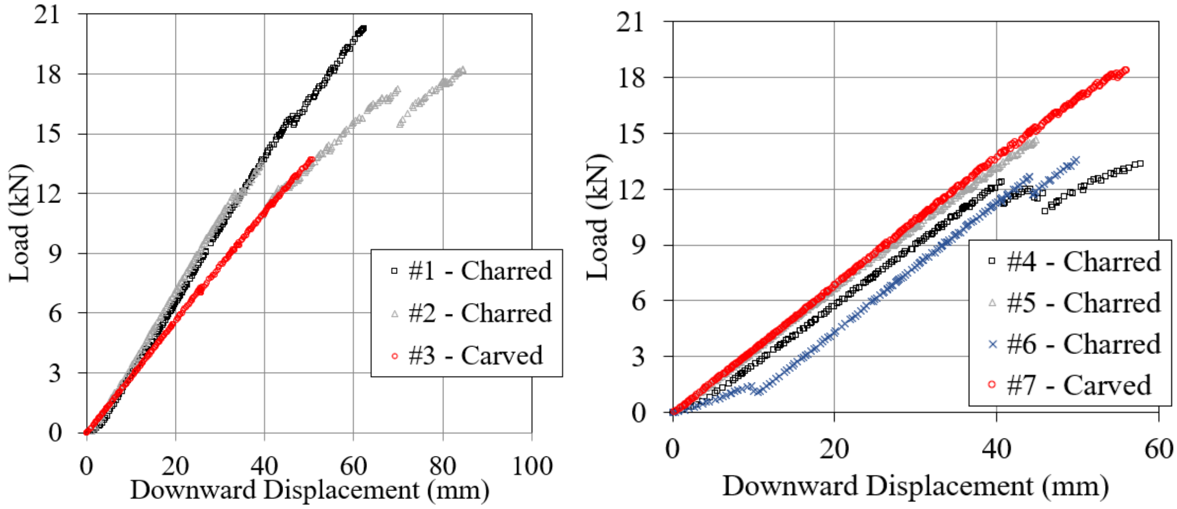



Figure 6.5. Load versus downward displacement beams damaged in the moment region (left) and shear region (right).

The two control beams failed at relatively high loads with the difference between them possibly due to inherent material variability between the specimens. Amongst beams damaged in the moment region (midspan), the results were quite variable; the beam with mechanically reduced cross section failed at a relatively low load compared to the charred specimens, which withstood relatively high loads, losing only 8.9% (1.9 kN) of their capacity. It is possible that the carved beam had a material defect that was not visibly apparent, causing the low failure load. A large reduction in moment capacity was not expected from the exposure as the depth of the cross-section was largely unaltered, which is the dimension that moment capacity is most dependant on.

Regarding beams damaged in the shear region, the beam that had its cross section mechanically reduced through carving displayed the highest stiffness, as the slope of its load-displacement curve is the greatest, and experienced a higher failure load than any of the charred beams. The beams charred in the shear region failed at relatively low yet consistent values of load, while the mechanically carved beam performed better, and failed at a higher load. Following guidance provided by CSA O86-14, a failure load of 10.6 kN was predicted for a cross section reduced by 5 mm on two sides of the beam (so that the width is effectively reduced by 10 mm). All of the shear damaged beams failed at a higher load than this prediction. The charred beams failed on average at a load 24.6% lower than the beam that has been mechanically carved in the shear region. Since the beams that were damaged through charring had the same effective cross section as the beams that were damaged through mechanical carving, this difference is indicative of adhesive degradation. This is in line with the loss of strength observed in the previous research discussed in Section 2.3.

To achieve a predicted failure load for the charred beams 24.6% lower than the predicted load of the carved beam, the equivalent cross section of the beam would be reduced further by 4.3 mm on both sides (beyond the reduced dimensions of the carved beam). This reduction in area would be considered to be due to degradation effects (that is, a zero-strength layer), as the char depth has already been accounted for in the reduction in area of the carved beam. Continuing to examine the beams charred in the shear region, the burnt beams failed at a load 34.5% lower than the control beams. A reduction in cross sectional area of 7.8 mm on two sides of the beam would be required to generate a predicted value 34.5% lower than the predicted failure load of the undamaged beams. Examining standard allowances, and in particular CSA O86-14, the amount of cross sectional area lost to charring and other effects is calculated first by determining the char depth, and then adding allowances for the zero strength layer. The remaining area is assumed to retain its full, initial strength. Annex B.4.2 in CSA 086-14 quantifies the rate of char of Glulam as 0.70 mm/min, indicating that at five minutes of exposure the char depth would be calculated as 3.5 mm. As previously mentioned, this standard guidance is not entirely applicable to beams damaged as per the procedure used for these tests, but for comparison purposes is still considered. In addition to the calculated char depth, Annex B.5 quantifies the zero-strength layer for exposure times less than 20 minutes as being interpolated linearly between 0 mm and 7 mm, depending on the time exposed. At five minutes of exposure, this would predict the zero-strength layer as being 1.75 mm, meaning that the total calculated depth lost due to char and the zero-strength layer would be 5.25 mm. In order to create a loss of depth of 7.8 mm (needed to replicate the loss in strength between carved and charred shear beams), the zero-strength layer would need to be calculated as 4.3 mm rather than 1.75 mm (assuming the predicted char depth is correct). This value of 4.3 mm, which would be considered to be due to degradation effects, is the same depth that has been found to be compromised in the comparison of the charred and carved shear region beams. To achieve a zero-strength layer of 4.3 mm, the depth of the zero-strength layer must be interpolated linearly between 0 mm and 17.2 mm rather than 7 mm (for exposure times less than 20 minutes).

### 6.5 Future Research

Globally there is a demand to create increasingly taller timber structures, as well as the ability to leave timber structures unencapsulated. In Canada, interest in heavy timber construction has been renewed by the new guidance proposed by the 2020 National Building Code of Canada. However, with heavy timber construction comes large Glulam (or other engineered timber) structural elements which have the potential to be exposed to fire in an extreme scenario, and current fire protection strategies enabling tall timber structures may rely on the notion that these timber members will retain sufficient strength, considering both area lost to char as well as degradation beyond the char layer. In larger members, it has been seen in previous research that material defects or timber cracks propagating into adhesive lines have significant potential to govern the critical failure of these elements. The stress concentrations from these defects may induce delamination of adhesive layers in heated engineered timber and is of the utmost importance to be studied in the near future.

There is one significant difference when considering the results of this study to the results of other comparable studies. The study considered in this chapter had no water suppression, as opposed to other studies which did use water for fire suppression such as Quiquero (2018) [102]. This difference could account for discrepancies in the observed zero-strength layer, as Quiquero (2018) suggested a slightly higher zero-strength layer of 23 mm (compared to the zero-strength layer of 17 mm observed in this chapter). In a real fire, water will be utilized to suppress a fire in a timber building (regardless of whether its encapsulated or exposed), which can complicate the degree of damage to the adhesives. At very high temperatures (such as during a fire), adhesives may not be completely solid, with the potential to re-solidify during cooling. When water is used for suppression, some of the adhesive may be lost. The comparison of the tests within this chapter to the tests described by Quiquero (2015) therefore suggest that short term exposures without water suppression may have lesser adhesive degradation in comparison to short term exposures with water suppression. Further testing is needed to investigate the effect of water suppression on adhesive degradation.

Furthermore, while auto-extinction was observed in the beam samples (hence not needing water suppression), it will be necessary to study this phenomenon to a greater degree where fire spread is allowed. A comprehensive listing of future research needs for enabling high rise timber beyond adhesive degradation is provided in Jeanneret et al. (2017) [93].

To study the effect of longer term exposure it is necessary to scale the cross-sections up to representative sizes for mass timber. This will also allow discussion into real specimen section behaviour and direct conclusions may be drawn about realistic performance. Until these tests are performed there is concern that a prescriptive rate for the zero-strength layer criterion of 7 mm for engineered Glulam may not necessarily be conservative. These future tests may allow a conclusive solution or criterion to be drawn, however for now a range should be expected that depends on more factors than just the type of heating as discussed in other literature. Factors including member size, adhesive composition, heating duration and exposure should be considered for all types of engineered timber.

While the work done herein has been compared to prescriptive code methods of predicting the capacity of heavy timber structural elements in fire, the suggested increase in zero strength layer is drastic and likely largely over-conservative. The results have shown, however, that the behaviour is so variable and highly complex that a very conservative prescriptive approach would be required. However, finite element modelling of timber proponents may be used to more accurately predict the behaviour of such components if an appropriate model is used. Computer modelling and analysis should be developed and validated incorporating the effects of these findings in order to accurately predict the performance of complex engineered timber structures. Chapter 8 further discusses finite element modelling of timber structures.

It should also be noted that only one type of adhesive in manufactured Glulam was considered. Additional adhesives by various manufactures and of different compositions should also be considered, and it should be recognized that there currently is significant research being performed into advancing adhesives so that they do not degrade to the same degree in high temperatures seen in fires.

Finally, the tests described in this chapter were small in number, with only nine beams considered in total. There is a need for similar testing to be performed on a larger number of samples, to further verify the findings of this chapter. Smaller scale samples could help to achieve this (though a high number of large-scale samples should also be tested). Examining small scale samples would also help to reduce variability induced by material defects (in addition to adhesive defects as mentioned above), as the smaller size would decrease the probability of any given sample having a defect but increase the impact of the defect on the final results. Such tests will be described in Chapter 7, where 28 small scale Glulam and Laminated Veneer Lumber (LVL) samples are examined.

### 6.6 Conclusions

Due to the drivers towards massive engineered timber construction as of late, it is paramount to delve deep into the details of the material's performance in and after fire scenarios. Studying the material post-fire damage (as opposed to in-fire) allows details in the mechanics of the material's behaviour and failure to be observed. Additionally, the resilience of massive timber post-fire is an important topic to be discussed. The capability to build with and understand materials that are resilient to fire, and to rehabilitate and reuse the structures after such an event also holds immense merit in the realm of property value, business continuity and insurance. If Canada is to build exemplar structures with engineered timber exposed, having confidence in the degree of post-fire strength including adhesive degradation and strength loss is invaluable.

The full scale testing of Glulam beams within in this chapter showed that charring reduced the strength of the beams when compared to the control samples. The moment damaged beams had their capacity reduced by only 1.8 kN (on average) in comparison to the control beams. This relatively small reduction in strength between the control beams and the charred beams should be expected, as the beams were charred on their longer side, but tested in bending standing vertically, such that the depth of the beams was not greatly impacted. Bending is more impacted by depth and section modulus, while shear is more impacted by overall cross-sectional area. Material defects may have played a role in the variability of the beam carved in the moment region. The beams charred in the shear region had their capacity reduced by an average of 7.2 kN compared to the control beams and 4.5 kN compared to the carved beam, which are significantly larger reductions in strength compared to the beams damaged in the moment region. In all instances, the beams failed at a higher load than directly predicted by current guidance, in particular CSA O86-14 equations for Glulam. However, in examining reduction in strength of the charred shear region beams in comparison to the carved beam, the determination of the zero-strength layer may not fully account for all degradation effects that are occurring.

The tests discussed in this chapter showed that the current guidance that exists for approximating the zero-strength layer (7 mm), may in some instances be under conservative. Appropriate values of the zero-strength layer may be affected by suppression operations (such as water) along with fire type and duration, and the size and defects of the specimens. It is recommended that until a more holistic database of tests is established, conservative approximations be used in calculations involving exposed engineered timber with adhesives.

The results found from this chapter are valuable in understanding the degree of adhesive strength loss in Glulam timber beams, however it would be beneficial to examine a larger number of test specimens to reduce variability and isolate the effects of material defects. The following chapter (Chapter 7) will begin to address these research needs through a test series comprised of a larger number of smaller scale Glulam and LVL beams.

## Chapter 7 : Mechanical Performance of Laminated Veneer Lumber and Glulam Beams after Short-Term Incident Heat Exposure

### 7.1 Introduction

Chapter 6 found significant thermal degradation of the adhesives in Glued Laminated Timber (Glulam), though material defects impacted the overall results due to the large size of the members. The size of the members also meant that only nine beams were tested in total, directing a need to further evaluate thermal adhesive degradation in a larger number of members where material defects are more controlled. Furthermore, Chapter 6 examined Glulam only, even though there are many different types of engineered timber with varying configurations, and that use different adhesives. Many of the research needs outlined in Chapter 6 are therefore what prompted the study which will be discussed within this chapter.

The use of engineered timber, such as Glulam and Laminated Veneer Lumber (LVL), is increasing especially in the construction of tall timber buildings, which is raising an urgent need to explore the fire resistance of such materials [110]. The thermomechanical performance of these materials under both standard and non-standard heat exposures should be explored to provide a better understanding of the material's potential for repair after a fire [111]. In terms of the quantity of resources required to return to an operable state, this research can help to demonstrate a timber building's ability to enable operational resilience to approval and insurance agencies [112]. Since the post-fire strength of the engineered timber has a significant impact on buildings, the strength-loss due to heat exposure of Glulam and LVL are explored in this paper using a very controlled heating setup which leads to a controlled damage state. Herein, 18 small scale LVL beams will be considered, along with 10 Glulam beams as a point of comparison. The aim of this chapter is to assess the after-fire performance of LVL (as well as Glulam) through looking at strength loss due to adhesive degradation, which may contribute towards enabling tall and unencapsulated engineered timber buildings.

## 7.2 Background

### 7.2.1 Current State of Practice

The use of timber in tall buildings is challenging since timber is a combustible material [30, 113, 114]. Residual strength of the structural timber members after fire need to be understood to provide in depth guidelines for the designers. Current code allowances enable the calculation of the strength of an engineered timber member after fire [29]. The strength losses can be determined by calculating the char depth and adding an allowance for degradation effects known as the zero-strength layer. The remaining cross-section is considered to be undamaged. Char depth is typically calculated as a function of the time exposed to fire, and the type of timber in consideration. For Glulam and LVL, the charring rate is taken as 0.70 mm/min for notional charring, which accounts for effects such as corner rounding [29, 115]. A visualization of the thermal degradation of wood can be seen in Chapter 2, Figure 2.7.

Current practices take the zero-strength layer as 7 mm for heat exposures over 20 minutes and a proportionally smaller value for shorter exposure times [29, 116, 117]. The lack of confidence in these values adds to the uncertainty of the expected strength after a fire, and therefore how to fully rationalize leaving engineered timber exposed [11, 102, 114]. It should be noted that while the research herein examines the post-fire performance of timber, the material properties (including at the pyrolysis layer) of timber may vary during high temperature exposure and following high temperature exposure.

### 7.2.2 Previous Studies and Research Needs

Currently, there is a need to study the effects of adhesive degradation in all types of engineered timber. To date existing research has focused on investigating the properties of ‘cross laminated timber’ (CLT) [4, 30, 98, 100, 111, 113, 118] with very limited studies on the effect of fire on other types of engineered timber such as LVL and Glulam [111, 119, 120]. The main outcome from investigating the effect of fire on CLT was that the fall-off of layers in fire may be a consequence of adhesive degradation [98, 111, 113]. These studies are outlined in Chapter 6. Studies by other researchers are underway to improve engineered timbers performance in fire with the introduction of melamine based fire resistant adhesives (that are meant to not delaminate during standard temperature-time heating curve tests) (see [100]).

Recent studies have shown that fire performance, and particularly charring of timber, is dependent on its physical properties more than the kinetics and chemical composition of different wood [26, 27, 121]. However, the fire performance can also partially be affected by the grain orientation, species, moisture content, and natural defects of the timber [26, 122]. The structural fire performance of timber structures can be mainly dominated by its strength [57] and the adhesive between the timber layers therefore it is advised to avoid heating the adhesives [123]. However to date, there is not enough research to suggest a temperature limit, or an appropriate depth considered to be compromised [123].

To the author’s knowledge, the study herein is one of the first of its kind to consider the adhesive degradation of LVL. The limited studies available regarding adhesive degradation (and the reduced cross section method) in Glulam include studies by Lange et al (2015) [11] and Schmid et al (2015) [12] (both out of the SP Technical Research Institute of Sweden). The study by Lange et al. (2015) considered two standard temperature-time heating curve tests as well as two parametric heating curves, applied to 32 Glulam beams in total which were loaded to failure. Lange et al. (2015) found the zero-strength allowances to be unconservative, with their results showing a zero-strength layer of 8-16 mm is needed depending on the fire exposure [11]. The study by Schmid et al. (2015) considered five 140 x 269 mm Glulam beams subject to standard temperature-time heating curve exposure and loaded in bending with a load that was maintained until failure. Schmid et al. (2015) suggested zero-strength layers of 9.5 mm to 20.1 mm in their study [12]. The findings of the studies by Schmid et al. (2015) and Lange et al. (2015) reinforce the need to study adhesive degradation, as clearly their results showed that the current zero-strength layer may not be conservative. Quiquero (2018) also looked at adhesive degradation in Glulam [102]. The study by Quiquero (2018) consisted of small-scale (100 x 100 mm) Glulam samples heated in a Cone Calorimeter at varying heat exposures, and then mechanically loaded along the adhesive line to look at shear strength. The findings of Quiquero (2018) concur with the above studies in that adhesive degradation may not be adequately accounted for in code procedures [102].

This study focuses only on the post-fire performance of under-studied Glulam and LVL samples. While in-fire performance is another aspect that could be considered, it is outside the scope of this study, as the goal is to improve the current understanding of engineered timbers resilience towards fire. A better understanding of the post-fire performance will be beneficial towards evaluating an engineered timbers potential for post-fire repair; and may help to enable the defensible implementation of exposed engineered timber in a structure.

## 7.3 Methodology

### 7.3.1 Specimens

This study involved 18 LVL and 10 Glulam samples. A greater focus on LVL was considered as this material has been understudied as compared to other engineered wood products.

Properties of the timber are seen in Table 7.1.

The thickness of each laminate of the LVL was 3 mm, and the thickness of each Glulam laminate was 38 mm. Both specimens fall under the S-P-F (Spruce Pine Fir) species category. The Glulam beams were of Spruce species, while the LVL beams were of Pine species. All of the beams were damaged to the severity and in the locations described in Table 7.2 (where damage was incurred on both sides of the beams, while the tops and bottoms were left undamaged). It is seen from this table that two samples were observed for each damage state (ensuring repeatability).

Table 7.1 Timber material properties (from manufacturer's documentation).

| **Type** | **Bending Strength (MPa)** | **Shear Strength (MPa)** | **Modulus of Elasticity (MPa)** | **Density ($kg/m^3$)** | **Moisture Content[1] (%)** |
|---|---|---|---|---|---|
| LVL | 39.5 | 3.8 | 13 790 | 569 | 10 |
| Glulam | 30.7 | 2.5 | 13 100 | 560 | 10 |

[1] Moisture content from author's measurement

The Glulam samples were cut from beams of original dimensions 45 (width) x 195 (height) x 4200 (length) mm. All Glulam beams were from the same production batch. The LVL samples were cut from beams of original dimensions 45 (width) x 241 (height) x 1829 (length) mm. All LVL beams were from the same production batch. Both the Glulam and LVL samples were cut to be 35 (width) x 155 (height) x 800 (length) mm for the heat exposure. These dimensions were selected to accommodate the Lateral Ignition and Flame Spread Test (LIFT) apparatus used for controlled heating. After heating, the height was cut to 75 mm (where no charring had occurred along the top or bottom of the member) prior to mechanical loading. This height which was chosen in order raise the span : depth ratio to be more representative of what has been observed in construction (for example the Mjøstårnet building in Norway [94]), while still preserving two adhesive layers in the Glulam (note that as the damage was only inflicted along the two sides of the beams, there was no significant damage along the top or bottom of the beam prior to reducing the height). The beams were all selected to be relatively free of defects, apart from small knots (which did not appear to alter the char depth or failure modes of the specimens). The Glulam laminates were joined together by finger joints (which again did not seem to impact charring or failure modes of any of the beams).

Table 7.2 Damage states and failure loads of all beams tested.

| Sample Number | Type | Damage State | Damage Region | Average Failure Load (kN) | Individual Failure Load (kN) | Standard Deviation (kN) |
|---|---|---|---|---|---|---|
| 1 | LVL | None (Control) | -- | 19.7 | 19.21 | 0.5 |
| 2 | | | | | 20.27 | |
| 3 | LVL | Charred (5 mm) | Center | 11.8 | 14.20 | 2.4 |
| 4 | | | | | 9.33 | |
| 5 | LVL | Reduced Cross Section (5 mm) | Center | 17.6 | 17.39 | 0.2 |
| 6 | | | | | 17.83 | |
| 7 | LVL | Charred (5 mm) | Side | 15.3 | 14.76 | 0.5 |
| 8 | | | | | 15.81 | |
| 9 | LVL | Reduced Cross Section (5 mm) | Side | 18.3 | 17.69 | 0.6 |
| 10 | | | | | 18.97 | |
| 11 | LVL | Charred (10 mm) | Center | 9.4 | 7.58 | 1.8 |
| 12 | | | | | 11.20 | |
| 13 | LVL | Reduced Cross Section (10 mm) | Center | 12.7 | 14.10 | 1.4 |
| 14 | | | | | 11.28 | |
| 15 | LVL | Charred (10 mm) | Side | 13.9 | 13.55 | 0.3 |
| 16 | | | | | 14.20 | |
| 17 | LVL | Reduced Cross Section (10 mm) | Side | 11.4 | 11.13 | 0.2 |
| 18 | | | | | 11.58 | |
| 19 | Glulam | None (Control) | -- | 18.1 | 18.45 | 0.4 |
| 20 | | | | | 17.74 | |

| Sample Number | Type | Damage State | Damage Region | Average Failure Load (kN) | Individual Failure Load (kN) | Standard Deviation (kN) |
|---|---|---|---|---|---|---|
| 21 | Glulam | Charred (10 mm) | Center | 14.8 | 15.97 | 1.1 |
| 22 | | | | | 13.64 | |
| 23 | Glulam | Reduced Cross Section (10 mm) | Center | 15.5 | 16.06 | 0.5 |
| 24 | | | | | 14.97 | |
| 25 | Glulam | Charred (10 mm) | Side | 13.1 | 16.41 | 3.3 |
| 26 | | | | | 9.87 | |
| 27 | Glulam | Reduced Cross Section (10 mm) | Side | 18.2 | 16.43 | 1.8 |
| 28 | | | | | 20.03 | |

Two char depths were selected, 5 mm of char per side and 10 mm of char per side. The severe damage state of 10 mm was chosen so that it would theoretically have effectively no remaining cross-section after heating as per CSA O86. The original width of the samples was 35 mm, subtracting 10 mm of char depth and 7 mm of zero-strength layer per side, there would theoretically only be 1 mm of 'undamaged' cross-section remaining (approximately 0 mm, as each char depth was +/- 1 mm). 5 mm was chosen arbitrarily to be half of this char depth, as a point of comparison.

The 5 mm or 10 mm of controlled damage (produced by heat exposure or mechanical carving as described in the 'Heating and Carving' section below) was applied in two different locations along the beams. The first location is a 100 mm length in the center of the beam, with 350 mm of undamaged length on either side. This was chosen as it is in the center of the region of maximum moment and zero shear, when tested in four-point bending. The second location began 83 mm away from one end of the beam, for a damaged length of 100 mm. This is the center of one of the side thirds of the beam. This location is the center of the region of maximum shear, with an average amount of moment, when tested in four-point bending. These locations allow for an evaluation of the performance of the members in bending, and in shear. The length of the damaged region of the beam was selected as 100 mm because this length is small enough to obtain uniform damage when exposed to the radiant heater, while large enough to create a significant damage state.

The LVL samples contained phenol formaldehyde adhesive, while the Glulam contained a polyurethane-based adhesive. These materials were procured from local manufacturers in the Ottawa, Canadian region. They would be typical of recent Canadian construction in Ontario. The LVL was manufacturer specified of the grade 2.0e - 3100Fb (graded in accordance with ASTM D5456-19 [124]). The Glulam samples were of the grade 24f-ES (graded in accordance with CSA O122-16 [125]). The flexural strength of the control beams was calculated from the four-point bending test to be 70 MPa for the LVL and 64 MPa for the Glulam (unfactored and determined from the maximum bending moment, and section dimensions). The modulus of elasticity calculated as 14 133 MPa for the LVL and 17 427 MPa for the Glulam (unfactored and determined from the beam deflection, and section dimension).

All samples were allowed to acclimatize to the laboratory conditions at 50% relative humidity and approximately 20°C for several months.

### 7.3.2 Heating and Carving

The damage was created using two procedures. The first procedure was charring using a LIFT apparatus as per a modified ASTM E1321 [16], and the second was by mechanically carving away a portion of the cross-section. The purpose of using the LIFT radiant heater apparatus for the charring procedure was to obtain a well-controlled and repeatable damage state between tests. It should be noted that the pilot burner was not used. This was because the purpose was not to measure or propagate flame spread across the beam, only to use radiant heat to achieve a specific char depth. Additionally, the holder of the beams within the LIFT apparatus was modified so as to only expose specific regions (in the center or the side) of the beam to heat. Multiple ceramic boards designed to prevent heat penetration were placed in front of the engineered timber samples in locations where char depth was not desired. This is seen in Figure 7.1. This configuration ensured that only the exposed portion of the beam would be damaged. The adhesive lines in the Glulam were parallel to the heat flux while the adhesive lines in the LVL were perpendicular to the heat flux (orientation of the specimens was retained from the original beam orientation). The Glulam was only one laminate thick, therefore the Glulam beams did not have any adhesive lines perpendicular to the heat flux. The angle of the radiant heater was left unchanged from ASTM E1321 specifications, where it is placed closest to the member near the side and angled 15 degrees away towards the middle.

Due to the extended exposure duration of the beams exposed in the center, three layers of ceramic board were used for the moment damaged beams instead of the one layer that was otherwise needed, to ensure no damage was created where it was not desired. The extra boards were fastened externally to the holder (using Nickel-Chromium wire).

One consequence of placing ceramic boards in front of the engineered timber samples is that the samples were approximately 12 mm (the width of the ceramic board) further away from the radiant heater than typical. This caused the heat flux to vary slightly from its usual capacity. A calibration was performed to determine the heat flux that would result from an offset of 12 mm. The results can be seen in Figure 7.2. This figure also displays the prescribed error of the LIFT apparatus heat flux gauge, which is taken as 10% of the incident heat flux.

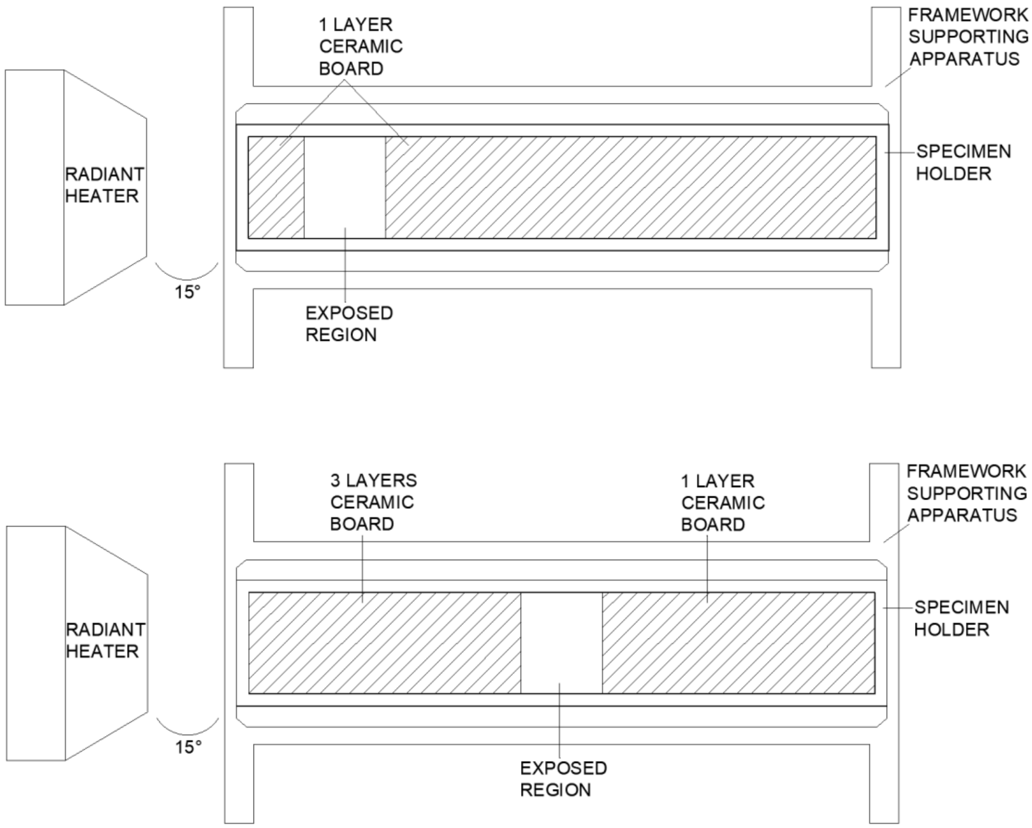



Figure 7.1 The heating test setup for the beams damaged in the shear region (top) and the moment region (bottom).

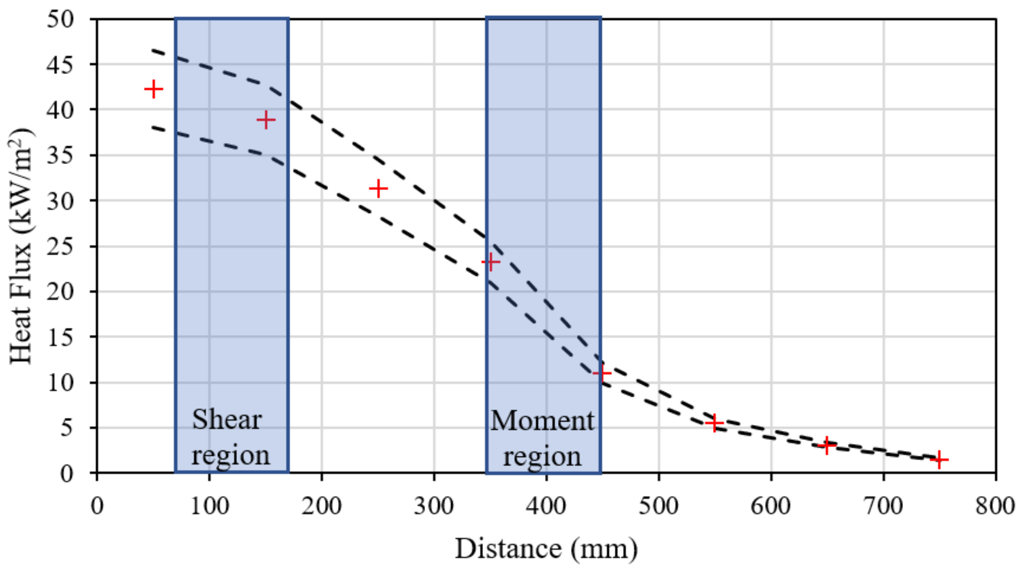



Figure 7.2 Heat flux measured by LIFT apparatus after an offset of 12 mm was applied, with the error of the apparatus displayed as contour lines.

A consistent char depth was achieved in varying locations along the lengths of the beams by exposing them to the radiant heater for varying amounts of time. This method was selected over an alternative procedure of altering the distance of the radiant heater so that it would be parallel with the test specimen. The reason this method was avoided was that it significantly alters the standardized test conditions of the LIFT and impacts the studies reproducibility. Future research could explore more customized uses of radiant heaters as has been done by others [126]. One implication of this test setup is that the members damaged in the shear and moment regions were exposed to heat for varying lengths of time, since the radiant panel is initially closer to the end of the member and angled away from the member in the middle. While the differences in fire duration and distance from the member to the radiant panel may create some variation in the overall heat exposure, this test setup achieves a consistent and repeatable char depth. Using varying heat severities and exposure durations may create differences in the degradation of the timber (even if the same char depth is obtained), however at this time these mechanisms are not well understood and are in need of future research.

The exposure durations were determined by using trial samples of LVL and Glulam in the LIFT apparatus for varying amounts of time. These trial beams were cut in the regions of interest and the char depth was measured, to ensure a consistent char depth across the length of the exposed region. While the beams were exposed to a slightly different heat flux along their exposed length, the char depth observed is relatively uniform (+/- 1 mm across the area of interest).

In this test setup, the damage severity may be somewhat dependent on the ventilation conditions [127]. While the exact ventilation conditions may be difficult to replicate, the purpose of the test setup is to achieve a set amount of damage, and future researchers could alter the heat flux and exposure as needed to achieve the required damage state (measured in this paper by char depth). Though it is possible that otherwise identical damage states may have microstructural differences dependent on their heat flux and duration, as per the current state of knowledge, this has not been confirmed and there is little information available on these aspects.

The heat flux of the radiant panels reaches a maximum of 50 kW/$m^2$ (the heat flux along the entire length of the beam is seen in Figure 7.2). While a real fire will be more severe than 50 kW/$m^2$, these small-scale tests will still give an indication of the adequacy of the values used for the zero-strength layer. Moreover, this test series primarily examines the strength remaining given a particular damage state (char depth) and attempts to assess whether current code procedures are conservative given the damage, not the severity of the heat exposure.

The result of this heating procedure was that a consistent char depth was produced across all samples. This was achieved by carefully controlling several aspects within the procedure; such as the use of a radiant panel (as opposed to a pool fire or other type of heat exposure) that generated a consistent heat flux during each exposure. All other aspects of the testing environment remained constant between tests (such as ventilation conditions). The smaller beams that were tested, were cut from fewer larger beams, ensuring relatively consistent density, and were inspected to be relatively free of defects. For each of the damage states, trial specimens were used to determine the exact duration of heating needed to create the desired damage state. The result was a very consistent heat exposure induced on very similar beams across the intended heated region, which generated a reasonably controlled char depth. Each specimen was observed to ensure the char depth was either 5 mm or 10 mm as desired (+/- 1 mm due to author's interpretation of the initiation of the pyrolysis zone).

### 7.3.3 Mechanical Loading

At this stage, the char depths of the charred beams were measured and confirmed.

Mechanical loading occurred at a rate of 2.5 mm/min, in line with the loading rate used for ASTM D143 for four-point bending tests [128]. A load actuator applied two-point loads onto the simply supported beams. The total span of the beam was 800 mm.  The ends of the beams were aligned with the centre of the supporting rollers, with a small plate that could rotate freely in between the roller and the beam. This setup negated the need for the beam to overhang past the support (such that the beam length and span are both 800 mm).  The setup of the mechanical loading procedure can be seen in Figure 7.3 (where Glulam is depicted, and damaged regions would be on the front side and back side of the beams, with the top and bottom being undamaged).  All beams were loaded to failure. The damaged areas of the beams were oriented to be on the two sides of the beam, and not on the top and bottom.

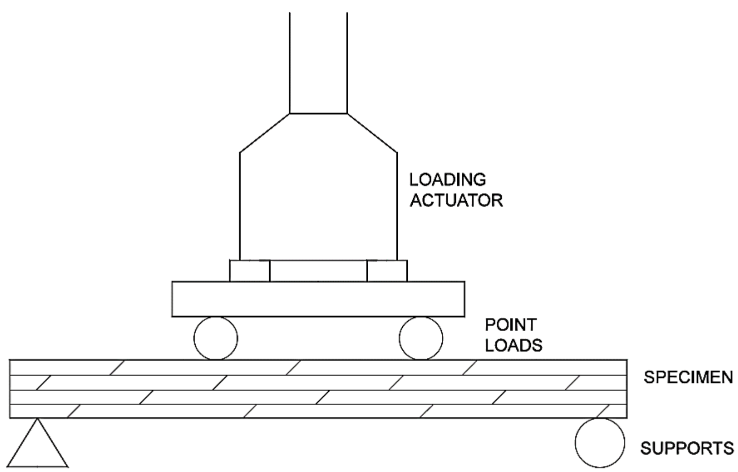


Figure 7.3 The four-point bending test setup.

### 7.3.4 Deformation Measurement

The deformation of the beams was measured using Digital Image Correlation (DIC), and specifically GeoPIV RG software [62]. This method was selected over using traditional strain gauges. This software has been proven to be accurate in the measurement of strain and displacement of wood with an error of 0.16 pixels [108].

GeoPIV RG software is able to observe specific patterns located on the beam and measure their displacement. These unique patterns are created by painting a speckled pattern on the beams. For these tests, black paint was used on the uncharred timber and white paint was used on the charred portion, to create a high contrast pattern for the software to track. High-resolution photographs were taken at five-second intervals using a Canon EOS-5Ds camera. For this test series, DIC was primarily used to measure deformation at the center of the beam.

**7.4 Results and Discussion**

All of the beams failed while they were tested in four-point bending. The average failure loads for each type of damage is seen in Table 7.2. The LVL has been divided into its two damage states (5 mm and 10 mm) for this analysis.  The failure loads of both sets of LVL beams and the Glulam can be seen in Figure 7.4. The vast majority of the beams experienced a tension failure within the moment region. The carving process did not reach a very substantial depth, and therefore no significant local stresses were created.

Displayed in Figure 7.4 is the calculated failure load of each beam, as per CSA O86. The beams with 10 mm char have a predicted failure load of approximately 0 kN. This is due to a significant reduction in predicted strength due to lateral stability as the effective width is very small. As the purpose of these tests is not to evaluate the accuracy of the current procedures for calculating char depth, the measured char depth has been used (either 5 mm or 10 mm) in the prediction of the charred beams' failure load. A calculated zero-strength layer has been added to the actual char depth, and the predicted capacity has been calculated based on the remaining cross-section. The zero-strength layer is taken as 7 mm for exposures of 20 minutes or greater in duration, and proportionally less for exposure times of less than 20 minutes [29]. The predicted strength of both the carved beams and the charred beams takes into account the reduction in cross-section, however only the predicted strength of the charred beams considers the effect of the zero-strength layer. Predicted strength was calculated based on the lesser of the moment and shear capacities as per CSA O86-14 [29], seen in Equations 7.1 and 7.3.

$$M_R = lesser\ of\ \Phi F_b S K_x K_L\ and\ \Phi F_b S K_x K_{zbg} \quad [7.1]$$

$$taking\ F_b = f_b(K_D K_H K_{sb} K_T) \quad [7.2]$$

where $M_R$ is the moment resistance, $\Phi$ is 0.9, S is the section modulus ($mm^3$), $K_x$ is the curvature factor, $K_L$ is the lateral stability factor, $K_{Zbg}$ is the size factor, $f_b$ is the specified strength in bending (MPa), $K_H$ is the system factor, $K_{sb}$ is the service condition factor for bending, $K_D$ is the load duration factor, and $K_T$ is the treatment factor.

$$V_R = \Phi F_v 2A_g/3 \quad [7.3]$$

$$taking\ F_v = f_v(K_D K_H K_{Sv} K_T) \quad [7.4]$$

where $V_R$ is the shear resistance, $A_g$ is the gross cross-sectional area ($mm^2$), $f_v$ is the specified shear strength (MPa), $K_{Sv}$ is the service condition factor for shear, and all other variables are as before.

In all cases, the beams performed significantly better than predicted. Properties used in the strength calculations are seen in Table 7.1.

For the most part, the LVL 5 mm damage state beams performed as expected. For both the beams damaged in the moment and shear regions, the carved beams carried more load than the charred damaged beams. When compared to the control beams, the charred moment beams had their capacity reduced an average of 40%, while the charred shear beams had their capacity reduced an average of 22%. This indicates that, for LVL, the moment capacity may be more sensitive to thermal degradation of the adhesives than the shear capacity. As the structure of LVL is composed of layers of thin vertical laminates (where the adhesive layers are oriented vertically, parallel to the application of the load), that individually have little moment capacity, it may be more important that the adhesives hold the laminates together to create a single composite unit, which has significant moment capacity. This may be less important for shear.

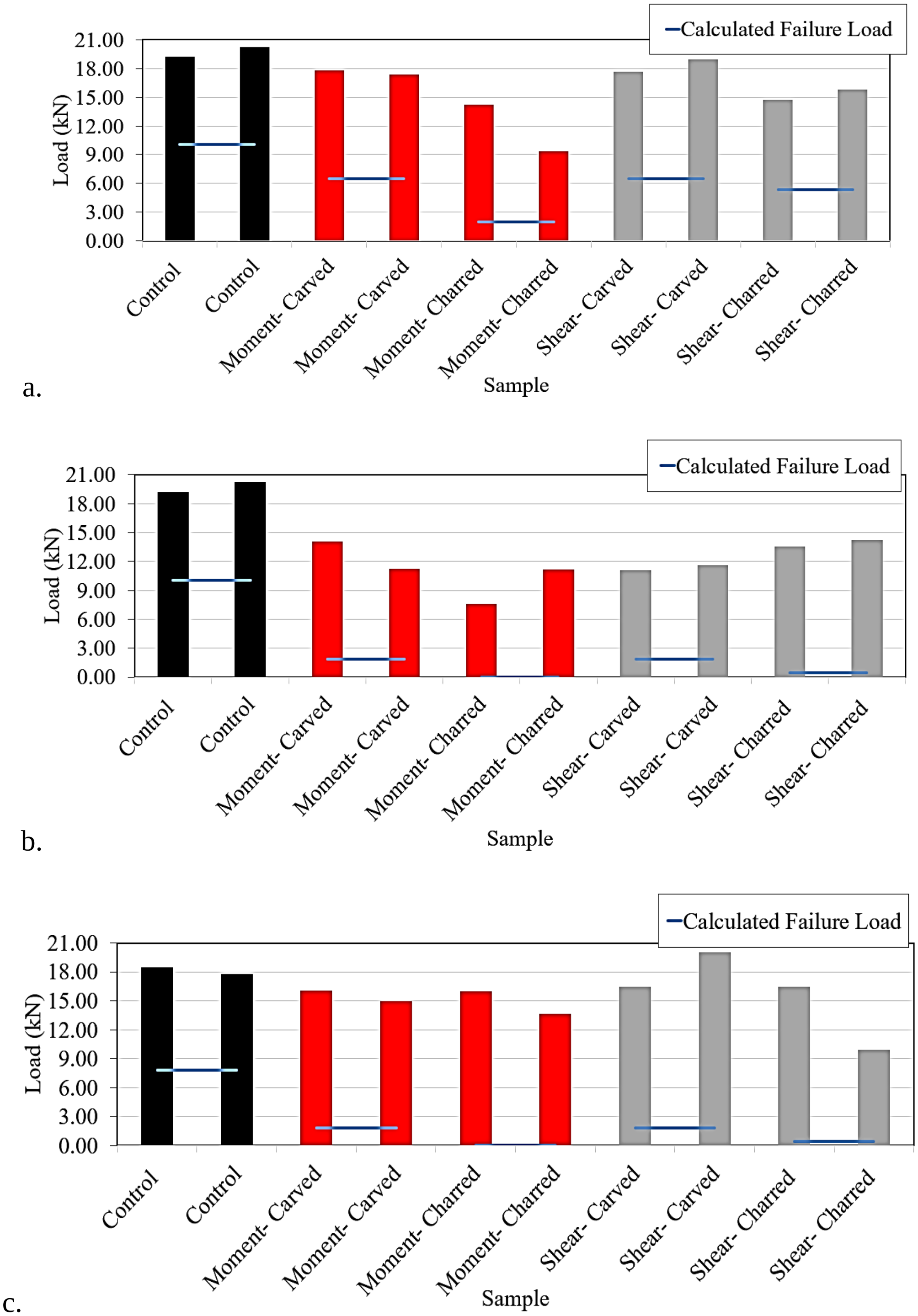



Figure 7.4 Failure loads for all beams, a. LVL at the 5 mm char depth, b. LVL at 10 mm char depth, and c. Glulam at 10 mm char depth.

The LVL beams carved in the shear region displayed differing results between the 5 mm and 10 mm damage states. For the 5 mm damage in the shear region, the carved beams failed at a higher load than the charred beams. The opposite is true for the 10 mm damage state. The reason the carved beams failed at a lower failure load than anticipated may be that the carving of the beams causes the full width of a number of the laminates to become exposed. As a result, the failure mode that is observed is that the laminates that have become detached fail earlier than the rest of the cross-section. This failure mode can be seen in Figure 7.5 (where the carved area seen on the left-hand side of beam, bound by the split in the wood, and the support). This is less of an issue for the less severely damaged beams, as fewer of the layers of laminates have become exposed during the carving process.

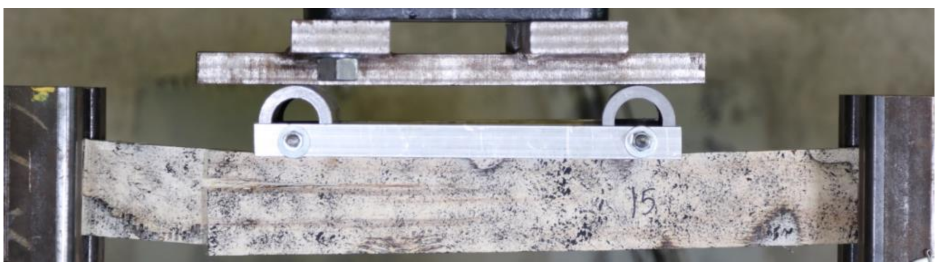
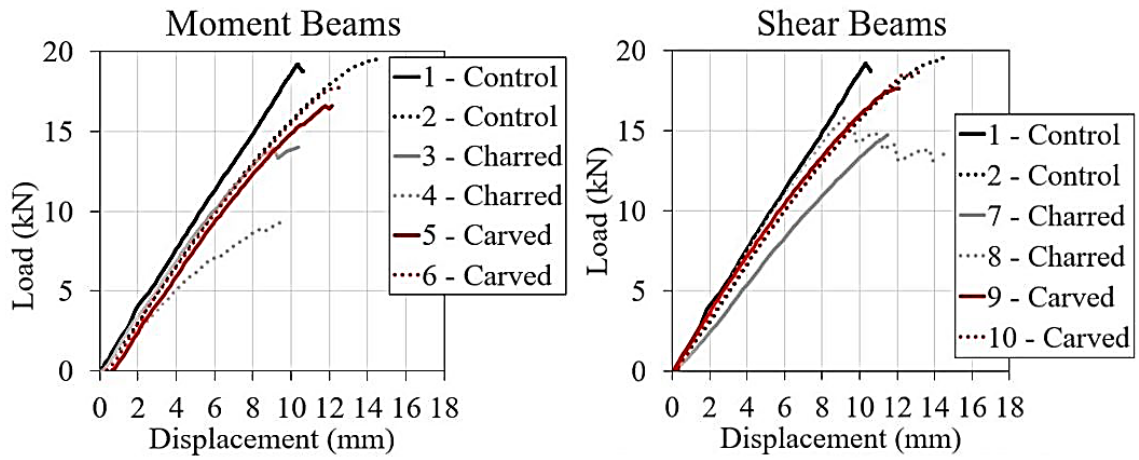



Figure 7.5 Failure of an LVL beam, carved to the 10 mm damage state.

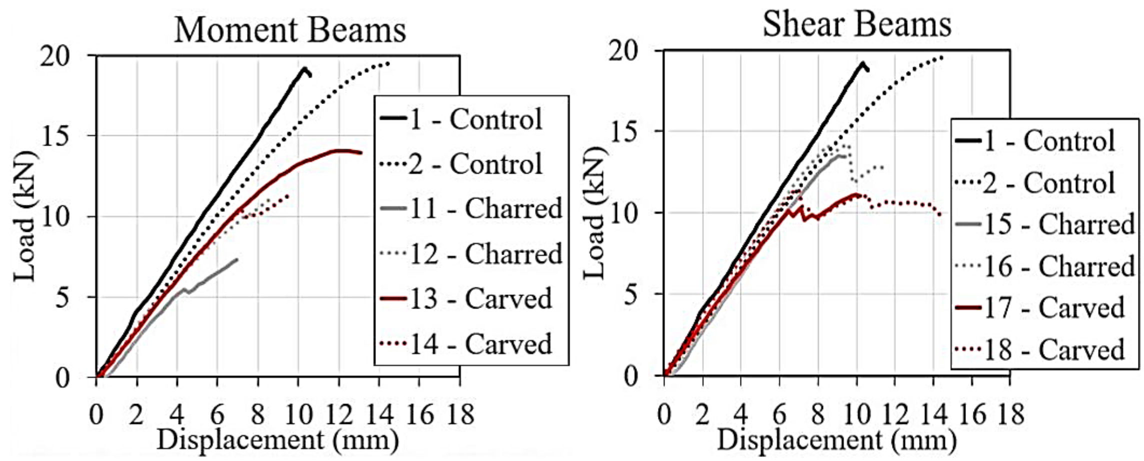
Similar to the LVL, the observed failure loads of Glulam were significantly higher than the calculated failure loads. The failure loads of the Glulam beams show that the charred moment beams did not have their capacity significantly reduced compared to the carved beam; on average, the failure load was only lowered by 0.71 kN (4.6%). The beams charred in the shear region were more impacted by the heating. The beams charred in the shear region experienced an average failure load of 5.09 kN lower than the carved beams (27.9%). The finding that the beams damaged in the shear region had their capacity reduced significantly more than the beams damaged in the moment region is consistent with previous studies [102]. Contrary to the LVL, the laminates within the Glulam are adhered together in horizontal layers (such that adhesive layers are perpendicular to the load). In a larger Glulam section, more laminates would be joined with vertical adhesive lines to increase the thickness, however in these sections the thickness consisted of only one laminate and therefore no vertical adhesive lines are present. This orientation is in line with the orientation of the original beam sections from which the samples were extracted and may explain some differences between the performance of the LVL and the Glulam.

DIC was used to plot the load versus displacement curves for all the beams. These graphs may be seen in Figure 7.6. One of the LVL shear beams charred to 5 mm in the shear region had its capacity drop suddenly a number of times (denoted by Sample #8 – Charred). This beam failed by gradually deflecting, and ultimately cracking in its damaged region. This was also the failure mode for the other charred beam, though they did not exhibit such a sudden failure. This discrepancy may be explained a possible material defect within the LVL, causing it to fail at a lower load than expected.

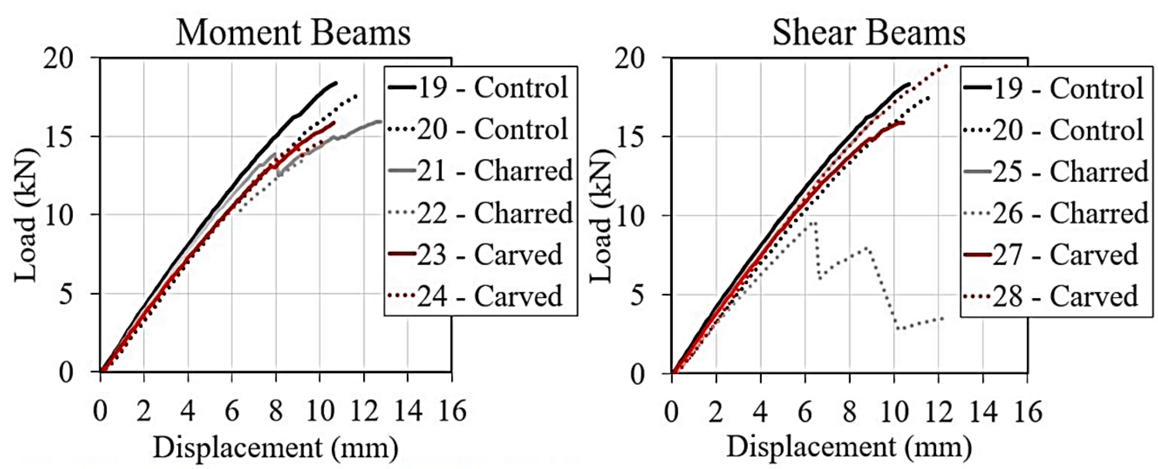
The slope of the load-displacement curves of the LVL beams carved to 10 mm in the shear region (Figure 7.6 b) begin similarly to the charred and controlled beams, but they eventually begin to plateau. This represents the point at which the outer laminates fail (the failure mode seen in Figure 7.5), though the remainder of the beam is still able to carry some load. Also notable is that the load versus displacement curves for the Glulam (Figure 7.6 c) show that one of the beams charred in the shear region (Sample #26 – Charred) experienced a number of drops in its carried load. The initial drop occurs upon initiation of a crack within the shear region. The following drops represent the growth of this crack, which ultimately led to its failure.




a.




b.




c.

Figure 7.6 Load versus displacement curves a. LVL at the 5 mm char depth, b. LVL at 10 mm char depth, and c. Glulam at 10 mm char depth.

These results show differences between the performance of the Glulam and LVL beams. The Glulam was more impacted by the heating in the shear region, while the LVL was more impacted in the moment region. This may due to the inherent properties of the timber and how it is fabricated. The moment capacity of Glulam may be less reliant on the adhesive strength and rather reliant on the strength of the wood itself, whereas the finger joints of the Glulam may be more vulnerable to shear. As mentioned earlier regarding the LVL, it may be more important for each layer of laminate to act together as a single unit to withstand moment, as individually each laminate has little moment resistance but together, they have significant resistance. For this reason, the performance of the adhesives may be more significant in the moment region than the shear region.

Other differences in the performance of the LVL and Glulam beams may also be attributed to their material differences, as the Glulam and LVL beams were made of differing timber species and have different material properties [129]. The adhesives used in each timber type were also different, with Glulam using a polyurethane based adhesive and LVL using a phenol formaldehyde based adhesive. The two adhesives will perform differently when heated, which may further contribute to any variation between the results of the Glulam and LVL.

### 7.4.1 Evaluation and Determination of the Zero-Strength Layer

The differences between the carved and charred beams, as observed and as predicted, may be seen in Table 7.3. In a number of cases, the observed difference in strength is larger than the calculated difference in strength. This is indicative that the allowance for the zero-strength layer may not be conservative in accounting for strength loss for all cases.

Table 7.3 The difference between the failure loads of the carved and charred beams, as observed and as calculated by CSA O86-14.

| Type | Damage Severity (mm) | Location | Observed Difference (kN) | Observed charred beam capacity/ carved beam capacity (%) | Calculated Difference (kN) | Calculated charred beam capacity/ carved beam capacity (%) |
|---|---|---|---|---|---|---|
| LVL | 5 | Moment Region | 5.84 | 66.82 | 4.49 | 30.60 |
| LVL | 10 | Moment Region | 3.30 | 73.98 | 1.90 | 0.00 |
| LVL | 5 | Shear Region | 3.05 | 83.37 | 1.11 | 82.84 |
| LVL | 10 | Shear Region | -2.52 | 122.21 | 1.90 | 24.74 |
| Glulam | 10 | Moment Region | 0.71 | 95.43 | 1.80 | 0.00 |
| Glulam | 10 | Shear Region | 5.09 | 72.09 | 1.36 | 24.44 |

The revised zero-strength layers were determined by calculating the beam width that would correspond to the observed difference in failure load between carved and charred beams, for each case in Table 7.3 where the observed difference exceeds the calculated difference. While standards such as CSA O86 and Eurocode 5 [29, 116] linearly reduce their suggested zero-strength layers for exposure times less than 20 minutes, this has not been done due to the short exposure times, and therefore the zero-strength layers discussed herein should be considered an absolute minimum value. The results suggest that a minimum zero-strength layer of 11.7 mm would be needed for the LVL, and 12.3 mm would be needed for the Glulam.

In comparison to other studies, the results for the Glulam beams are similar to the results observed in Chapter 6 (LVL was not studied in Chapter 6 so no comparison can be made to LVL). Similar trends were observed in that the capacity of the beams damaged in the moment region were not as severely impacted by fire exposure as the beams damaged in the shear region. The findings of Chapter 6 also showed that the calculated strength was lower than the actual strength in all cases, however, the difference in observed capacity between the carved and charred beams was not adequately accounted for by allowances for the zero-strength layer.

The zero-strength layer found in Chapter 6 of 17.2 mm is slightly higher than the value found for Glulam in this Chapter 7 study (12.3 mm). These beams tested in Chapter 6 were significantly larger than the beams tested within this chapter and were therefore more likely to contain a defect that is not visible. These defects could significantly reduce the strength of these beams, therefore implying a larger zero-strength layer. Moreover, these larger beams failed frequently along the finger joints, and the larger beams had a higher quantity of these joints than their smaller counterparts. In Chapter 7, the finger joints did not appear to influence the failure of any of the beams. Finally, the larger beams were loaded using an apparatus that restrained the beams laterally at the supports, but only restrained the beams laterally at quarter span until halfway down the depth of the beam. This may have allowed for some degree of lateral-torsional buckling to occur that was not present with the smaller sample size as seen within Chapter 6, causing an earlier failure.

Quiquero (2018) suggested the use of a zero-strength layer of 23 mm, compared to 12.3 mm found for Glulam in this study [102]. Factors that may account for this discrepancy are that the tests performed by Quiquero (2018) utilized 100 x 100 mm samples, tested using an apparatus meant to shear the specimen along the adhesive line. This mode of loading intentionally created failure at the adhesive line, presumed to be the weakest part of the specimen. This loading setup was significantly different from the four-point bending test setup used in this test series where combined forces will act on adhesive lines.

Additional tests by other researchers which offer a revised value for the zero-strength layer include the study by Schmid et al. (2015), which considered Glulam members in tension, compression, and bending [12]. In terms of the members in bending, Schmid et al. (2015) found the zero-strength layer to range from 9.5 mm to 20.1 mm. Lange et al. (2015) found the zero-strength layer to range from 8 mm to 16 mm dependent on the type of heat exposure [11]. The zero-strength layer proposed by this study for Glulam of 12.3 mm has relatively good agreement with the range of values proposed by both Schmid et al. (2015) and Lange et al. (2015).

CLT is a comparable timber product for which researchers have also proposed revised zero-strength layers. Wiesner et al. found the zero-strength layer of CLT walls to be between 15.2 mm and 21.8 mm [130]. This is slightly higher than the zero-strength layers previously found in this paper, however this could be due to the type of timber product considered. This may be the case due to differences in additives that may be unique to each product, or that the configuration of timber laminates and adhesives may also play a role. The large size of the CLT walls tested by Wiesner et al. (2017) will, as previously mentioned, also introduce increased potential for material defects or more complex failure mechanisms than the small beams considered in this paper.

The LVL examined in this test series is, to the authors' knowledge, the first study to investigate adhesive degradation in LVL through controlled tests, so there are presently no previous studies to compare suggested zero-strength layers. It is apparent, however, that adhesive degradation is present in LVL. Although the factors outlined in the above paragraph assist in understanding the variation in different author’s proposed zero-strength layers, all the studies discussed concur that the 7 mm currently used as the thickness of the zero-strength layer does not adequately account for degradation effects in all cases.

### 7.5 Limitations and Future Research

The tests described above provided significant insight as to the adhesive performance of Glulam and LVL beams post-fire. These tests have helped to identify a number of future research topics that would aid to further understand the extent of the adhesive degradation.

The small size of the beams and the relatively short exposure times considered within this chapter is one constraint that could be addressed in future research. For beams exposed to fire than less than 20 minutes, standard procedures suggest reducing the zero-strength linearly according to time exposed [29, 116], however this has not been done in the calculation of the zero-strength layer due to the short heating times, and therefore the zero-strength layers suggested by this paper are an absolute minimum value. It would therefore be beneficial to perform tests with longer heat exposures. Tests with larger cross-sections may be affected less by this consideration. It would be beneficial if the larger scale tests utilized members that were of a cross-sectional area representative of what would typically be used in construction (realistic scale), which would negate lateral-torsional buckling effects that may occur.

Moreover, the adhesives used for the LVL and Glulam samples featured in the test series were phenol formaldehyde and polyurethane-based, respectively. These adhesives vary between manufacturers and are constantly evolving in material design, so it would be beneficial to understand the post-fire performance of a wide number of specific adhesives. As new adhesives are developed, additional testing will be required to understand how these perform post-fire.

The upper end of the heat flux emitted by the radiant heater in these tests was around 50 $kW/m^2$. Other fire exposures, including to standard time temperature curves such as CAN/ULC S101 [7] or ISO 834 [19], will expose the timber to different heat fluxes which may result in a different size of pyrolysis zone. The required zero-strength layer may therefore vary according to heat flux. The damage applied to the beams in this test series varied from what is likely to be observed in a real fire in that the bottom of the beams were not damaged. As the beam height is an important factor in determining residual strength, and if the bottom of the beam were exposed to fire the strength may have been more greatly reduced, this difference between these tests and a real fire must be considered.

It is important to note that the zero-strength layer will be dependent on the particular geometry of members, the specific material properties, and fire duration and severity (to name just a few factors which can affect overall fire performance). More research is needed in the development of a method in determining zero-strength layers in these different scenarios. The research study described in this paper reinforces the notion that a 7 mm zero-strength layer is not always conservative and highlights the need for future research. While this study has begun to address some of the research needs identified previously, future research described in the above paragraphs would further help to fulfil the objectives outlined by Yang et al. [57], such as gaining acceptance of design guides. It would also help to address knowledge gaps as identified by the ASCE Fire Protection Committee [123] such as defining a depth of material affected by the degradation of adhesives at elevated temperatures. Additional future research topics could address the degradation of adhesives at high temperatures from a material chemistry perspective. This would be beneficial in understanding the deterioration mechanisms of the adhesives, especially as new adhesives continue to be developed.

## 7.6 Conclusion

A comprehensive understanding of the Glulam and LVL's post-fire performance is critical to provide a safer approach in designing tall timber buildings. Understanding their post-fire performance will also be beneficial in enabling the ability to leave engineered timber exposed without encapsulation, fulfilling architectural desires. For these objectives to be implemented there is a need to evaluate the current procedures for determining the losses due to adhesive degradation.

The results demonstrated that loss in strength beyond the char layer occurs when the beams are exposed to fire, as observed by comparing the carved and charred beams. The LVL experienced a larger loss in strength for the beams damaged in the moment region, failing on average at 70% of the capacity the mechanically carved beams. The Glulam beams observed a different trend, with the beams damaged in the shear region experiencing a larger reduction in strength, failing on average at 72% of the capacity of the mechanically carved beams. This difference in the performance of the two timber types may be due to the inherent differences in their macro-structures (including differences in the configurations in which Glulam and LVL are assembled).

The existing zero-strength layer guidance of 7 mm for exposures of 20 minutes and greater was found to not conservatively account for losses due to adhesive degradation. For the LVL tested in this series, a minimum zero-strength layer of 11.7 mm may be required to be able to adequately account for losses due to adhesive degradation. For the Glulam beams tested in this series, a minimum zero-strength layer of 12.3 mm would be required to adequately account for losses due to adhesive degradation. These values for the zero-strength layer may not be conservative for larger-scale beams and in many other cases where the heat exposure, member geometry, material properties, etc. may vary. Further testing is required to determine a more appropriate value in these cases. Nevertheless, these results make it clear that for both LVL as well as Glulam, a 7 mm zero strength layer is not always conservative. These findings reinforce the need to better understand the severity of degradation beyond the char layer in a variety of commonly used engineered timber types through additional full-scale tests and further research into adhesive development, in order to enable the construction of tall and unencapsulated timber structures.

# Chapter 8 : Timber Fire Dynamics and Modelling

## 8.1 Introduction and Motivation

The previous chapters of this thesis have looked at the performance of historic timber systems, and timber systems that are currently being used worldwide. It is clear from trends of recently constructed or planned timber structures that two desires for timber construction are the presence of exposed (unencapsulated) timber, and the desire to have large, open spaces. These architectural desires present unique challenges for fire safety, as open plan compartments of other materials have been found to have non simultaneous ignition across the floor plate in disagreement with traditional notions of fire dynamics, and these fire dynamics will be further complicated with the presence of timber as an additional fuel source and fire spread medium. Given our current understanding of the thermomechanical performance of timber and other non-combustible materials, combined with architectural and client desires to build timber buildings in open-plan well ventilated configurations, the question is raised of how timber structures will be designed going forward.

Current methods of analysis for assessing timber fire performance in Canada are largely prescriptive based, as described in Chapter 2. These methods typically rely on a reduced cross section method, where a calculated damaged depth is considered to be compromised but the remainder of the cross section is considered to retain full strength. Additionally, encapsulations such as fire rated Type X gypsum board are used to meet fire requirements [29]. With the continual demand for taller timber structures, there is a need to better understand the performance of the timber beyond prescriptive assessments. Timber buildings in Canada have been proposed as upwards of 37 storeys [131], making fire management and firefighting strategies more challenging at these heights. It has been argued by some that contemporary tall structures are beyond the applicability of current fire safety codes [132].

Several approaches are taken by practitioners in evaluating the fire performance tall timber structures. In Canada, many of these methods rely on alternative solutions to achieve approvals which can allow for designs not directly accepted within the building code (acceptable solutions). These can include risk-based approaches. As outlined in *Ontario's Tall Wood Building Reference* [133], risk analysis can take the place of qualitative methods (which do not entail calculations, and can be used where the difference between the alternative and acceptable solution may not alter the risk). Semi-qualitative methods can also be used, where either the consequence of unwanted events or the frequency of unwanted events is quantified (but not both). Quantitative methods are also used, which often consist of computational tools and can consider both the consequence of unwanted events, as well as the frequency. If the risk can be demonstrated to be no greater than the acceptable solution, then the alternative solution may be considered to have met the required performance level [134].

Fire safety strategies that are used in tall wood building design include encapsulation using fire rated Type X gypsum board (as discussed above and in Chapter 4), where Canadian structures have also included sprinkler system with a backup water supply to meet site-specific regulations and to suppress the fire before it poses a threat to the structure [135]. Some Canadian designs of timber structures have been criticized in the past for their reliance on encapsulation, where concern has been expressed over the performance of the encapsulation, where if the encapsulation were to fail, the fire protection strategy would fail to eliminate feedback between the fire and the structure [136]. Other strategies used include exit stair pressurization and sprinkler reliability [133]. Exit stair pressurization plays a role in allowing the evacuation of a multi-story building in the event of the fire, by attempting to keep the exit stairs free from smoke [133]. Automatic sprinkler systems are also considered, where anything that can be done to increase the reliability of the sprinkler system will be beneficial to reducing risk (which in some cases includes redundancy in the system). Upper estimates of the effectiveness of sprinkler systems are around 95% (i.e., there is a 95% probability that the sprinkler will activate when intended, and if it does operate, it will affect the development of the fire) [137].

Furthermore, additional Canadian designers have described their approaches as containing a fire in its room of origin, ensuring it will decay even if not suppressed, and allowing for safe egress, firefighting access, and retention of structural stability. The design for auto-extinction considers burning elements of a timber room radiating energy to neighbouring sources, even after the initial heat source is removed, and therefore certain configurations of exposed timber are preferred and the expected heat flux onto a surface from the burning timber must be considered (i.e. an energy balance will be solved for the compartment to indicate auto-extinction of the timber) [138]. Reliance on auto-extinction is challenged by char fall off, or delamination of timber layers.

Similar approaches have been taken internationally, where designers have described having objectives of either allowing for adequate egress time (where members of assemblies meet required fire resistance performance), or having adequate likelihood of surviving cooling and extinction (where the structure is prevented from contributing as a fuel source though encapsulation, or auto-extinction is demonstrated) [139]. Where timber is exposed or partially protected, the structure is assumed to contribute to the fire, and it must be demonstrated that the structure will survive cooling and extinction. Failure consequences are also considered, where failure consequence can inform the compliance route (guidance-based or performance based) [139]. Other international designers have characterized their approaches as first calculating the expected fire without considering combustible linings, and then re-calculating to account for the fuel from the timber. Computational fire dynamics can then be used to assess the fire, with finite element modelling used to assess char, which would be validated against available experimental test results [140]. Challenges have been described as considering travelling fires (non-uniform fires), incorporating delamination and char fall off, and ensuring extinguishment [140].

Other approaches are almost certainly taking place in Canada and internationally, though many designers have not made their design processes publicly available.

Some level of risk remains in tall structures of any materials, including challenges that may by faced by fire service intervention. These include physical limits of the fire service, in which long travel distances within a building can make the firefighting conditions more difficult, with the physiological effects upon the fire fighters needing to be considered [141]. This, in addition to other risk factors such as the notion that that the sprinkler is not always effective at controlling the fire's development, are limitations to present fire protection strategies. These limitations are important to consider in all structures and are complicated by the combustible nature of wood in timber structures. These risks emphasize the importance of having an accurate understanding as to the fire performance of structural timber.

The challenges in ensuring fire safety within increasingly tall timber structures contribute towards the need to develop alternative methods of creating fire safe designs, which can include finite element modelling when done correctly and sufficient information is available.

Finite element modelling can help to illustrate the anticipated fire performance of timber, which may be more aligned with anticipated fire dynamics than prescriptive methods that can rely on charring rates derived from standard temperature-time heating curve exposures. From having a more precise understanding of the structural and fire performance of the timber structure, it becomes possible to understand what is needed to meet performance objectives for ensuring life safety. It also becomes possible to illustrate the anticipated level of resilience that the building will have in the event of a fire, such that the time and resources needed for a structure to recover from a fire are better understood. The importance of understanding the fire risk of building a tall timber structure, including understanding requirements that must be met to ensure life safety and the required level of operation resilience, highlight the importance of finite element modelling in these applications. It should be noted that finite element modelling is not without limitations which include limited data availability and research/knowledge gaps, which will be discussed throughout the chapter. In developing these knowledge gaps, finite element modelling can help to progress design tools for practitioners addressing the realization of tall timber structures. The need for further data to be collected experimentally to address current knowledge gaps in developing design tools enabling safer, tall timber structures is the motivation behind this thesis chapter. The purpose of this thesis chapter is to identify data sets that need to be collected experimentally in order to refine and calibrate an a priori model of a Cross Laminated Timber (CLT) ceiling. This endeavor will be complimented by examining case studies of fires of timber structures, to emphasize the unique fire dynamics of open plan, well ventilated timber structures.

## 8.2 Background

Traditionally, fire dynamics of a compartment have been characterized as going through a growth phase, in which the fire is established and begins to spread. This leads into a fully developed fire, where the highest temperatures of the fire are reached, before moving into a decay phase where the temperature and energy release rates decrease [142]. Flashover is sometimes seen in compartment fires, marking the transition between the growth phase and the fully developed phase, considered to have taken place when all temperatures within the compartment are 600 °C or greater, or that the radiation to the floor of the compartment reaches 15-20 kW/$m^2$ [142]. However, the concept of flashover remains debated, particularly in large compartment sizes where it is not well understood. There have been fires in large compartments or open plan steel and concrete structures, that have been observed to not fully involve the compartment simultaneously, but rather there is spatial non-uniformities. In some instances, fires have been observed to travel across floor plates and/or across stories [143], going against the tradition notions of uniform burning and temperatures within a compartment. These fires can be of prolonged duration, and using uniform gas temperatures could have led to significant errors in thermal and structural analysis [143].

Materials such as steel and concrete have had simplified methods developed to assess non-uniform fires in large open-plan spaces [143–145] providing estimates of temperatures or heat fluxes at the ceiling of a compartment. Experimental and computational research has shown that peak temperatures in materials can be higher in localized fires than in post-flashover fires [146], and that localized fires can create non-uniform temperature distribution inducing simultaneous heating and cooling [147].

Combustible materials such as timber have not yet seen the same study for fires in open plan, well ventilated spaces that could support non-uniform fires, though these spaces are becoming architecturally and aesthetically desirable. Several of the challenges of designing open-plan buildings with exposed mass timber elements are outlined in Rackauskaite et al. (2020) and are related to the lack of available data regarding travelling fire size, fuel load, heat release rate, near field heat flux, and far field thermal exposure (all impacted by timbers combustibility) [148]. In this context, the near field represents flames directly impinging on the ceiling from an external fuel source, whereas the far field represents cooler temperatures away from this direct impingement.

Other aspects unique to timber include the effect of delamination. Experimentally, delamination has been observed as contributing to a second flashover [4, 97], where the fall off of timber laminates along with a freshly exposed timber surface provides an additional fuel source to the fire. To the author's awareness in terms of modelling, many models completed to date assumes that timber will not delaminate [149], as adhesives meant to limit delamination are being developed [150].

Smouldering combustion, a slow and low temperature form of flameless combustion [151], involves surface oxidation of the char layer, providing sufficient heat for thermal degradation. As volatiles are continually driven from the active combustion zone, fresh char begins to burn [23]. Smouldering effects contribute to the uncertainty regarding the auto-extinction of timber. Different researchers have considered auto-extinction to consist of either flaming extinction [152, 153], or termination of any type of combustion process including smouldering [113]. In the case where smouldering is still present, the timber will continue to degrade, and the smouldering will still need to be extinguished (e.g., through suppression by the fire brigade). In modelling, it has been shown that consideration or non-consideration of smouldering can alter the peak temperature of the model [103].

Thermal and structural modelling is a technique that has been used to assess material performance and can range in complexity from simplified analytical models to fully developed finite element models. Existing research on thermal modelling of timber has included work by Werther et al. (2012) [154] that examined obstacles in modelling timber structures with ANSYS, SAFIR, and ABAQUS software. Challenges were identified as accounting for a discontinuity in specific heat capacity of timber as described in the Eurocode 5 [32] to account for latent heat of vaporization of water, which was addressed by the removal of this discontinuity and the addition of a latent heat [154]. Further recommendations by Werther et al. (2012) included checking the mesh size for suitability for the analysis, optimizing time-steps during different intervals of the analysis to optimize computational time, and that special attention should be given to the mesh size at the location of impinging 2D heat flows.

Quiquero et al. (2019) [118] created a thermal and structural finite element model of post-tensioned timber beams at ambient and fire conditions. ABAQUS was used to create a post-tensioned timber model, compared against previous experimental studies, and it was found that the thermal gradients reported by the model aligned with the recorded thermocouple readings and char depths of the experimental studies. Challenges (as related to thermal modelling) were identified as adequately capturing the effects of moisture evaporation, for which a latent heat method was used. Mesh refinement was also determined through a sensitivity study.

Thi et al. (2017) [155] modelled heat transfer (pyrolysis and charring) through timber elements in ABAQUS using a user-defined subroutine. Model inputs were adapted from the Eurocode 5 as well as from alternative sources where deemed more suitable. The temperature gradient of the models was assessed at varying times during the fire exposure, and the location of the char layer, pyrolysed wood, dried wood, and ambient wood were all identified. Geometric configurations included a large scale Cross Laminated Timber (CLT) beam, and in general Thi et al. (2017) deemed their temperature distributions to have good agreement with experimental studies available in literature.

Richter and Rein (2020) [156] have also explored thermal modelling of timber elements. A chemical kinetic model was developed at the micro- and meso-scales meant to capture the pyrolysis, fuel oxidation, and char oxidation reactions. Richter and Rein (2020) felt that discrepancies between their model results with experimental values was attributed to uncertainty in material properties. Richter et al. (2020) went on to examine the thermal response of timber slabs exposed to travelling fires as well as parametric and standard temperature-time heating curves, and found that the charring rates and zero-strength layers varied based on the thermal exposure [149].

Gernay (2021) modelled the fire resistance (including cooling and extinction) of timber columns using SAFIR, considering 'natural' fires which included a cooling phase [21]. Gernay (2021) found that timber columns were susceptible to failure during the cooling phase as a result of delayed heating and loss of mechanical properties.

Each of the previously mentioned research studies helps to better understand the capabilities of modelling timber, and to better understand the strengths and vulnerabilities of timber under various thermal and/or structural exposures. Given the demand for structural timber to be used in open plan, well ventilated spaces, there is a need for further data to be collected experimentally in order to develop a better understanding of the expected fire dynamics of these configurations.

### 8.3 Modelling Methodology

The purpose of the model considered herein is to identify datasets that should be collected experimentally that will allow for model calibration. The intent is not to assess the fire performance or anticipated fire dynamics, nor is it to create a precisely calibrated model, but rather to understand which data sets are needed for calibration and recommend instrumentation of future experimental studies. Future research (not included within the scope of this thesis) could then perform the appropriate experiments and create a calibrated model that could be developed into a simplified analytical methodology for understanding the fire performance of open plan, well ventilated timber structures.

LS DYNA was selected as a software for this modelling endeavor. This software was chosen for its capabilities in modelling both thermal and structural aspects (if the model were to be further developed to consider structural performance). Furthermore, this software is being widely used by industry practitioners[5]. LS DYNA is a general purpose nonlinear finite element program, which can accommodate modelling complications such as changing boundary conditions, large deformations, nonlinear materials, and transient dynamic events [157]. LS DYNA allows for user defined thermal materials, and the solution methodology is based on explicit time integration. The LS DYNA solver is provided a keywork input file [158]. The mathematical theory of the heat transfer equations used in the solver are based on the notion that the change in internal energy is equal to change in conduction in and out of the system, plus any additional heat sources or sinks [159].

The model was created using LS DYNA as the solver, though Solidworks was used to create the geometry, Altair Hypermesh was used to mesh the model, and Oasys Primer and D3Plot were used for pre and post processing, respectively. The preprocessing step involves defining the boundary conditions, initial conditions, material properties, solution control and output parameters. The postprocessing step involves plotting the results of the parameters with respect to time.

Herein, a CLT ceiling will be considered. The associated material parameters are intended to represent the scenario that could be seen in future experimental endeavors. The moisture content

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[5] LS DYNA is also more economically accessible, at a fraction of the cost of similar software such as Abaqus and Ansys.

of the timber was taken as 8%, which was found to be an equilibrium moisture content for a laboratory, representative of where the CLT could be stored. The emissivity of the wood was taken as 0.8 and the convective film coefficient was taken as 25 $W/m^2K$ [32]. The thermal conductivity was taken from the Eurocode 5 Annex B [32] and is summarized in Table 8.1. The timber was modelled using LS DYNA thermal material type 10; characterized as being thermally isotropic, with properties that are temperature dependant and that can be defined by load curves. These features are the reason that this material type was selected; as it readily allows for properties such as specific heat capacity and thermal conductivity to be defined as a function of temperature.

Table 8.1 Material properties used according to Eurocode 5 Part 1-2 Annex B

| Temperature (K) | Conductivity (W/mK) | Specific Heat (J/kgK) |
|---|---|---|
| 293 | 0.12 | 1.53 |
| 372 | - | 1.77 |
| 372 | - | 13.60[a] |
| 393 | - | 13.50[a] |
| 393 | - | 2.12 |
| 473 | 0.15 | 2.00 |
| 523 | - | 1.62 |
| 573 | - | 0.71 |
| 623 | 0.07 | 0.85 |
| 673 | - | 1.00 |
| 773 | 0.09 | - |
| 873 | - | 1.40 |
| 1073 | 0.35 | 1.65 |
| 1473 | 1.5 | 1.65 |

[a] Data points omitted due to latent heat method

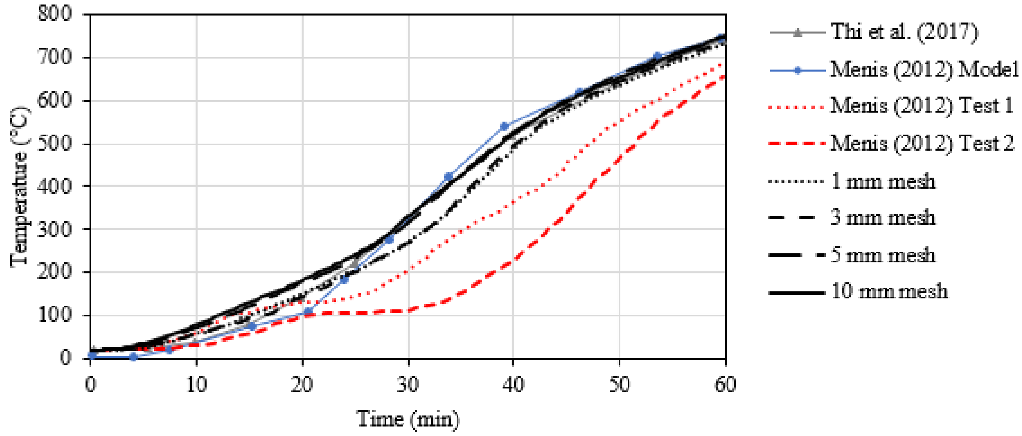
The specific heat capacity was also determined from the Eurocode 5 Annex B, however the discontinuity between 99 °C and 120 °C (372 and 393 K) was omitted. This was done in accordance with the latent heat method as described by Werther et al. (2012) [154] to avoid the discontinuity caused by moisture vaporisation. Instead, this phenomenon is accounted for by considering a latent energy corresponding to the moisture content of the wood. The heat of evaporation of water was taken as 2260 kJ/kg [160]. The latent energy was therefore calculated as:

$$\Delta H_{vap,\ wood} = \Delta H_{vap,\ water} * \%MC \qquad [8.1]$$
$$= 2260\ kJ/kg_{\ water} * 0.08$$
$$= 180\ kJ/kg_{\ wood}$$

A sensitivity study was completed to determine the most appropriate mesh size. Previous studies of modelling full scale timber structures have considered mesh sizes of 3 mm – 9 mm [118, 154], and thus mesh sizes of 3 mm, 5 mm and 10 mm were examined, with sizes chosen to be within the scale of previous timber models and to align with dimensions used. A mesh size of 1 mm was also considered, to aid in evaluating convergence of the larger meshes. The dimensioning used for this mesh sensitivity analysis is based on the heat transfer model outlined by Thi et al. (2017) [155] and the tests performed by Menis (2012) [161], consisting of a 150 mm thick CLT panel, with a moisture content of 12% and a density of 460 kg/m$^3$, subjected to ISO 834 [19] thermal exposure. The tests performed by Menis (2012) were chosen for examination in this context due to the similarity of the test series with the purpose of the model (i.e., it considers CLT exposed to fire from below). Further, this test series was selected as it clearly reports temperatures throughout the test duration at multiple depths within the timber slab.

Figure 8.1 shows the results of the mesh analysis, compared to the modelling results of both Thi et al. (2017) and Menis (2012), as well as the data from two experimental tests performed by Menis (2012).

a)




b)

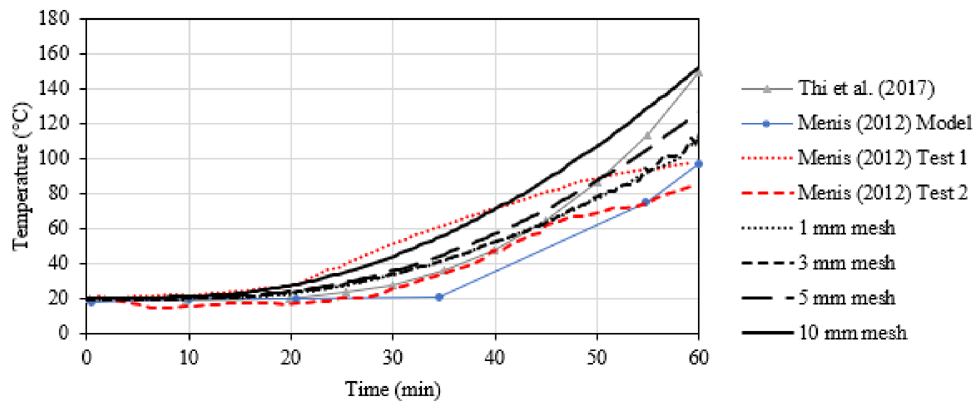



Figure 8.1 Comparison between predicted temperatures of different mesh sizes, with measured temperatures and previous studies by other authors at a) a depth of 21 mm and b) a depth of 52 mm.

Following the mesh sensitivity analysis, it was determined that a mesh size of 3 mm would be adequate for this modelling endeavour of identifying data sets needed for model calibration. The results from the 3 mm mesh were nearly identical to the 1 mm mesh, though the computational time was only 4% of that of the 1 mm mesh. The final temperature difference at 60 minutes between the 3 mm and 1 mm meshes was 1% at a depth of 21 mm, and 2% at 52 mm. Thus, the increased computational time did not seem justified given the very small result discrepancies. The

5 mm and 10 mm meshes had even faster computational times but did not readily converge with the 1 mm and 3 mm meshes.

Fire exposure was applied to the soffit of the CLT model. As a baseline, the thermal boundary condition of the area of CLT directly above the localized fire was characterized as radiation and convective contributions from the pool fire described in Chapter 4 and seen in Figure 4.7. This boundary condition does not account for the contribution of the timber, and therefore experimental results could expect to see different temperatures or heat fluxes.

To verify that the model was working as intended, two previous experimental tests were modelled. The first considers the long Glulam beams considered in Chapter 6 (45 mm x 195 mm). Five beams were exposed to a kerosene pool fire for 10 minutes on each of the longer sides of the beams (i.e., one of the 195 mm sides was exposed to the pool fire, and the member was then flipped and the opposite side was exposed to the pool fire). The char depth was found to be 5 mm +/- 1 mm. The full details of these tests are described in Chapter 6. Further, two heritage timber members as described in Appendix C were also modelled. The heritage members had an average density of 657 kg/m$^3$ and a moisture content of 10%. These members were exposed to a 30-minute methanol pool fire, and were found to have maximum char depths on the soffit of 25 mm and 21 mm for the first and second trials. For the model verification, the heat flux was calculated from the fuel, based on the burning rate, and the heat of combustion of the fuel [23]. The mass burning rate was taken as 0.039 kg/m$^2$s for kerosene and 0.017 kg/m$^2$s for methanol, while the heat of combustion was taken as 43,200 kJ/kg for kerosene and 20,000 kJ/kg for methanol [162]. The empirical constant further used for heat release rate calculations of the fuel representing the product of the extinction absorption coefficient and the beam-length corrector was taken as 3.5 $m^{-1}$ for kerosene[6] [163]. Due to the proximity of the fuel to the members, the incident heat flux on the members was taken as the heat release rate of the fuel. The incident heat flux on the soffit of the members was therefore taken as 52.6 $kW/m^2$ for the Glulam members (kerosene pool fire), and 24.2 $kW/m^2$ for the heritage members (methanol pool fire). In this context verification indicates testing that the model meets the requirements at this stage of development, whereas validation would ensure a final model meets the needs and expectations of the model.

Current methodologies for non-combustible compartments consider several parameters for the design of non-uniform fires. These include flame length (as a function of ceiling height and heat release rate), incident heat flux on the ceiling relative to the location of localized fire flames, fire spread rate, time for fuel to auto-extinguish, and ambient room temperature, among other parameters [144]. As previously mentioned, adapting existing methods for timber structures becomes challenging due to the contribution of the timber to the fire, as well as the lack of existing data regarding the thermal performance of CLT ceilings. There is limited experimental evidence available regarding the fire spread and extinction rates of CLT ceilings, as well as expected heat fluxes or temperatures in the near and far field regions.

The need for experimental evidence in these areas has contributed towards the motivation of this study. In terms of available information regarding fire spread and extinction rates, there has been some investigation regarding non-combustible structures, as well as flame spread/extinction along the top of wood cribs. Gupta et al. (2021) looked at the flame spread characteristics of wood cribs, considering the experimental setup and results of the Malveira Fire Test, from which the

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[6] Heat release rate calculations of fuel were taken as $\dot{q}=\Delta h_c*\dot{m}_\infty*(1-e^{-k\beta D})$, where $\Delta h_c$ is the heat of combustion, $\dot{m}_\infty$ is the mass burning rate, kβ is the empirical constant, and D is the diameter of the pool fire [163].

location and velocity of the flame front was determined [164, 165]. The x-ONE and x-TWO experiments also considered full scale experimental tests of large scale, open plan non combustible structures, in which it was found that the fire was observed to travel with clear leading and trailing edges [166].

For this model, the parameters of incident heat flux, flame spread rate, and extinction rate will be examined for their effect of the fire performance of a strip of the CLT ceiling. These findings will help to inform the design of future experiments. From a review of the literature, it was found that each of these parameters is lacking detail as to what might be expected when considering CLT ceilings. There is a need to understand likely heat fluxes and flame temperatures of CLT ceilings in the near- field region. For this, a localized fire underneath the ceiling will be considered, with two incident heat fluxes. These heat fluxes will be taken as 23.9 $kW/m^2$ [167] and 77.5 $kW/m^2$ [168], meant to represent the high and low end of heat fluxes provided by timber flames as observed in literature. These heat fluxes are derived from studies by Tewarson and Pion (1976) [167] and by Petrella (1979) [168] in which both sets of researchers studied the ideal burning rate in which small samples of various combustible materials (including several timber species) were exposed to radiant heat. The heat flux provided by the materials' flames was then calculated. It should be noted that the heat fluxes considered are meant to represent a range of values more than accurate values that would be expected, as expected heat fluxes and flame temperatures specific to the soffit of CLT ceilings have yet to be experimentally collected. It should also be noted that these heat fluxes consider only contributions from the timber ceiling and not from external fuel sources. From this analysis, parameters needed for calibration will be explored.

Dimensions of the ceiling strip were selected as 0.5 m x 0.1 m x 2.4 m, chosen as large enough to observe heat transfer through the depth of the ceiling and along the length, but not so large as to cause unnecessary computational expense. The thickness of 0.1 m is aligned with available CLT thicknesses, and the length of 2.4 m is a scaled down version of what could potentially be considered in experimental tests.

In terms of relevant information to use as a starting point for horizontal flame spread and extinction rates of CLT ceilings, to the author's awareness, there is no readily available data. Data in general regarding fire spread rate in realistic fires is limited, though some data has been reviewed by Rackauskaite et al. (2015) [143] and by Grimwood (2018) [169]. Collected fire spread rates include the reconstruction of the World Trade Centre Fired, tests on natural fires in large scale (non-combustible) compartments, the St. Lawrence burn tests from 1958, and the First Interstate Bank fire from 1988. Of these, fire spread rates ranged from 1.5 mm/s to 19.3 mm/s [143], however, most of the experiments examined considered non-combustible structures. Both the maximum and minimum flame spread rates are derived from tests by Kirby et al. (1999) which considered nine compartment fire tests at the Cardington lab [170]. The structure was primarily concrete with insulated lining (ceramic fibre or plaster board) with fuel provided by wooden cribs. Given the lack of data related to flame spread rates of combustible compartments, these data will be considered as a starting point for the a priori model considered in this chapter– however these setups are notably different from solid CLT members for several reasons, including that the flame is propagating along the porous crib, where in a CLT compartment it could be propagating along a solid ceiling. This again reinforces the need for experimentally collected data to understand the potential rates of fire spread and extinction of CLT ceilings.

In terms of appropriate extinction rates, to the author's awareness, even less data has been collected than for flame spread. Of those that have considered the rate of the trailing edge are the aforementioned x-TWO experiments, in which a concrete building was fitted with wood cribs throughout the length of the building, and flame spread and the rate of the trailing edge were observed [166]. Two trials were performed with varying fuel load densities, the first with a higher fuel load density that had a non constant rate of the trailing edge, and the second that had a lower fuel load density that did reach a steady state rate of travel. For the purposes of this model, the steady state rate of the trailing edge will be considered, which was evaluated to be 0.02 m/min (0.33 mm/s) less than the flame spread rate of the leading edge. This value again stems from experiments in non-combustible structures, highlighting the need for this data to be collected in combustible structures. Nevertheless, the values selected should be reasonable in achieving the objective of this thesis, recommending data sets for experimental collection using an a priori model.

Important assumptions made in the creation of this model are assumptions related to delamination and char fall off, as well as assumptions related to auto-extinction. This model assumes that the adhesive does not allow for delamination, and char fall off is insignificant. Otherwise, additional timber would be newly exposed to the thermal exposure following the delamination or char fall off, providing additional fuel to the fire impacting the severity of the thermal exposure. If the timber being modelled were to delaminate, several aspects of its fire performance would be altered, including its char depth. Further, in this chapter, the model assumes timber will auto-extinguish, where for the purposes of this model, auto-extinction considers timber that is free from flaming or smouldering combustion.

## 8.4 Modelling Results and Identification of Data Sets for Collection

The temperature distributions of the Glulam as well as the heritage members used for verification are seen in Figure 8.2. In both figures, the red line at 300°C is used to visualize when a certain depth of timber might char. It can be seen that in Figure 8.2 a) which considers the Glulam beams, that the beam chars to a depth of 3 mm at approximately 7 minutes and 9 seconds, and the peak temperature at a depth of 6 mm is 262 °C after 10 minutes. From the experiments, it was recorded that the beams charred to a depth of 5 mm +/- 1 mm. Through interpolation, it is expected that after 10 minutes, the timber would be at a temperature of 308 °C at 5 mm from the soffit (and would be considered charred). The percent difference between the modelled char depth and the experimental char depth is 3.5%. The charring rate observed in the model is on average 0.52 mm/min over the 10-minute period. Figure 8.3 shows a comparison of the cross section of the Glulam members post fire, as well as the results of the numerical model. Cracking shown in the photograph was induced by the mechanical loading as described in Chapter 6, and the projected initial areas as outlined in red are adjusted to account for these cracks.

Similarly, in Figure 8.2 b), the heritage members are considered. The experimental tests of these members showed a char depth of 21 mm and 25 mm in the two trials. From the figure, it can be seen that the depth of 24 mm reaches a peak temperature of 292 °C after 30 minutes. Interpolation between 24 mm and 21 mm shows that the depth which would reach 300 °C after 30 minutes and would therefore be considered charred is found at 23.85 mm, well within the range observed in the experimental trials. The percent difference between the modelled char depth and the experimental char depth is 3.7%. The charring rate observed in the model is on average 0.80 mm/min over the 30-minute period. Figure 8.3 shows a visual comparison of the char depths at the end of the heat exposure of the experimental trial that showed a maximum char depth of 25 mm, and the numerical model. Note that in Figure 8.3, a heritage member is shown rather than an engineered member – the initial surface of the member was not perfectly even prior to fire exposure.

Though the results of verification models showed good alignment with the experimental studies, it should be noted that in these models the thermal properties of timber were input as being reversible. This was done following the material properties outlined in Annex B of Eurocode 5 [32], in attempt to develop a modelling procedure that was accessible and straightforward. However, the models considered for verification were short in duration, and cooling and auto-extinction were not considered. Had other heat exposures been considered, including those that have a cooling phase, the models may not have aligned as well with the experimental results.

The results of the heat transfer of the two heat flux models are shown in Figure 8.4, where the legend shows the distance from the soffit (the application of the heat flux). Figure 8.5 also shows the temperature distributions within the CLT ceiling at 15, 30 and 60 minutes. Further, the flame spread models were used to highlight needs for data collection. The temperature distribution of the flame spread models is seen in Figure 8.6. It is seen that the temperatures, as expected, are highly dependant on the rate of flame spread and the rate of extinction.

Figures 8.4 and 8.5 highlight the importance of having a clear understanding of incident heat flux of the soffit of the CLT ceiling and its effect on temperature distribution throughout the depth of the ceiling. It was found that the maximum char depth of the models was 2.32 mm for model with a flame spread rate of 19.3 mm/s, and 11.88 mm for the model with the flame spread rate of 1.5 mm/s (assuming that there is no residual smouldering on the member). The slower flame spread rate therefore had a maximum char depth of over 5 times the quicker flame spread rate, emphasizing the importance of flame spread rate in determining the damaged area of a timber member, and resultantly, the residual strength. Figure 8.6 further demonstrates the uncertainty related to flame spread rate and extinction rate, and the impact of these metrics on the temperature distribution of the ceiling, and as a result, the structural capacity of the ceiling.

a)

b)

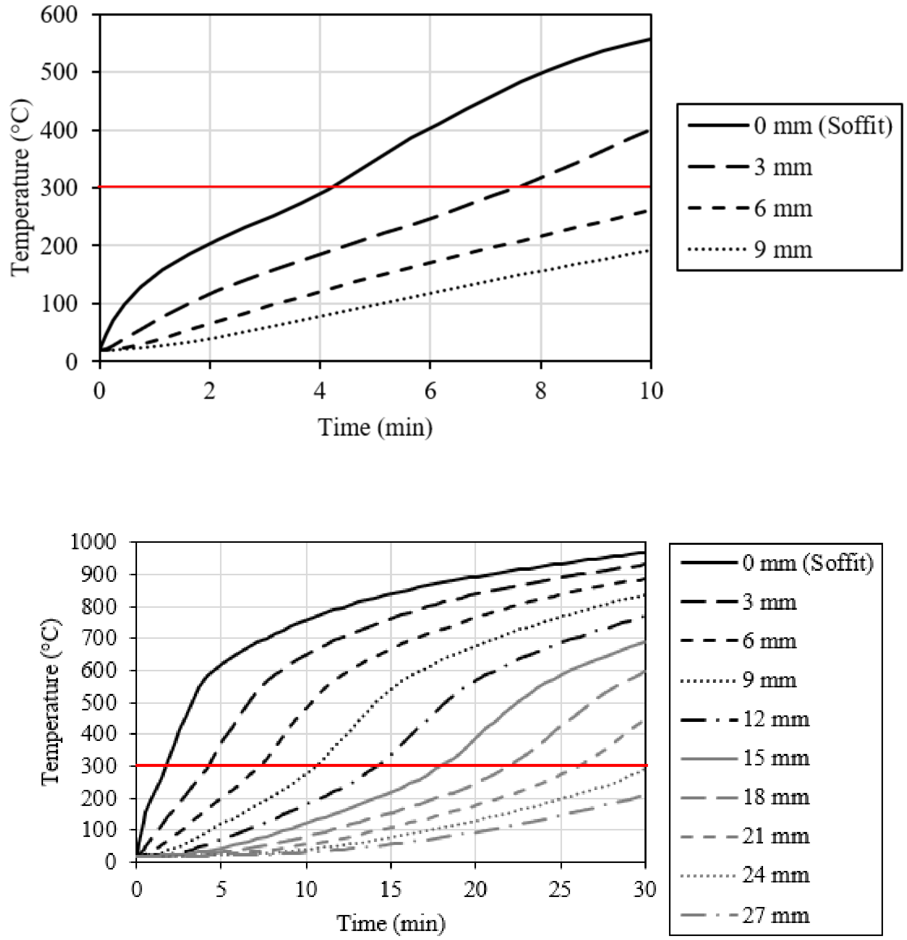
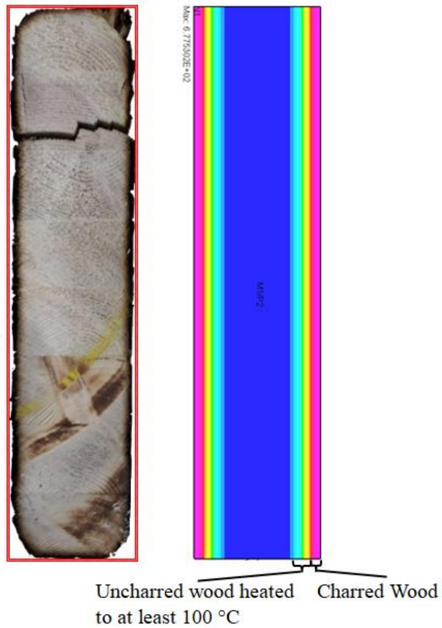



Figure 8.2 Temperature distributions of a) the Glulam members and b) the heritage members. Depths in the legend represent the distance from the soffit of the member, red horizontal line indicates the anticipated charring temperature

a)




b)

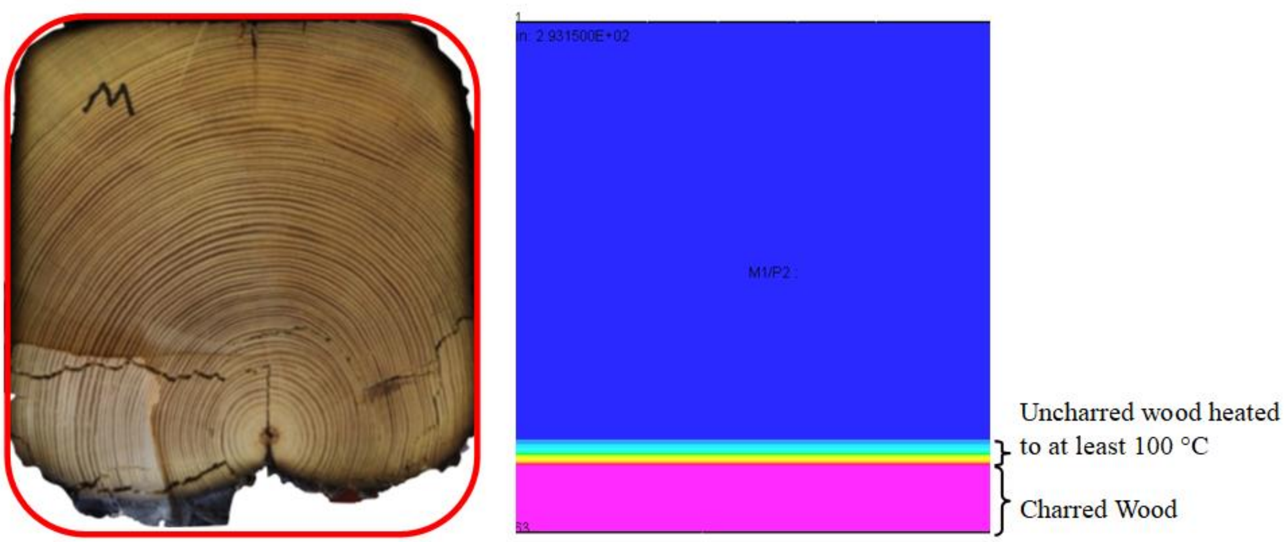
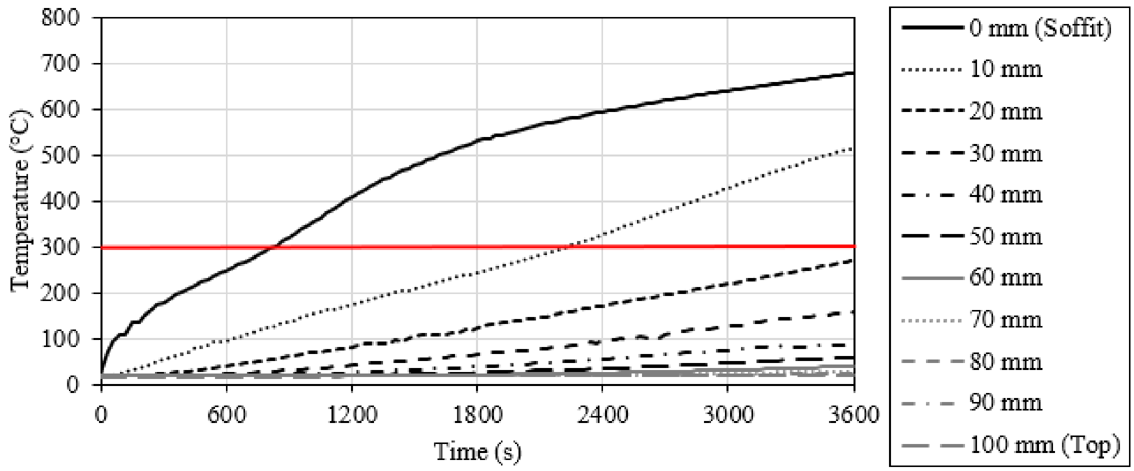



Figure 8.3 Comparison of the charred member and numerical model of a) the Glulam members and b) the heritage members

a)




b)

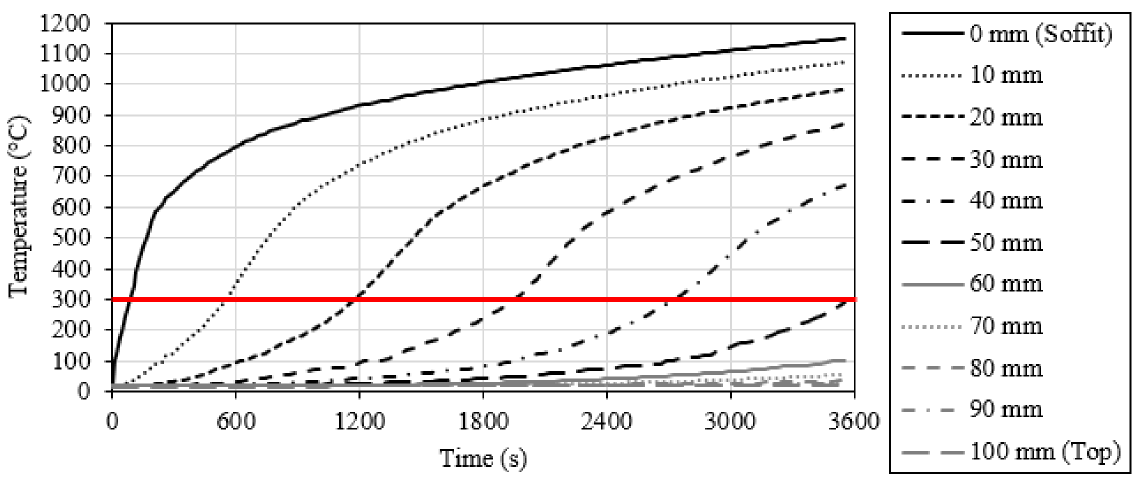
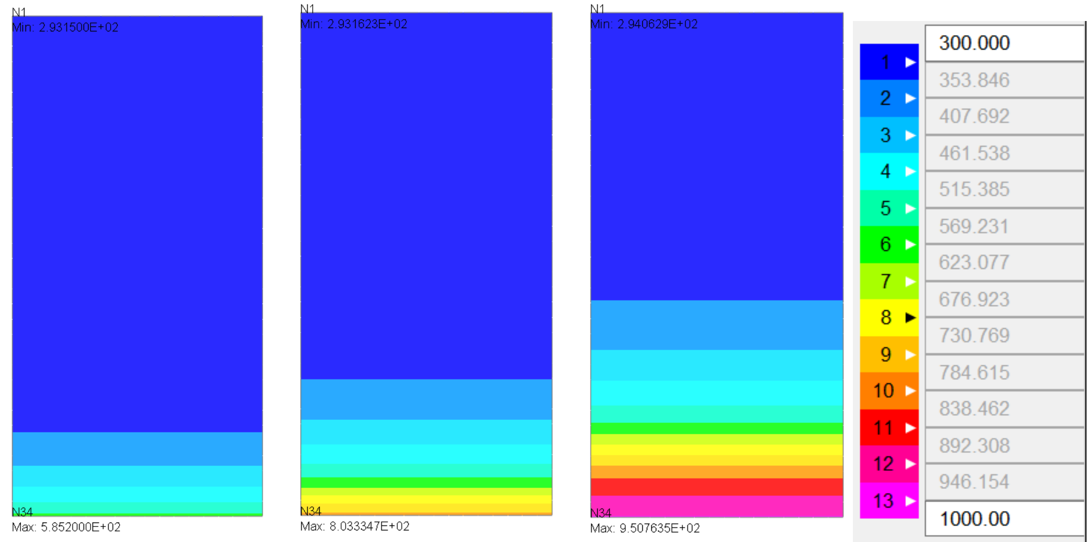



Figure 8.4 Distribution of temperatures based on heat fluxes applied at the soffit of a) 23.9 kW/m$^2$, and b) 77.5 kW/m$^2$. Depths in the legend represent the distance from the soffit of the member, red horizontal line indicates the anticipated charring temperature

a)




b)

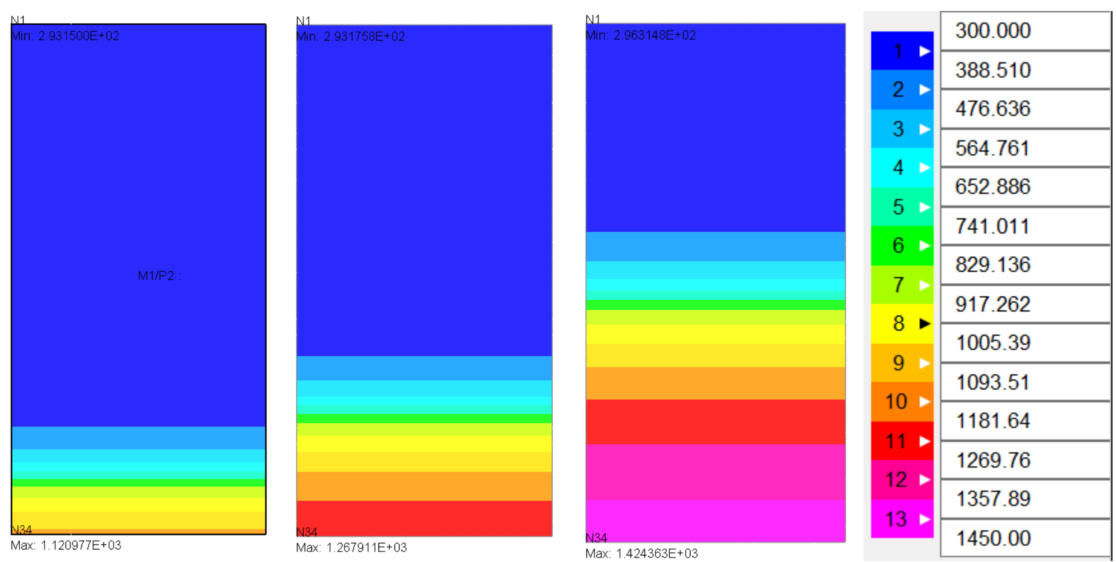
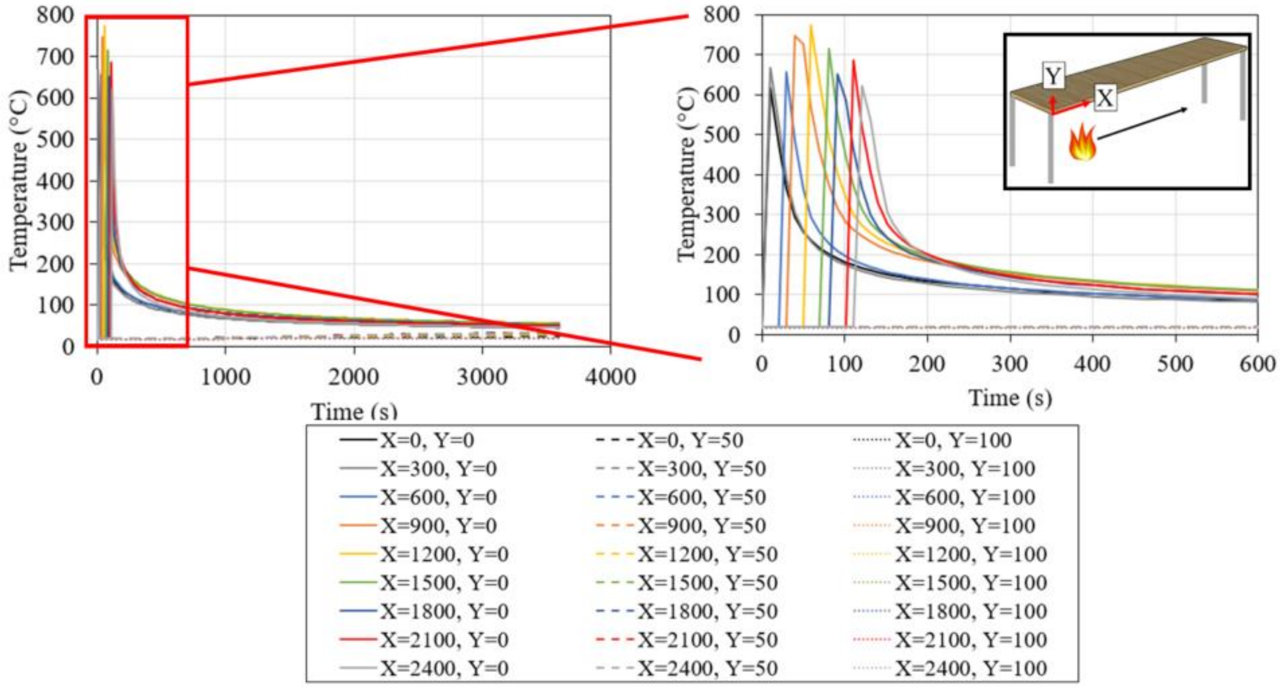



Figure 8.5 Temperature distributions throughout the CLT (from left to right) at 15, 30 and 60 minutes of a) an applied heat flux of 23.9 kW/$m^2$, and b) and applied heat flux of 77.5 kW/$m^2$ (units of temperature are K)

a)




b)

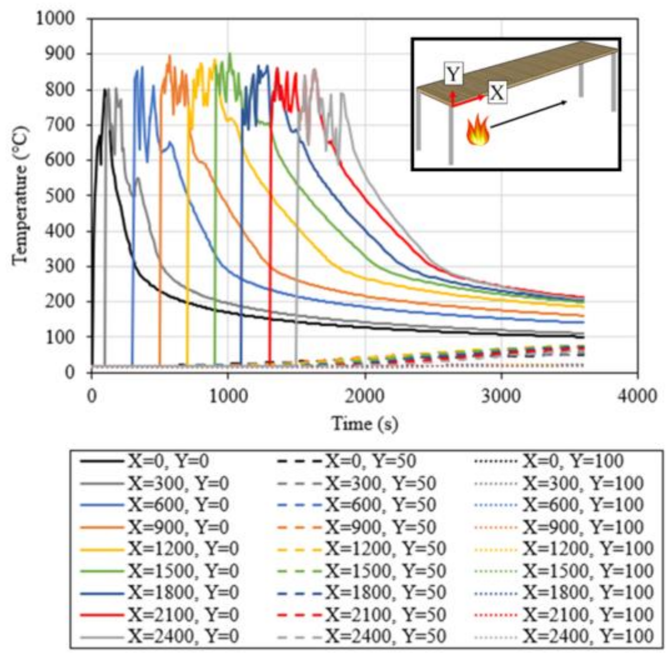



Figure 8.6 Temperatures at varying points along the ceiling considering flame spread rates of a) 19.3 mm/s and b) 1.5 mm/s

In order to calibrate these models precisely, the following datasets are recommended for experimental collection:

- The heat flux distribution on the soffit of the ceiling, in relation to position of the ignition source below the ceiling. Understanding the incident heat flux on the ceiling will allow for a better determination of the expected temperature profiles.
- An assessment of flame spread rates, along the ceiling, if any. With an exposed timber ceiling, there is the potential for the ceiling to ignite and for the flame to propagate along the ceiling at a different rate of any fuel at the floor level. This flame spread rate may be non-constant throughout the fire.
- An assessment of burn-out rates/speed of the trailing edge of the fire, if any. An understanding of the burn-out rate of the timber (if burn-out occurs) will give a better idea as to the overall projected size of the fire.

One aspect that was not considered within the model was the iterative nature of the timber's contributions to the thermal exposure. When timber burns, it creates its own heat, which in turn has the potential to induce additional charring. A flow chart depicting the process that would be needed to incorporate this effect within the model is seen in Figure 8.7.

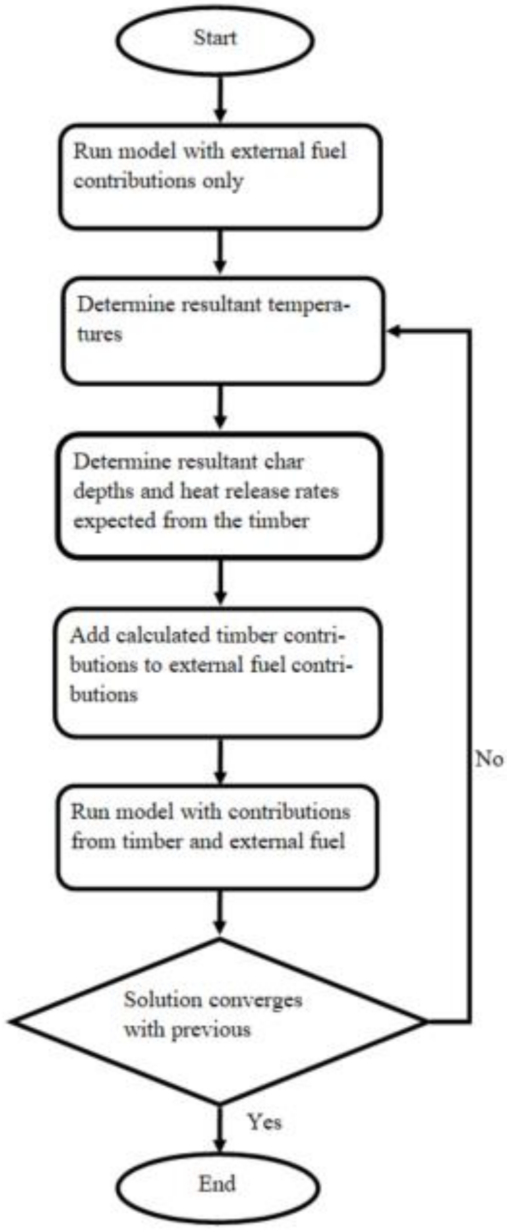



Figure 8.7 Process for incorporating the contributions of timber within the thermal exposure

The primary reason that the iterative contributions of the timber to the thermal exposure were not considered was due to the limited information available for inputs. These missing inputs can be used to identify datasets that should be collected experimentally, along with the datasets needed for model calibration. In terms of datasets needed for model calibration, instrumentation that should be considered within future experimental studies of flame spread along CLT ceilings includes:

- An array of cameras positioned along the length of the ceiling. Cameras could help to determine flame spread rates, and potentially extinction rates of the ceiling. These can be used as model inputs. Further, cameras could further allow for qualitative observation.
- Thermocouples along the length of the CLT ceiling. At minimum, these should include thermocouples on the top and soffit of the CLT at regularly spaced intervals. Intervals could be dependant on the length of ceiling in the experiment in consideration. Recording temperatures along the top and soffit of the CLT will allow for an assessment regarding if the model is working as intended. Further, assessing the ceilings after the experiments for the undamaged depth of timber will give an idea of the depth of timber that reached 300 °C which could be further compared to the model. Measuring the temperature of the ceiling will be vital for model calibration.
- The heat flux incident on the soffit of the CLT ceiling should be measured, though means such as a plate thermometer. The incident heat flux should be measured directly above a potential ignition source (e.g. radiant heater or pool fire), and at periodic intervals along the length of the ceiling (e.g. every 300 mm or as is deemed appropriate).

In terms of data sets needed to incorporate the contribution of timber into the thermal exposure, the following data sets should be collected experimentally:

- Charring rates of timber at extreme heat fluxes. While charring data of timber is available, many tests accommodate lower heat fluxes as available through traditional apparatuses. Charring rates may be greater under larger heat fluxes, as might be expected in large fires. An accurate assessment of the charring rate will help to determine the amount of char formed during a given thermal exposure, and better estimate the contributions of the timber to the overall thermal exposure.

- The heat flux generated by the timber itself should also be quantified. While again there is some data available to this extent, the data is limited. It would also be useful to understand expected heat flux when flaming is present, and when smouldering is present. These datasets would also help to better determine the contributions of the timber to the overall thermal exposure.
- Criteria for extinction, if extinction is to be considered within the model. This includes both flaming extinction and smouldering extinction. This will help to better understand the thermal environment predicted at a given heating or cooling state.

### 8.5 Case Studies

Non-uniform fires in open plan spaces have been observed in steel and concrete structures – for example, World Trade Centre Towers 1, 2, and 7 (New York - 2001), Windsor Tower Fire (Madrid - 2006), TU Delft Faculty of Architecture (Netherlands – 2008) [143], to name a few. Lesser of these real fire events have been documented in timber structures perhaps attributed to the lack of existing open plan, well ventilated timber structures being monitored. In this section, case studies illustrating the unique aspects of the possible fire dynamics of fires in open plan, well ventilated structures will be described. These case studies provide some indication of what might be expected in future experimental tests described in the previous section, to address knowledge gaps needed for finite element modelling and eventually design methodologies for these spaces.

Moreover, these case studies demonstrate the need to look at the full structure interaction. Many experimental tests and models consider only one element, which is understandable within the context of consistent crudeness [171] or where available data is limited (such as for the case for the modelling endeavour of this thesis chapter). The fire performance of the full structure can be different from what is expected from tests or analyses of one element only.

The ventilation conditions of the structure will play an important role to the expected fire dynamics and consequent fire performance. At the time of publication of this thesis, reports are emerging in attempt to define the effects of leakages and ventilation conditions on fire dynamics in highly ventilated configurations [172].

The first fire which will be discussed is the fire at Pier 45, Fisherman's Wharf in San Francisco, California on May 23, 2020. The structure in consideration consisted of a steel frame supporting a timber roof, and was reported to be approximately 660 ft by 125 ft in area (over 7600 $m^2$). The timber was exposed/uncovered from below, and skylights were present along the ceiling. The fire of unknown cause which occurred on May 23, 2020 was believed to be fueled primarily by fishing equipment. The firefighters characterized the fire as being fully developed and having attained flashover upon their arrival [173]. Following the fire, much of the structure had collapsed inwards, and the timber roof had completely failed. In this case, the authors of the Pier 45 Report [173] hypothesized that while origin and flame spread patterns of the fire remain unknown, they did describe the fire as reaching flashover and becoming fully developed. This fire provides an opportunity to look at the fire dynamics of large open plan, well ventilated fires, in this case of a steel structure with a timber ceiling.

Next, the fire in the barn structure described in Chapter 4 will be considered. The barn fire is another example of a fire in an open plan, well-ventilated timber building, further illustrating the possible fire dynamics of this type of structure. Details regarding the barn structure and the conditions of the day of the fire can be found in Chapter 4. One of the timber columns within the barn was encapsulated with fire rated type X gypsum, however all other timber elements were left exposed. The area of the main portion of the barn was 316.8 $m^2$.

A progression of the fire can be seen in Figures 8.8 through 8.14. The times reported are relative to time zero, that is, the time at which the firefighters who were igniting the fire exited the barn structure. A sacrificial GoPro camera was placed inside the barn to monitor the fire, until the camera stopped reporting data 22 minutes and 35 seconds after the firefighters exited the barn.


Figure 8.8 15 minutes, 0 seconds

Light is beginning to be obscured from the smoke. Outside, smoke is observed coming from the vents.


Figure 8.9 17 minutes, 30 seconds

Flames begin flowing from the door of the compartment of origin. Additional smoke is observed, with the smoke layer descending.


Figure 8.10 19 minutes, 30 seconds

The fire continues to grow, emitting embers. The fire begins spreading on the ground.


Figure 8.11 20 minutes, 30 seconds

The fire continues to grow, and a ceiling jet is observed.


Figure 8.12 21 minutes, 30 seconds

Flames fill the ceiling very quickly until the entire ceiling is engulfed.


Figure 8.13 22 minutes, 30 seconds

Smoke and flames continue to develop. Members along the southern side of the building are engulfed, while members away from this location show no flaming.


Figure 8.14 22 minutes, 35 seconds

This is the last image before the camera fails.
There is a descending smoke layer, but members near the camera are not yet flaming.
Outside, the cameras track fire spread to the location near the camera shortly after.

Figure 8.14 shows the last image after the interior camera was disconnected due to fire damage. As is seen from Figures 8.8 through 8.14, the fire generally progresses by first developing in the location of origin. Smoke begins collecting at the ceiling and can be seen flowing from vents in the ceiling, before beginning to descend inside the structure. The fire begins to spread along the floor, supported by amounts of hay within the barn, at which point embers begin to be emitted. As the fire continues to grow, a ceiling jet is observed. The ceiling begins to fill with flames until the entire ceiling is engulfed. Towards the floor, members at the Southern side of the structure become engulfed in flame. Members near the Northern side of the structure near to the camera location are not observed as flaming throughout the duration at which the camera was transmitting video.

The examination of this barn fire was intended to visualize unique aspects of fire dynamics that are possible in an open plan, well ventilated timber structure. There were similarities in the fire dynamics as to what could be expected in a smaller compartment. Fire spread seemed to be fueled by the ceiling jet, as well as by embers that travelled to previously unignited areas of the barn.

From the above case studies, it seems that flashover is possible within large, open plan, well-ventilated timber structures, though the exact anticipated fire dynamics will certainly depend on the specific factors to a given situation, including the ventilation conditions of the space. Given the uncertainty regarding the anticipated fire dynamics of timber structures, future experiments meant to understand the fire dynamics of open plan, well ventilated timber structures will be of utmost importance in understanding their anticipated fire dynamics and as a result, their expected fire performance. Experimental tests are beginning to take place at various research centres aimed at addressing these research gaps. These research programmes will facilitate the creation and calibration of models such as the one discussed in this chapter, contributing towards to safe design and construction of timber structures.

### 8.6 Conclusion

Previous chapters of this thesis highlighted and advanced the current state of knowledge regarding the thermomechanical performance of heritage and contemporary timber structures. Given this background understanding combined with the current push for the development of open plan, well ventilated timber structures, the question is raised of how open plan, well ventilated combustible spaces will be designed in the future. These spatial configurations have been to experience unique fire dynamics when considering non-combustible structures, and these fires become further complex with the introduction of timber, which has the capacity to both contribute additional fuel to the fire and propagate flame. Finite element modelling offers several advantages in the design and analysis of these types of spaces, including having a better understanding of the resilience of the structure, beyond what can be determined through prescriptive based analyses. This type of modelling can help to assess the fire risk of these structures.

The purpose of this thesis chapter was to identify data sets recommended for experimental collection, to support the creation of future design methodologies which address open plan, well ventilated timber structures. This was done by examining which data would be required for model input and calibration, using an a priori model. The fire performance of open plan, well ventilated timber structures was further examined using case studies.

LS DYNA was used to create an a priori model. The results of the model, which considered a range of heat fluxes, flame spread rates, and extinction rates from literature highlighted the importance of future experiments related to the fire performance of CLT ceilings. Each of these areas greatly impacts the expected temperature distribution throughout the ceiling, and therefore the area of timber of which the structural capacity would be reduced. From the creation of this model, recommendations were possible regarding the instrumentation of future experiments of the fire performance CLT ceilings, making use of cameras, thermocouples and/or plate thermometers. The collection of these data sets will help with provide model inputs, and data sets for model calibration.

Future research needs for modelling of timber include the further development of thermal-structural models. These have begun to be addressed by other researchers [21, 118], but additional modelling endeavors considering loaded thermal models could examine different thermal exposures and structural loading scenarios. This would help to make thermal-structural modelling of timber more established, contributing to the development of these models being used for design. Other properties unique to timber could be investigated through modelling. These include the effect of moisture content, including the effect of having varying localized moisture contents throughout the timber caused by moisture migration during heating. Smouldering is also a phenomenon not seen in all structural materials, but that can affect the temperature profile of the section. The development of a model which considers smouldering through software currently used by industry members (such as LS DYNA) would contribute towards more accurately modelling the fire performance of timber structures. The case studies of the fires that took place at Pier 45 in San Francisco, and within the barn structure, illustrated the importance of collecting information regarding the fire performance of well ventilated, open plan timber structures. The fire brigade that attended Pier 45 noted that the fire was fully developed and experienced flashover [173]. Observations from the fire within the barn include that flame spread seemed to be caused by ceiling jets and embers, but ultimately the fire grew until the structure was largely engulfed in flames. These case study highlighted the importance to consider fires in large, open plan and well ventilated timber structures.

Although there are several steps that need to be taken before design simplified design methodologies for open plan, well ventilated timber structures can be created, the fire research community is beginning to mobilize an address some of these research gaps. These planned and in-progress experiments and analyses are anticipated to help better understand the expected fire dynamics of these types of spaces. By understanding how fires in well ventilated, open plan spaces differ from compartment fires recently considered in experimental research, analysis of these types of fires becomes possible, and the creation of methodologies for design of these spaces becomes more accessible.

# Chapter 9 : Conclusions and Recommendations

## 9.1 Summary

This thesis addressed the thermomechanical response of timber to real fire exposures, focusing on areas of research that have seen relatively little study.

Motivation for this study included that countless heritage buildings around the globe are constructed of timber. These structures can be invaluable to their communities, yet many heritage timber structures are vulnerable to fire. There is little information available to practitioners regarding the fire performance of heritage timber and encapsulations, which could lead some to remove or alter heritage materials where it may not be necessary. Meanwhile, while heritage timber continues to be removed from historic structures, contemporary timber buildings are being constructed increasingly taller. Given the tall demonstration timber buildings that have been recently constructed in cities worldwide, paired with several nations amending their building code to allow for taller and larger timber buildings; it is almost inevitable that we will continue to see timber being more widely used in construction. Though these structures are being constructed, there remains uncertainty regarding aspects of their fire performance, including if encapsulation meant to protect timber from fire is effective, and the severity of adhesive degradation in timber. Of the studies that have been done, many utilize the standard temperature-time heating curve, where questions have been raised regarding the applicability of this test for combustible materials. Moreover, recently constructed and planned timber structures have demonstrated the architectural desire for exposed timber within well ventilated, open plan spaces, for which there has been little research study for combustible materials. Finite element modelling could be used in these situations in assessing the resilience of the structure, though finite modelling of timber is still limited by several research gaps. This environment, surrounding the current state of existing timber structures and the development of future timber structures, has prompted the studies discussed within this thesis.

The overarching goal of this thesis was to better understand the thermomechanical response of timber in real (non-standard) fire scenarios. This includes timber encapsulations and looks at materials dating from the 1800s through to today, and ties into how timber structures might be designed going forward. A graphical representation of the relationship between thesis chapters is seen in Figure 9.1.

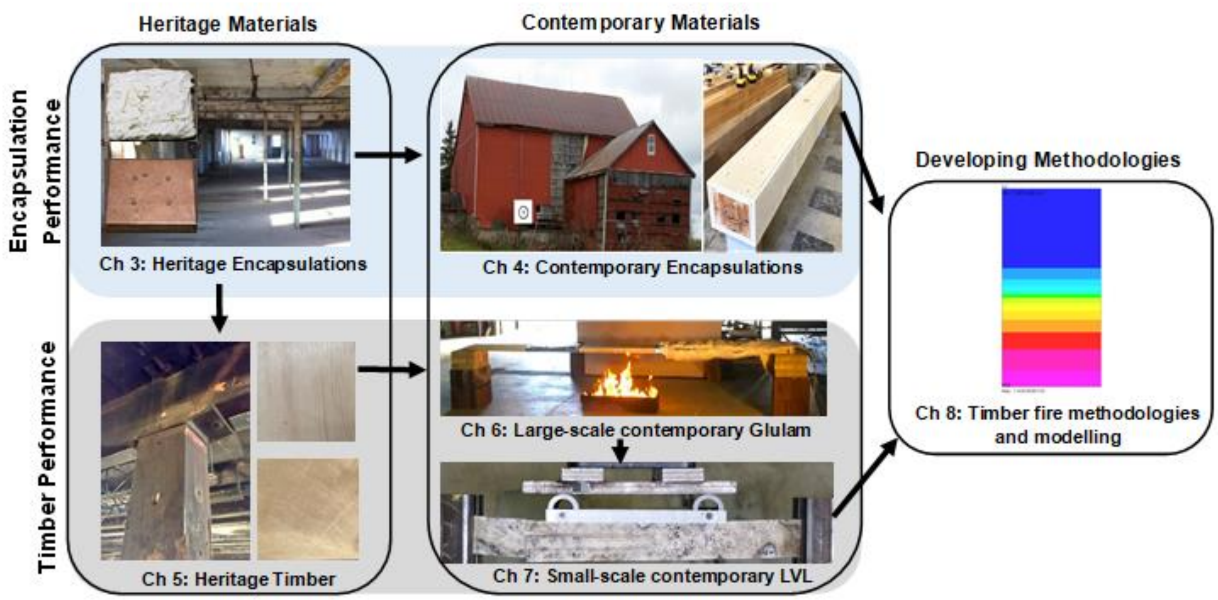



Figure 9.1 Relationship between thesis chapters.

Background information of fire safety engineering of timber was discussed in Chapter 2. This chapter was meant to help contextualize the following chapters by providing a review of current knowledge and practices regarding timber fire safety engineering. This included reviewing timber material properties and composition and exploring what constitutes engineered timber. Fire testing technologies were also discussed in this section, including the Lateral Ignition and Flame Spread Test (LIFT) and Cone Calorimeter apparatuses, both which were used in multiple chapters later in this thesis. Fire dynamics was also discussed on a high level, including outlining the standard temperature-time heating curve and some of its draw backs. The thermal performance and decomposition of timber is discussed, covering some of the factors which influence charring and pyrolysis of timber. Current practices for determining structural capacity of fire damaged timber were highlighted, including standardized charring rates, zero-strength allowances, and fire resistance ratings. Finally, the use of encapsulations to improve timber fire performance was briefly examined.

Both Chapters 3 and 4 addressed the effectiveness of encapsulation systems at protecting timber from non-standard fire exposure. These chapters provided an improved understanding of the effectiveness of historic and contemporary encapsulation materials, as well as developed an understanding of the underlying failure mechanisms of contemporary encapsulation materials.

An in depth- discussion regarding heritage structures is found in Chapter 3. In this chapter, the importance of heritage conservation was reiterated, and the history of timber encapsulation materials was brought to light (dating to the 18$^{th}$ century), showing the development of how we have come to use encapsulations for fire protection today. These materials included metal plates (copper and wrought iron), two plasters proposed by different architects, whitewash paint, as well as contemporary gypsum board (for comparison). Each of the encapsulations was recreated, and a Cone Calorimeter apparatus was used to test these materials (applied to a piece of timber) at a small scale. Findings of the tests included that while the plasters protected the timber from charring, they did not stay attached during heating, and are therefore impractical for any ceilings or walls. The metal plates experienced 75% less charring than the control sample, though the relative success of the plates is largely due to their reflective surface, which in a heritage structure would have oxidized (greatly impeding fire performance). The whitewash paint merely delayed the ignition of the timber by about 20 seconds, with total char depth only reduced by 1 mm compared to control. The only encapsulation that therefore showed any promise at the small scale was the contemporary gypsum board. To the author's knowledge, this study was the first contemporary fire test for many of these encapsulation materials and will therefore assist any practitioner who may come across one of these encapsulations. Each of the encapsulations was concluded to have no positive effect on the fire performance of the timber, though it may be necessary to evaluate these encapsulations for their heritage value, should they be found in practice. This chapter helped to direct Chapter 5, which further built upon heritage materials by looking at the fire performance of heritage timber itself. Furthermore, as it was seen that contemporary gypsum board was the only material that had some benefit to timber at the small scale, the study of the fire performance of contemporary gypsum board in fire was scaled up significantly in Chapter 4.

The performance of contemporary fire rated gypsum board was examined through both field and laboratory studies in Chapter 4. This chapter was motivated by many tall timber buildings around the world using Type X gypsum board to improve the fire performance of timber, yet previous studies (by other authors) have shown that gypsum board may fall off of surfaces (often tested on Cross Laminated Timber) during a fire. This chapter therefore examined the performance of Type X gypsum board applied to columns (rather than walls, ceilings, etc. which have been considered in previous research), and aimed to investigate what the potential mechanisms might be causing gypsum board fall off. The field study considered one column within a barn structure that was fully encapsulated akin to what has been done in tall timber structures in Canada. The barn was ignited and allowed to burn without intervention, with thermocouples between each gypsum layer as well as cameras inside and outside the barn allowing for observation. It was found in the field study that the gypsum layers did not significantly delay a rise in temperature at the surface of the timber, as the temperatures at the surface of the timber rose to over 900 °C less than one minute after this temperature was recorded on the outer layer of gypsum board. This prompted the controlled laboratory study, in which four columns were encapsulated with either one or three layers of gypsum board. The columns were individually subjected to a pool fire, with thermocouples again recording temperature in between each gypsum layer. Narrow spectrum illumination (blue light) technology was used to record the fire exposure and filter out the flame. This technology, along with digital image correlation, allowed for observations to be made regarding the deterioration of the gypsum board. The results of the laboratory study showed that gypsum board seems appear to be opening during heating and cooling of the columns, with seam openings up to 129 mm in length, and temperatures under one layer of gypsum reaching up to 800 °C. Redundancy appeared to be provided by using multiple gypsum layers.

Following the study of encapsulation materials, the performance of timber itself was examined in Chapters 5 though 7. Chapter 5 specifically looked at the heritage aspect, as there is little information regarding the fire performance of heritage timber, and thus in some instance's heritage timber may be removed or altered in structures due to lack of guidance, rather than reflecting its actual fire performance. Of the available documents that address heritage timber, many consider the performance of heritage timber to be similar if not identical to contemporary timber, without supporting data to confirm they will perform the same. Differences in the timber such as the presence of adhesives as well as differences in contemporary versus historic growing practices all have the potential to alter the fire performance. The objective of this chapter was therefore to compare the relative performance of heritage and contemporary timber. Heritage timber was therefore obtained from two industrial structures dating to the 1800s. These samples were compared to contemporary Glued Laminated Timber (Glulam) samples. The timber was tested in the LIFT and Cone Calorimeter apparatus'. Results showed that the heritage timber ignited faster than the contemporary timber on average (13.6 seconds faster on average, considering samples of the same grain orientation), and experienced up to 20% greater charring. The LIFT tested showed that the heritage timber had flame spread up to 50 mm further, and faster than the flaming on the Glulam. These findings indicate that it cannot be conservatively assumed that heritage timber will perform as well as contemporary timber in fire. Chapter 5 was effectual in addressing the thermomechanical response of historic timber, and provided a preliminary evaluation of its charring, flame spread, and ignition characteristics.

Chapters 6 and 7 both looked at the performance of contemporary timber. The findings of Chapter 5 provided a foundation into some of the factors affecting timbers fire performance. In Chapter 6, the same factors apply and are further complicated by the presence of adhesives used in engineered timber. As tall timber structures are being constructed, some research suggests auto-extinction of timber might be possible to achieve compartmentation as a fire safety strategy. However, adhesive degradation is of high importance to consider in these designs, as adhesive degradation can significantly reduce the strength of the timber. Regardless of if auto-extinction is achieved, the timber must retain sufficient strength to support the structure above. Chapter 6 therefore looked at the adhesive degradation in Glulam. Five realistically scaled (4.2 m in length) Glulam beams were exposed to a pool fire, with two additional beams mechanically carved to achieve the same effective cross section. The carved beams would allow for identification of degradation effects beyond the char layer. All beams along with two control beams were tested in four-point bending. Results showed that the Glulam beams were impacted by material defects in the timber. The beams damaged in the shear region showed a greater loss of strength compared to those damaged in the moment region. The beams charred in the shear region failed at a load 25%

lower than the beams mechanically carved in the shear region. Furthermore, current allowances for zero-strength layer (7 mm) proved to be non-conservative in this context, where it was found that a zero-strength layer of 17.2 mm would be needed.

Chapter 7 aimed to expand on the findings of Chapter 6 by conducting similar tests with a larger number of specimens (28 in total), which would reduce variability. Furthermore, the experiments were extended to Laminated Veneer Lumber, another understudied type of engineered timber. Small scale beams were exposed to heat using a modified LIFT apparatus setup, allowing the damaged region to be tightly controlled. Additional beams were again carved to the same severity as the charred beams, to look at degradation exclusive of charring. Results from the four point bending tests showed that in these tests, the LVL experienced greatest strength loss when the beams were damaged in the moment region (charred beams capacity reduced 40% compared to control), while the Glulam beams experienced a greater reduction in strength when damaged in the shear region (charred beams capacity reduced by 27% compared to control). The findings of this chapter also extended some of the findings from Chapter 6 to LVL, including that current zero-strength values were not conservative in this test setup, where these experiments suggested a minimum zero-strength layer of 11.7 mm is needed. Together, Chapters 6 and 7 provided an examination of the thermomechanical response of contemporary engineered timber to non-standard fire, including degradation of the adhesives. The findings of these chapters have advanced the current understanding of thermal degradation of engineered timber in fire.

Chapter 8 set a framework for future research, considering the development of design methodologies for timber spaces. Given the current architectural demand for exposed timber in open plan, well ventilated spaces, Chapter 8 outlines data that needs to be collected in order to facilitate finite element modelling of these types of timber spaces. An a priori model created in LS

DYNA was used to model a CLT ceiling, from which multiple data sets were outlined as being required for either model input or model calibration. Further, data sets were outlined as being required for incorporating the iterative contribution from the timber to the fire into the model. An overview of case studies looking at open plan, well ventilated spaces with exposed timber elements gave a look into the unique aspects of the fire dynamics of these spaces, which showed that flashover seemed to be possible but will depend on the specific conditions of a space, including the ventilation conditions. The findings of this chapter can be used to inform future experimental design, ultimately contributing towards the development of design methodologies for timber.

## 9.2 Conclusions and Contributions to the State of the Art

The following key conclusions are drawn from the experimental testing presented within this thesis:

- While heritage restrictions may not allow the removal or alteration of historic encapsulations found in heritage structures, these encapsulations cannot be relied on to improve the fire performance of the structure. Each of the historic encapsulations tested had some degree of drawback, whether it be minimal contributions in protecting the timber from fire, or practicality considerations such as remaining fastened to the timber and oxidation that may reduce effectiveness over time.
- Multiple layers of Type X gypsum board alone cannot always be successful at delaying a rise in temperature at the surface of timber when subjected to real fire exposures, as observed in the field study of the barn structure.
- One layer of gypsum board seemed ineffective in the laboratory experiments; with char depths of 25 mm and a maximum charred region of over 40 cm in length still observed on the timber after testing. Causes for this included significant that seam openings between

gypsum boards (up to 129 mm in length) occurred during the heating and cooling phases of testing, allowing heat to penetrate beneath gypsum board layers. Discrete cracking patterns on the gypsum board became more exaggerated during the cooling phase of testing.

- Heritage timber cannot be assumed to perform as well as their contemporary counterparts in fire exposure. LIFT tests showed that while the heritage timber outperformed the contemporary timber in some respects, such as time for flame spread to stop, though the Cone Calorimeter experiments showed that the charring rate of the heritage timber was up to 20% greater than the charring rate of the contemporary timber, and that the heritage samples ignited significantly faster than the contemporary samples.
- The bending tests examined in Chapters 6 suggested that a minimum zero-strength value of 17.2 mm is needed for Glulam. The failure modes observed in the realistic length beams examined in Chapter 6 were influenced by the presence of material defects as well as cracks propagating into adhesive lines.
- Testing of LVL showed that 11.7 mm as a zero-strength value would be needed to conservatively consider degradation effects beyond the char layer. Like Glulam, adhesive degradation is occurring in LVL to a degree that is not adequately accounted for by zero-strength values.
- A framework for future research needs to facilitate the finite element modelling of timber in open plan, well ventilated spaces was set. Case studies of these spaces have shown that flashover appears to be possible, with the fire dynamics being dependant of the specific conditions of the space.

### 9.3 Research recommendations

The previous chapters of this thesis considered extensive testing of multiple types of timber and encapsulations. Observations made throughout these tests have been identified as areas in need of future research. Based on observations made throughout this thesis, research in the following areas would further improve fire safety developments in heritage and contemporary timber structures:

- **Further development of narrow spectrum technology** – This technique should be adapted for furnace testing, allowing for observational comparisons to be made when materials are subject to standard and non-standard temperature-time heating curves. Furthermore, digital image correlation for strain and deflection should be further validated for use with narrow spectrum technology.
- **The effect of water suppression** – The use of water (from sprinklers or suppression) may have an effect on gypsum board encapsulation performance. This should be explored through future research, possibly through wetting the gypsum pre- or post- fire. Future research could examine this effect.
- **Longer duration and full-scale testing** – Tests of multi-layered gypsum board encapsulation should occur to the point where all gypsum layers undergo dehydration (this effect in itself also warrants future research). Full scale testing of members with representative cross sections should also occur for both heritage and contemporary timber samples, to fully understand the effects that would occur in a building fire.
- **Testing of additional timber types** – From a heritage standpoint, only North American Softwoods were tested in Chapter 5. A broader range of species types that are found in heritage structures should also be tested, such as Hardwoods. As for the contemporary

timbers, adhesive degradation in additional adhesive types (such as melamine adhesives) need to be considered. Engineered timber from other manufacturers should also be studied. Timber systems seeing new or renewed interest are also in need of further research, these including Post-Tensioned Timber as well as Nail Laminated Timber.

- **Testing of additional Type X gypsum board** – While one and three layers of gypsum board were examined, future research could consider two-layered gypsum board to understand seam opening and deflection. Other manufacturer's gypsum boards should also be studied.
- **Repair options for fire damaged timber** – Should a timber structure experience a fire, there is a need for guidance regarding how to repair a damaged timber member. Appendix B begins by attempting a preliminary repair of timber members subject to localized fire damage. Extensive research is still needed on this topic to guide practitioners and inform insurance companies in assessing risk.
- **Charring rates for timber under extreme heat fluxes** – Though charring data is available, many tests consider lower heat fluxes, whereas larger fires might expect to see much higher heat fluxes. This will assist in determining the amount of char formed during a given thermal exposure, and as a result can help to better estimate both the structural performance of the member and the contributions of the timber to the fire.
- **Flame spread and extinction rates of timber** – With exposed timber, there is the potential for flame spread, with the flame propagating along the ceiling at a different rate than fuel that may be at floor level. This flame spread rate may be non-constant throughout the fire. Similarly, extinction rates of the trailing edge of the fire will give a better idea as to the overall projected fire size.

- **Heat flux distributions on the soffit of timber ceilings –** Understanding the incident heat flux on the ceiling will allow for a better determination of the expected temperature profile. This should be assessed in relation to the ignition source below the ceiling.
- **Heat flux generated by the timber –** In addition to the incident heat flux, there should be an understanding of the heat flux generated by the timber itself. While there is some data to this extent, research is limited especially when considering large fires. This data could consider both heat fluxes in the presence of smouldering and flaming timber. This would help to better define the contribution of the timber to the fuel load.
- **Development of an analytical framework** – An up-to-date analytical framework should be developed to highlight work that has been completed, and to bring attention to current research needs that would further enhance the fire performance of timber structures.

Beyond looking solely at research recommendations stemming from observations within the experiments discussed in the above thesis chapters, there are several other research needs that need to be addressed to support the fire performance of timber structures. In 2015 NIST published a report entitled, "*NIST Special Publication 1188: International R&D Roadmap for Fire Resistance of Structures Summary of NIST/CIB Workshop*" [57]. In the NIST 1188 Roadmap (developed during a May 2014 workshop), implementation plans outline research needs for timber structures. While many of the research needs identified in NIST 1188 have begun to be addressed (with some outstanding; assessed in 2017 by Jeanneret et al. [93]), the research needs since the development of the roadmap have expanded based on advances that have been made. Many of these research ideas affect the notion of compartmentation and auto-extinction. Overarching research needs requiring additional examination, as well as more newly identified needs beyond those discussed in NIST 1188 include:

- **Delamination –** the occurrence of delamination needs additional consideration. Delamination has been considered in research, however many studies have considered CLT, thermal exposure through the standard temperature-time heating curve, and a limited number of adhesives. Delamination effects should be explored in timber products beyond Cross Laminated Timber, such as Glulam. This includes thorough testing of products using newly developed adhesives (melamine based and otherwise), and to non-standard thermal exposures. The effect of delamination also needs to be well understood for its potential contributions to the fuel load in a structural timber fire.
- **Connections –** while timber connections have seen some research interest, uncertainty remains regarding the fire performance of timber connections. Additional study is needed for timber connections, including studies of large-scale non-standard fire exposure. Heat transfer through metal connections (including screws) into the timber continues to be of interest as well.
- **Auto- extinction –** previous studies have shown varying evidence surrounding decay and auto-extinction of timber [56]. While previous tests may have shown auto-extinction to be possible [174], recent studies suggest additional work is still needed regarding encapsulation performance, occurrence of delamination, and geometry of exposed timber [175], which could contribute to better assessing the potential for auto-extinction.
- **Timber contribution to the fuel load –** the performance of timber in fire has a large dependence on the fire scenario, and the fire scenario depends on a variety of factors including the fuel load (to which the timber contributes). The timbers performance and fire scenario therefore are dependant on one another. The contribution of timber

members to the fuel load is an overarching theme that encompasses several research needs as defined earlier in this chapter, including charring rates and heat fluxes generated by the timber at extreme thermal exposures, encapsulation performance, delamination and char fall-off.

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# Appendix A: Supplementary Information to Chapter 8

## A.1 Overview

This appendix is intended to compliment the model outlined in Chapter 8. The purpose of this appendix is to provide enough information for future adaptations of similar models. It should be noted that some parameters were outlined in Chapter 8 itself, and those parameters (such as material properties) are not repeated in this appendix. SolidWorks is a solid modelling computer aided drafting software that allows for 3D parts to be created from a series of 2D sketches, considering features including extrude, revolve, fillets, cuts, and holes [1]. SolidWorks was used in this model for geometry creation. Altair Hypermesh is another finite element pre-processor, that imports CAD geometry and can generate mesh as a core competency. Hypermesh was used in this model for meshing the part. The Oasys Suite offers pre- and post- processors created specifically to be compatible with LS-DYNA. Oasys Primer was used for pre-processing (after geometry creation and initial meshing) and Oasys D3Plot was used for post-processing.

LS-DYNA is a nonlinear finite element program that uses implicit time integration. As a nonlinear program, LS-DYNA can accommodate changing boundary conditions, large deformations, materials that do not exhibit elastic behaviour, and transient dynamic events [2]. The LS-DYNA solver is provided a keyword input file (which in this case was created in Primer). The model described herein used eight node hexahedral (brick) solid elements, which are integrated with a 2x2x2 Gauss quadrature rule, where the temperature dependence of the properties is accounted for at the Gauss points [3]. The heat transfer through the timber is assumed to be purely conductive. LS DYNA uses an energy balance in analyzing thermal problems, in which the change in internal energy is equal to the sum of the conduction in and out of the volume, the energy generation insider the volume, and the energy transfer from the surface.

Versions of the software used in this model were SolidWorks 2020, Altair Hypermesh 2019, and Oasys Products (Primer and D3Plot) version 17.0. The LS-DYNA executable used for this analysis was LS-DYNA R12.0.0.

In Chapter 8, it was described that SolidWorks was used to create the geometry, and Altair Hypermesh was used to mesh the part. In terms of logistic alterations made when importing the file into Oasys Primer, the units used in Solidworks and Hypermesh were millimetres, though in the Oasys software and LS DYNA, the units needed to be metres for unit consistency. As a result, the model was scaled (using the 'Scale' tool under the 'Orient – Mesh tools' option of Oasys Primer), down by a factor of 1000 in each of the X, Y, and Z directions. Oasys Primer relies on the user to keep track of units; thus the user must ensure that units are consistent across all inputs.

Other changes made in Oasys Primer include that the mesh was extruded. This was done by extruding the shells into solids, and specifying the number of shells over the required distance (in this case, 800 shells were extruded a distance of 2.4 m to achieve a consistent 3 mm mesh). Each of the following steps taken in creating the model keyword file was done using Oasys Primer, with an overview of the interface seen in Figure A.1. Figures shown herein are illustrative only, for readers to get an impression of how this modelling was done.

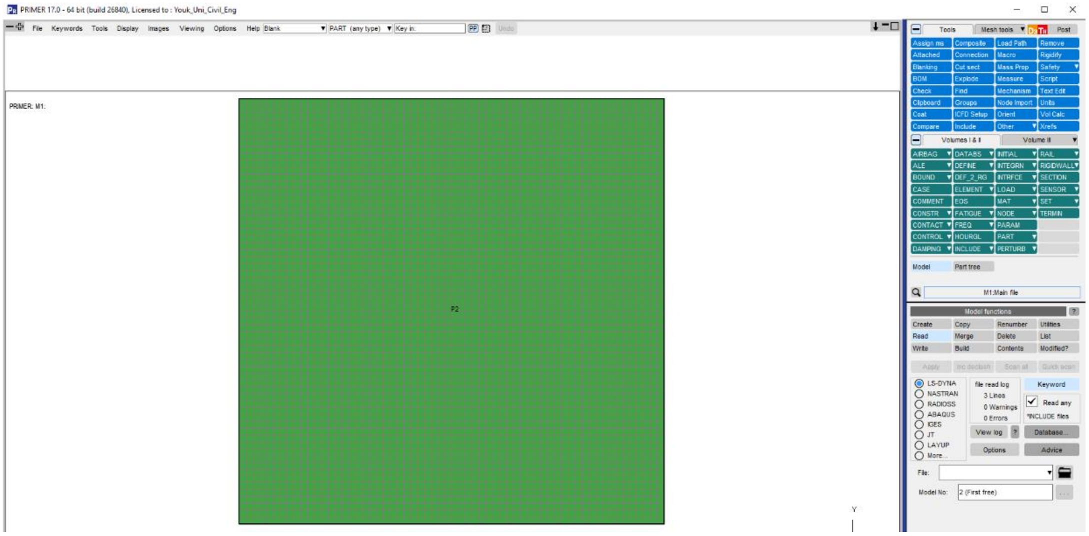

Figure A.1 Overview of Oasys Primer user interface.

## A.2 Boundary Conditions

Several boundary conditions were used in the development of this model. These included temperature, heat flux, radiation, and convection boundary conditions. On the top surface of the model, radiation and convection boundary conditions were implemented, to represent cooling, assuming the fire exposure is limited to the soffit of the ceiling. On the soffit of the model, both the heat flux and the temperature boundary conditions were implemented at different times. The sides of the model were considered to be adiabatic (i.e., no additional boundary condition was applied).

Considering the convection boundary condition on the top surface of the model, a set boundary condition was created. The convective heat transfer coefficient curve multiplier (hmult) was taken as 4 $W/m^2K$ for the non-fire side of the ceiling [4]. The environment temperature (tmult) was input as the ambient temperature (taken as 293 K). In selecting the Set for the convective boundary condition to be applied to, the Segment Set ID was created using the ‘Coat Elements’ function, in which an entire face can be ‘coated’ (i.e., the entire face will be selected), by the selection of a single node.

A radiation boundary condition was also used on the top surface of the ceiling, to represent radiative losses to the environment. Radiation Type 1 was used (where this type models radiation to or from the surrounding environment, as opposed to Radiation Type 2 which considers radiation in an enclosure). The radiation boundary condition was created by initializing a radiation keyword card, and selecting Type 1 as applied to a set. The Segment Set ID was then selected to be the same as was used for the convective boundary condition. The radiative heat transfer coefficient (fmult) is taken as the product of the surface emissivity, the Stefan-Boltzmann constant ($5.67*10^{-8}$ $W/m^2K^4$), and the view factor. The emissivity was taken as 0.8 [5], and the view factor was taken as 1.0. Thus, the radiative heat transfer coefficient was determined to be $4.54*10^{-8}$ $W/m^2K^4$. For surfaces that are radiating losses to the environment, the environment temperature (tmult) is taken as the ambient temperature. Figure A.2 shows the radiation boundary condition input.

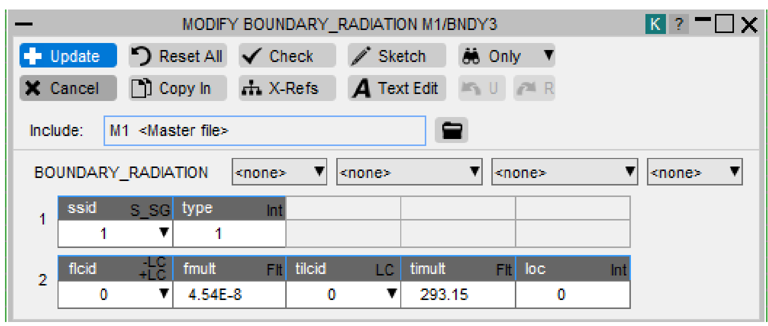

Figure A.2 Inputs for radiation boundary condition.

Heat flux boundary conditions were implemented on the soffit of the ceiling. The soffit of the ceiling was selected by creating a Segment Set ID and coating the soffit elements as described above. A curve was created to input the desired heat flux over the required duration of time. The temperature boundary condition was also implemented on the soffit of the ceiling to model flame spread. This was implemented similarly to the heat flux, though the curve would correspond to soffit temperatures over time. The curve multiplier was taken as 1.0, and the 'tdeath' and 'tbirth' functions were used. The 'tdeath' function deactivates the curve at the time specified, and the ‘tbirth’ function activates the curve at the time specified. Flame spread rates were used to inform the activation and deactivation times across the soffit of the ceiling.

## A.3 Material Properties

The thermal material properties were input into the model, with the specific heat capacity and the thermal conductivity as described in Chapter 8 and as adapted from the Eurocode 5 [5]. Properties were input as Thermal Material Type 10 – which allows for isotropic thermal properties that are temperature dependant and can be specified by load curves. Figure A.3 shows inputting a material property (thermal conductivity) as a load curve. The latent heat was calculated as per Equation 8.1, and the phase change temperature was taken as 373 K (corresponding to the point at which moisture would change phases). The moisture content of the timber is accounted for by the latent heat (the energy absorbed during the phase change of water).

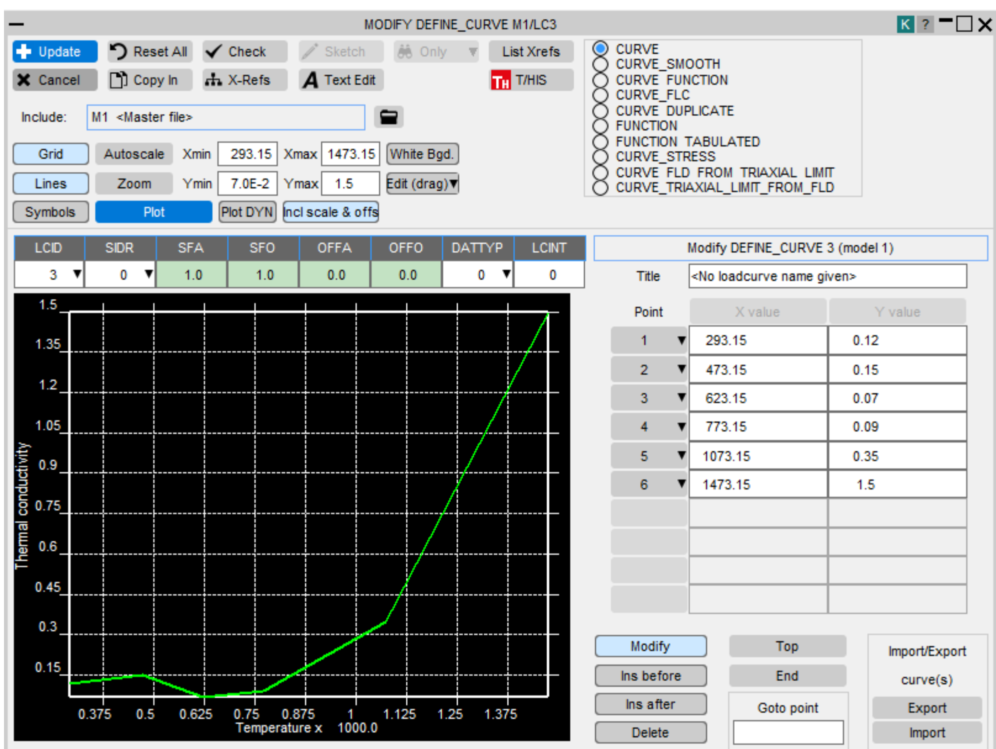

Figure A.3 Defining a curve (thermal conductivity shown here).

The Eurocode 5 defines density as a temperature dependant property [5], however, LS DYNA does not readily allow for temperature dependant density. In this case, the density was taken as the initial (or estimated initial) density, which demonstrated adequate alignment in the verification studies.

### A.4 Initial Conditions

An initial condition was added to set the initial temperature of the model. This was done by creating a set in which the entire model is selected. The initial temperature was taken as the expected ambient temperature of 293 K.

### A.4 Additional Input Parameters

Many of the input parameters are outlined on the Control card (seen in Figure A.4). The maximum number of matrix reformations per time step (refmax) was chosen as 9000, and the convergence tolerance for temperature (tol) was set to 1e-6. These were chosen as they have been identified as being used by other researchers. The thermal analysis was chosen as a transient analysis, and the thermal problem type was chosen as a nonlinear problem with material properties evaluated at every gauss point temperature.

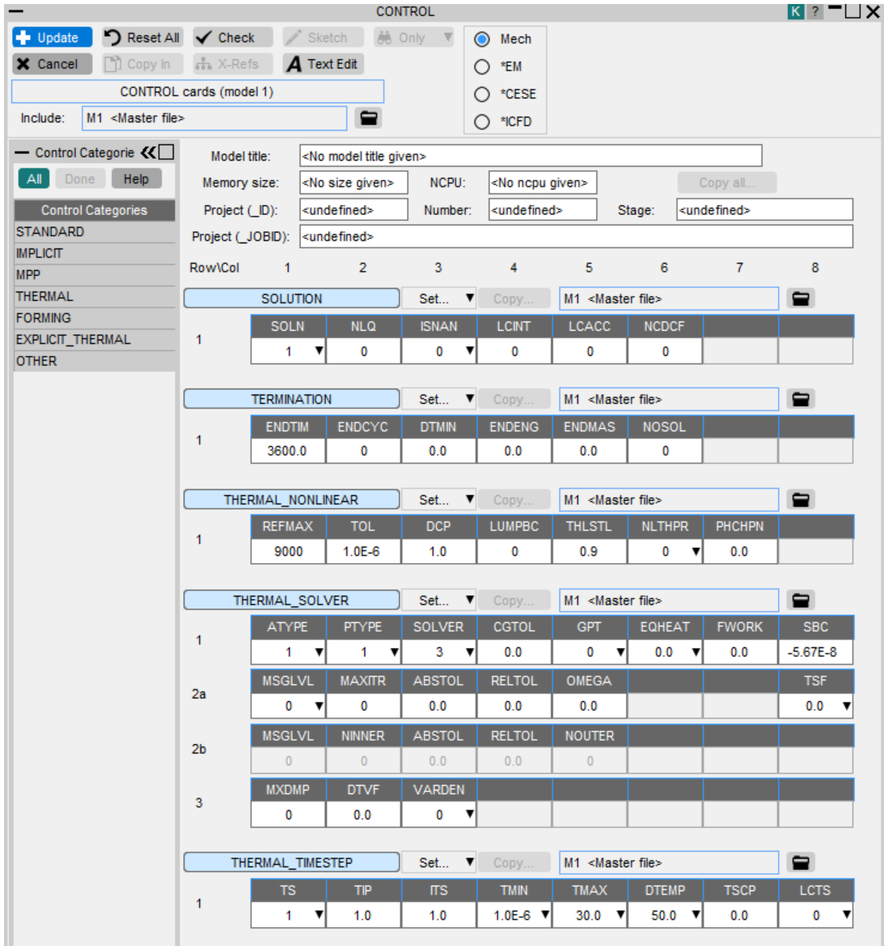


Figure A.4 Control inputs.

The processor used was the diagonal conjugate gradient iterative solver, which has been recommended as the faster solver requiring only non-zero entries in the stiffness matrix, and has been preferred for transient problems [6]. The criteria used by the solver to determine when convergence has been reached, is that the residual error of the matrix operations must be below a tolerance multiplied by the initial residual error. In this case, the tolerance is taken as 1e-6.

Regarding input parameters related to the thermal timestep, the time step control was chosen as a variable timestep, allowing the timestep to increase or decrease. The initial timestep was input as 1 s, with the minimum timestep input as 1e-6 s, and the maximum timestep input as

30 s. The maximum temperature change in each timestep was input as 50 s. These parameters were again chosen as being reflective of the thermal timestep parameters currently used by researchers.

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**Appendix B**: **Structural Repair of Fire Damaged Glulam**

**From:**

Chorlton B, Gales J (2020) Structural Repair of Fire-Damaged Glulam Timber. Journal of Architectural Engineering 27(1). doi.org/10.1061/(ASCE)AE.1943-5568.0000445

## B.1 Introduction and Background

While the main thesis text considered the thermo-mechanical response of timber to fire, another aspect that must be considered in timber construction is how a timber structure might be repaired, should a fire occur. To the authors knowledge, there is little to no information regarding a repair procedure or associated cost for a fire-damaged timber building. This notion prompts the research within this Appendix, in which a potential repair strategy is developed and tested, and associated costs of a hypothetical building repair are discussed.

Recently, there has been a worldwide trend to build increasingly larger and taller timber structures. Timber can be an appealing material choice for its environmental performance, with studies showing that using timber can significantly reduce carbon emissions (by 14-31%) compared to other materials [1]. In Canada, one of the first of these structures was known as the hybrid Brock Commons building, which opened in 2017 and stands at 18 stories (53 m) tall. The Brock Commons building was constructed with Glued Laminated Timber (Glulam) and Cross Laminated Timber (CLT), which was nearly entirely encapsulated in fire rated gypsum board. Since then, changes to the National Building Code of Canada (2020) have been made to reflect the demand for taller timber structures, allowing for 12-storey timber buildings (provided that several requirements are met in these structures, such as requirements over minimum levels of encapsulation) [2]. Given that these tall timber structures will continue to become more common, there remains uncertainty over how these structures may be able to be repaired should they experience a fire. This is important to consider for both building owners, as well as building insurers. For owners, the ability of a structure to recover (repair) from a fire is beneficial for operational resilience. If a structure can be quickly repaired, business can resume quickly, versus lengthy recovery times which may cause the building and businesses to close for some time. As for building insurers, it is critical to have an understanding of the recovery potential of a timber structure after a fire, so that insurance premiums can be balanced with risk.

When timber is exposed to a fire, it begins to decay. Timber is generally considered to char at 300 °C in structural applications [3], forming a char layer. Below the char layer, there is another layer of timber that has been heated to the point where the water may have evaporated and the timber may have degraded, but has not yet fully charred. Simplified methods have been created to assess the capacity of timber members post-fire. Charred areas of the timber are assumed to retain no structural capacity. In addition, a depth of 7 mm (for fire durations of 20 mins and greater, and proportionally less for shorter exposures) is often considered to have lost its capacity as well, accounting for strength loss in timber beyond the char layer [4]. This is known as the zero-strength layer. The remaining portion of the timber member (beyond the char and zero-strength layers) is considered to have retained it's full capacity, effectively creating a 'reduced cross section' member [4]. If the capacity provided by the reduced cross section member is insufficient, replacement or repair of the member may be needed.

Currently, there is little guidance on how structural timber elements may be repaired post-fire and what the associated repair is and what this financial cost may be – particularly in Canada where the author's jurisdiction is and focus. To the author's knowledge, there is no formal guidance on how to repair a timber structural member specifically post-fire. The Canadian standard for engineering design in wood (CSA O86-14) does not directly address how to repair timber sections (regardless of the cause and severity of the damage). It does offer guidelines regarding creating built-up sections, in which the fastening guidelines using nails, bolts, or split-rings are described including minimum spacing requirements and minimum penetration depths [4]. The Institution of Structural Engineers in the UK also offers some suggestions on the repair of fire damaged timber, though repair strategies are broadly described as potentially removing the char and repairing the member using nails, bolts, screws, steel plates or glue, with no formal guidance on the detailing of these repairs [5]. From the limited guidance available, practitioners would likely be required to use their engineering judgement in the design of a repaired timber member. As an aside, it may prove challenging to determine and utilize an appropriate procedure in Canada, as timber education in undergraduate civil engineering programs in Canada is often limited to one course, if any at most universities (see Appendix D). While experienced practitioners may also be able to take on timber repair tasks, the number of available practitioners willing and able to take on such a design may be limited.

Other researchers have proposed different methods of repairing timber structural elements. In all of these cases, the timber elements are not specifically fire damaged. Alam et al. (2009) proposed using steel or Fibre Reinforced Polymers (FRPs) to repair timber elements. In those experiments, 1.8 m long timber beams were loaded to failure using four-point loading and repaired along the tension or compressive face of the beam (as needed) using steel or pultruded FRPs and epoxy adhesives [6]. Alam et al. (2009) found that the repairs provided variable recovery of stiffness, though several repair configurations were effective in restoring the flexural strength of the beams to their original capacity. Morales-Conde et al. (2015) aimed to present a procedure for repairing or reinforcing timber beams using fibreglass and cork plates [7]. Two types of damaged beams were examined, the first being beams whose ends had rotted, and the second being beams with faults in the centre of the beam. The beams had grooves (towards either the side of the beams or the centre depending on the damage) into which the GFRP plates were bonded. The GFRP plates consisted of a cork backing material with two layers of fibreglass fabric. The beams were tested in four-point bending and shear. Morales-Conde et al. (2015) concluded that the repairs of both the shear and moment beams were effective at regaining the beams' original strength [7]. Procedures using GFRPs need to also consider the vulnerabilities to fire, often requiring additional fire protection measures which can increase cost should they be applied in a structure [8].

Ferreira et al. (2017) also proposed a method for repairing timber beams, this time using timber only as the repair material. Four sets of beams were examined; the first with no existing delamination, and the other three with pre-existing delamination in various regions along their length. All beams were tested in four-point loading and then repaired. The repair consisted of plywood sheets applied to the top and the bottom of the beam, attached using screws. Ferreira et al. (2017) also examined the stiffness before and after the repair. The beams with no pre-existing delamination recovered 79% of their initial strength and 81% of their initial stiffness [9]. The beams with pre-existing delamination recovered from anywhere between 86%-249% of their initial strength, and 68%-121% of their initial stiffness (as the repairs compensated for the damage from the previous failure as well as the initial delamination) [9].

While the authors of these previous publications found their methods of repair to be effective to some extent at least, none considered fire-damaged members. Fire-damaged timber is different from timber with mechanical damage or minor defects, in that, for a fire-damaged member, a considerable area of the cross section is lost due to char and adhesive degradation effects [10]. Thus, even following the methods reviewed above may not be sufficient for the repair of a fire damaged timber. Franke et al. (2015) reviewed state-of-the-art methods for repairing and reinforcing timber beams [11]. Franke et al. (2015) recommended replacing the fire damaged member, potentially by propping the beams and removing the damaged section of the beam, which is then replaced by a timber prosthesis connected by rods or plates [11]. This method may be beneficial in many cases; however, it may be costly to perform this repair for timber sections with only minor fire damage. Further, no strict guidance is provided on the requirements of connecting the remaining portion of the timber to the new timber. To the authors' knowledge, there are little to no publicly available documents providing insight into the potential cost of the repair methods proposed above, or other repairs.

Flexure members constructed of multiple materials (or multiple laminates) have the potential to achieve composite action. For instance, solid beams will be able to achieve a certain stiffness and strength. If a beam of the same dimensions and material is sliced horizontally and not adequately fastened together, their strength will be the sum of the individual pieces, which is less than what the capacity would have been of a solid beam with the same cumulative dimensions. This is because design procedures for moment resistance consider the square of the beam height [4]. If the connection is designed adequately to achieve composite action, the resultant capacity can be equal (or greater than) what would be expected from a solid beam of the same dimensions. Repair of timber beams in which a portion of the cross section is removed and replaced with an additional laminate of timber is essentially attempting to take advantage of composite action. Thus, if the repair and the connection are sufficient, it may be possible to restore the member to the serviceability and strength state of the original design.

The research herein examines the potential to recover fire damaged engineered timber members (Glulam) to their original serviceability and strength state. While we address the Canadian context, results may be more universally applied. The results of these experiments are subsequently considered in the analysis of a hypothetical repair of a fire damaged timber building case study to introduce the discussion of repair cost and more importantly future research needs for the reader. The following sections of this manuscript examines the performance of four repaired Glulam members that had been previously fire damaged. The members were repaired by carving out the fire damaged region (affected by char) and replacing the lost cross section with additional timber laminates of the same species, secured with structural screws. All members were loaded and unloaded three times in four-point bending (to a load below the ultimate capacity) to examine stiffness recovery of the repaired members. The Glulam members were then loaded to failure to examine recovery of strength of the repaired members relative to the undamaged control members. This manuscript concludes by recommending additional research needs in the development of repair strategies for fire damaged engineered timber members. This study is, to the authors' knowledge, the first of its kind to explicitly address the repair of timber damaged by fire. This paper therefore serves as a preliminary examination into the repair of fire-damaged timber members, where the experimental program and cost analysis allow for the identification of knowledge gaps that should be addressed through future research to enable the repair of fire-damaged timber structures.

### B.2 Experimental Methodology

The experimental research herein considers six Douglas Fir Glulam members of 16c-E stress grade (fabricated in accordance with CSA O122) [12]. The flexural strength of the beams was calculated from the four-point bending test to be 59 MPa, and the Modulus of Elasticity was calculated as 13 900 MPa (unfactored and determined from beam deflection, and section dimensions). This is above the Modulus of Elasticity required by CSA O122 for the 16c-E stress grade of 11 000 MPa [12]. The density of the Glulam was measured as 605 $kg/m^3 \pm 8$ $kg/m^3$ and the moisture content was measured as 10% ± 0.1%. These members are summarized in Table B.1. The members are of two different sizes, with Members denoted 1, 3 and 5 being 175 x 190 mm, and Members denoted 2, 4 and 6 being 175 x 228 mm. All members were 2532 mm in length (as delivered). The adhesive used in the Glulam members is a melamine-formaldehyde resin.

Table B.1 Summary of Glulam members and previous fire damage.

| Member Number | Size (mm) | Damage State | Maximum char depth (mm) |
|---|---|---|---|
| 1 | 175 x 190 | None (control) | 0 |
| 2 | 175 x 228 | None (control) | 0 |
| 3 | 175 x 190 | Fire damaged with encapsulation | 15 |
| 4 | 175 x 228 | Fire damaged with encapsulation | 27 |
| 5 | 175 x 190 | Fire damaged without encapsulation | 18 |
| 6 | 175 x 228 | Fire damaged without encapsulation | 23 |

### B.2.1 Fire Damage

The non-standard fire exposure used to damage the Glulam members is described in Chapter 4, in a study that examined the performance of fire rated Type X gypsum board applied to Glulam elements in lab and field scales. The test procedure described in the Chapter 4 created a damaged state on the lab scale timber elements, and these are the timber elements that are used in this paper's study. To summarize the damage created for the purposes of this paper: four Glulam members were subjected to an approximately 30-minute methanol pool fire, utilizing 14.3 L of fuel in a 0.48 m (width) by 0.6 m (length) pan. Two of the Glulam members were protected using one-layer of fire rated Type X gypsum board, and the other two were exposed to the fire without fire protection. The members cooled for 30 minutes after the pool fire. The members auto-extinguished (no external flaming) at the end of the heating period but continued to smoulder for the duration of the cooling cycle. At the end of the 30-minute cooling period, light amounts of water were applied to stop any remaining smouldering. Two additional control (undamaged) members will be considered herein, with the members summarized in Table B.1. While Members denoted 3 and 4 were protected using one layer of encapsulation during the fire, from Table B.1 it is seen that they still experienced considerable charring (especially Member 4, which had the greatest char depth even relative to the unencapsulated members). The high char depth of Member 4 is attributed to a smouldering fire, during the cooling phase of testing, under the gypsum board on the side away from the fire. The mechanisms allowing for this, as well as the full details of the fire damage created by the fire testing phase of the study are described in Chapter 4.

**B.2.2 Repair (Carving and Rebuilding)**

As discussed in the introduction, there is little guidance available regarding procedures for repairing damaged timber members particularly in the Canadian jurisdiction. The procedure discussed herein is an adaptation of the available guidance (the procedure set out for built out compression members as per CSA O86-14 [4]), modified where necessary to meet the specific requirements of the test setup. The general procedure is as follows. First, charred and pyrolyzed wood was removed mechanically. Then, panels of the same wood species were attached to the main member such that the panel secured to the bottom of the member spanned the width of the cross-section prior to damage (175 mm). Panels were also fastened to the sides of the member such that the original (undamaged) cross-sectional dimensions were restored by the fastened panels. This procedure was determined in hopes of achieving sufficient composite action to regain at least a portion of the pre-damaged strength and stiffness.

The members were loaded in bending. To the authors' awareness, CSA O86-14 offers no strict guidance on fastening requirements for built-up bending members. Structural screws were selected as fasteners, as previous studies by other authors have found them to be effective in repairing delaminated Glulam [9]. Other fasteners were considered as well. CSA O86-14 lists requirements for using nails, bolts and split rings to create built-up compression members, however, due to the sizing of the main member and the repair panels, the use of these fasteners becomes more difficult. Due to the final width of the section, driving nails to meet the minimum penetration depth becomes difficult, as does creating bolt holes. Further, adhesives could be used, though the use of adhesive requires stricter quality control [9]. Using adhesives also raised concerns regarding toxicity for on site application procedures. The repair procedure was meant to be a procedure that could easily be done on site, and the use of adhesives may require extra safety precautions and additional expense. Therefore, structural screws were selected as the fastener for this introductory research.

CSA O86-14 guidance for built-up compression members using mechanical fasteners (nails and bolts) was followed. In particular, requirements stating that the spacing of the fasteners parallel to the grain would be less than six times the thickness of the thinnest piece, spacing of fasteners perpendicular to the grain would be less than 10 times the fastener diameter, the fasteners would penetrate at least 3/4 of the thickness of the last piece, and there will be at least two rows of fasteners across the member width (due to the thickness of the member and panels) [4]. Therefore, to meet the required penetration length, 5/16" (8 mm) diameter, 6" (152 mm) length screws were used to secure the majority of the panels. The only exception to this was the bottom panels on Members 4 and 6. Due to the height of the member, longer screws were needed to meet the 3/4 penetration requirement, and therefore 3/4" (19 mm) diameter, 8" (203 mm) length screws were used. Due to the limited guidance available, many of the decisions regarding the fastening procedure relied on the authors' judgement for meeting as many of the requirements outlined in CSA O86-14 as possible, while at the same time maintaining a process that could efficiently be implemented in real, fire damaged structures. The configuration of fasteners used in each case created a predicted failure load of at least 1.5 times the predicted failure load of the section. The number and configuration of screws was dictated by the CSA O86-14 spacing requirements rather than capacity requirements in this case.

The char depth of each of the fire damaged members was measured, with the maximum char depths recorded in Table B.1. Any material that was damaged by the fire was removed (the charred layer as well as a pyrolysis layer), assessed visually by colour with the authors' interpretation of the char and pyrolysis layers seen in Chapter 2, Figure 2.7. Multiple researchers were used to concur on colour interpretation but in all cases definition of char depth was subjective but consistent between specimens.

The char depth was removed along the bottom of the members, and the two adjacent sides. This char depth was not removed along the top of the members, as char was not observed along the top of these elements. The damaged length of the member was determined by measuring the maximum length of char at any location along the member and considering that entire region to be damaged along all three sides. This, in theory, removed a greater area of the cross section than was necessary, however removing less than this would create an uneven length removed across the three sides, making the repair more complicated and less visually appealing. The carved (and eventually repaired) regions for each side of the damaged members are seen in Table B.2.

Table B.2 Carved and repaired area for each member.

| Member Number | Depth x length of area carved and repaired along bottom (mm) | Depth x length of area carved and repaired along side (mm) |
|---|---|---|
| 1 | 0 | 0 |
| 2 | 0 | 0 |
| 3 | 15 x 504 | 15 x 504 |
| 4 | 27 x 582 | 27 x 582 |
| 5 | 12 x 1128 | 18 x 1128 |
| 6 | 23 x 1110 | 23 x 1110 |

The carving procedure consisted of using a saw to create guides of a specified depth along the damaged region of the members. The majority of the damaged material was then removed with a chisel. A belt sander was then used to create a smooth and uniform surface, precisely to the desired depth. A carved member before repair is seen in Figure B.1 (where the sides of the member are parallel to the floor, and the bottom is towards the camera.

The members were repaired using new laminates of timber of the same species and equivalent grade (per NLGA Standard Grading Rules for Canadian Lumber [13]). The panels were cut to the appropriate size and planed to the appropriate depth, such that they would fit in the areas that were previously carved out. The panel along the bottom of the member spanned the entire width of the member (175 mm), while the panels along the sides of the members were in line with the top of the member, and the top of the bottom panel. This configuration was chosen to maximize the potential to recover strength from the contributions of the bottom panel, where the tensile stresses would be highest. A side panel is seen in Figure B.2.

Figure B.1 Carved member before repair.

Figure B.2 Side of a repaired member.

### B.2.3 Mechanical Loading

All six members were loaded in four-point bending at a rate of 2.5 mm/min (following a modified ASTM D143 procedure for small clear specimens of timber) [14]. The test setup is seen in Figure B.3. Each member was loaded six times, three after carving but before repair, and three after repair. Once each member was carved, prior to being repaired, it was loaded and unloaded three times to a load much lower than its ultimate capacity. After repair, the member was again loaded and unloaded three times to the same load, lower than its ultimate capacity. The six loading and unloading cycles were intended to help look at the recovery of stiffness at a serviceability limit state. Initially, the applied load for these loading cycles was meant to correspond with the theoretical load that would bring the members to their deflection limit, however, these loads were found to be extremely small to the point where differences in deflection between the control members and the carved members (prior to repair) were minimal. Thus, it was decided to increase the load to 45 kN to see a greater difference in displacement, and therefore more potential to recover member stiffness through repair. The 45 kN load was determined experimentally, by loading the members until the load displacement curves began to show a very slight plateau indicating the introduction of plastic deformations (the plateau was defined as the point where the load was being applied at 80% of the rate prior to plateauing). As the intent was not to damage the members, 45 kN was taken as a safe value much below the ultimate capacity of the members (this was eventually found to be at least less than half of the strength capacity of every member). After the loading and unloading cycles were complete, each member was then loaded until failure, and therefore each member was loaded seven times in total.

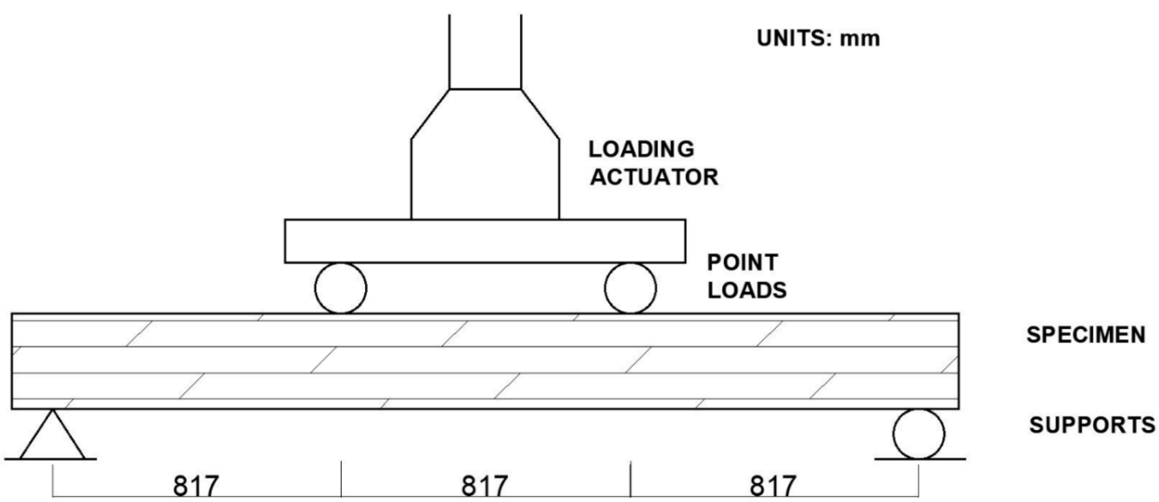


Figure B.3 Mechanical loading test setup.

Digital image correlation was used to analyze the displacements of the timber members, a technology that has proven to be accurate for measuring displacement in wood specimens [15]. A Canon EOS 5Ds camera was used to take images at 5 second intervals (Figure B.4). Members were speckled using white and black paint to create high contrast patterns for the GeoPIV RG software to track and analyze the test images [16].

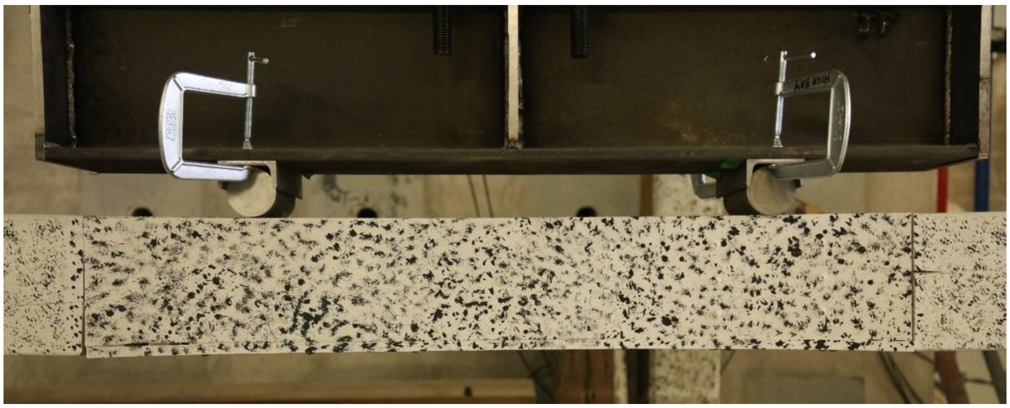

Figure B.4 Photograph that could be used in digital image correlation analysis, showing test setup and speckled pattern paint.

**B.3 Experimental Results**

The results of loading the members to 45 kN are seen in Figures B.5 and B.6. Note that in Figures B.5 and B.6, each data set represents the average of the three trials, where shaded areas represent standard deviation across trials. It should also be noted that in Figures B.5 and B.6, the displacement determined is from digital image correlation, and the force is the total force from both point loads. Figure B.5 shows that the members which were originally smaller in cross sectional area (Members 1, 3 and 5) saw a significant recovery of stiffness. Member 5, which was previously directly exposed to the fire and had more extensive damage (and therefore a greater repaired area), deflected 5.1 mm less once repaired (versus when carved), bringing the total repaired deflection to only 1.4 mm more than the control member. Member 3 which had a smaller repaired area had 1.2 mm less deflection than it did prior to repair. Because the initial degree of damage of the carved member had a deflection not significantly greater than the control member, the repaired member had less deflection than the initial control member.

For both Members 4 and 6, the maximum deflections of the repaired members have been reduced compared to those of the carved members. Member 4 saw a maximum deflection of the repaired member 0.7 mm less than that of the carved member, and Member 6 saw a maximum deflection of the repaired member 2.7 mm less than the maximum deflection of the carved member (about 30% of the total deflection of the carved member). In the cases of both these members, however, the repaired members were not able to return completely to the deflection observed by the control members.

Figure B.7 depicts the force displacement curve of each member loaded to failure (where again, displacement is from digital image correlation and force is the total force from both point loads). This figure shows that the control members were able to achieve a higher force than the repaired members, with all repaired members holding only 49 - 66% of the force that the control members were able to withstand. Members were not loaded prior to carving, however existing work examines the flexural performance of laminated timber members at high temperatures (see Chapter 6, Chapter 7, and [17–19]).

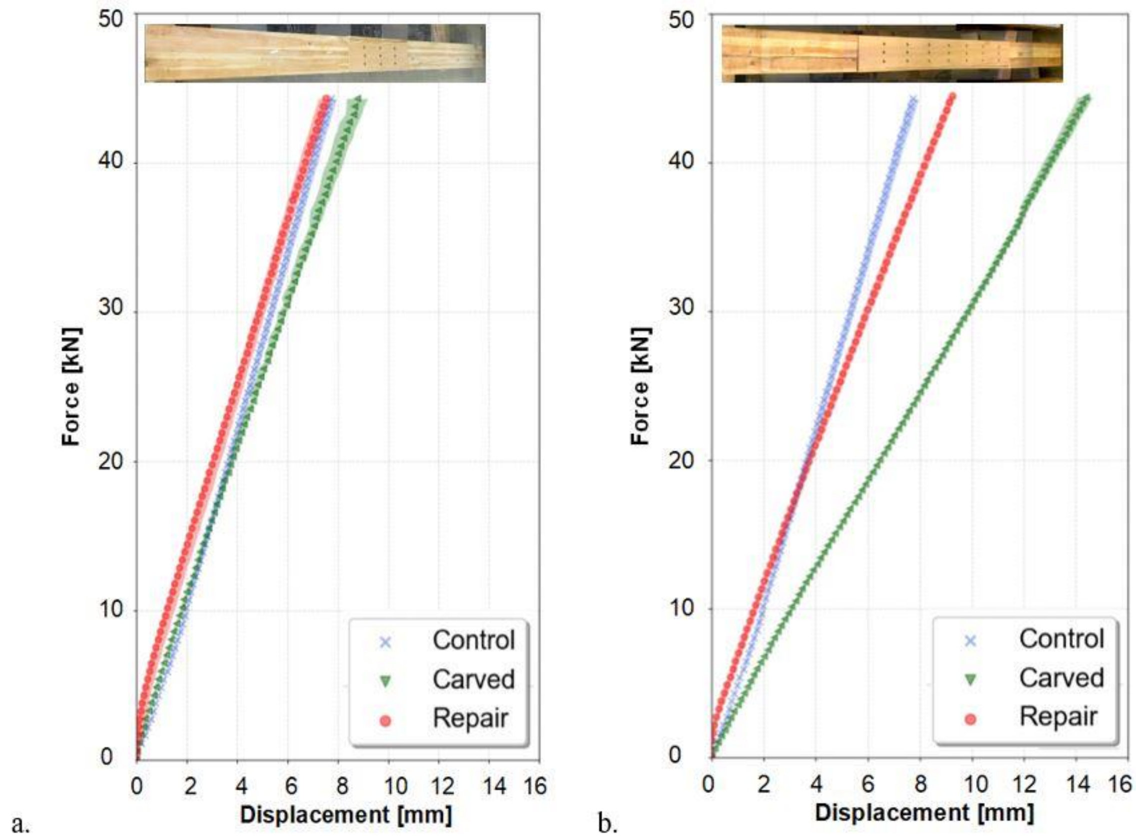


Figure B.5 Loading and unloading of the members of 175 x 190 mm cross section, a. Members 1 (control) and 3 (previously encapsulated), and b. Members 1 and 5 (previously exposed).

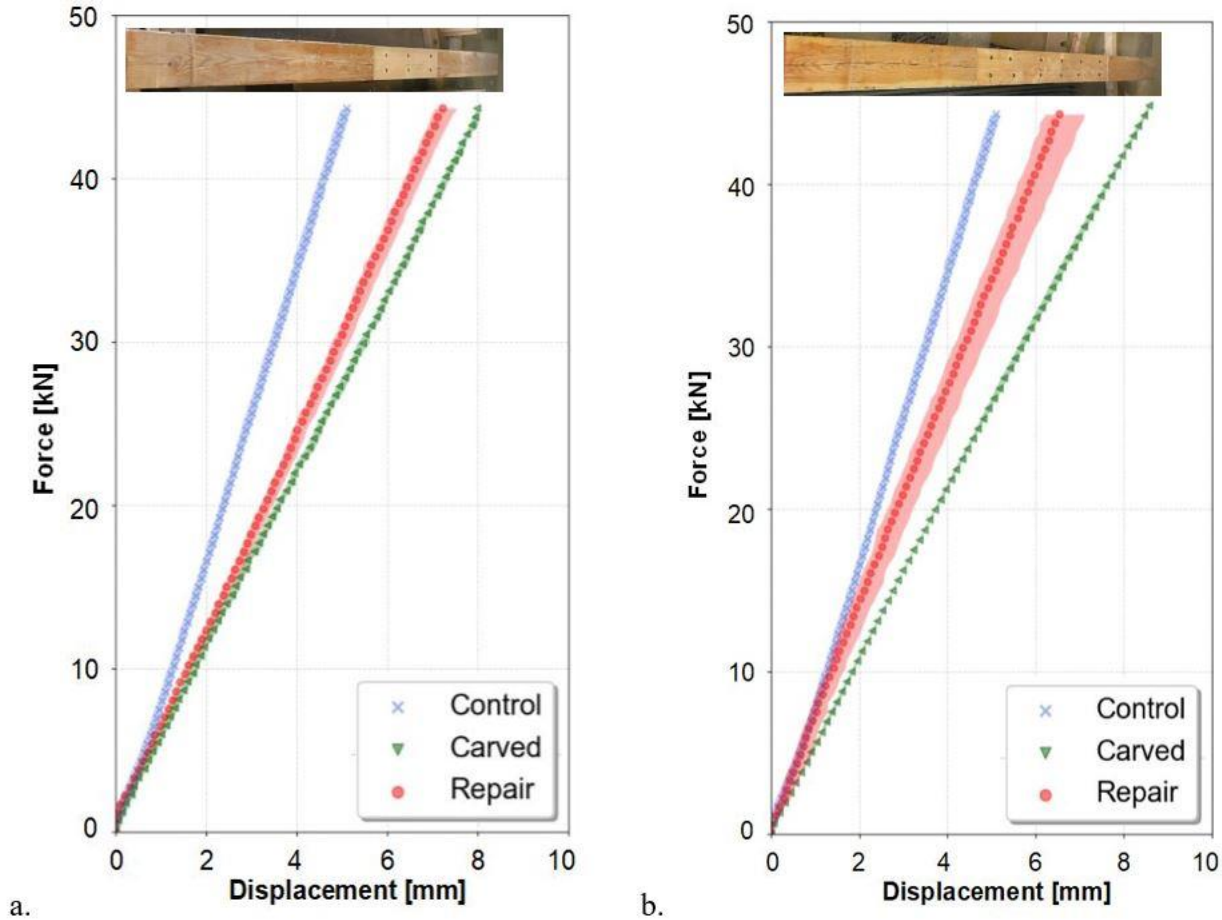


Figure B.6 Loading and unloading of the 175 x 228 mm cross section members, a. Members 2 (control) and 4 (previously encapsulated), and b. Members 2 and 6 (previously exposed).

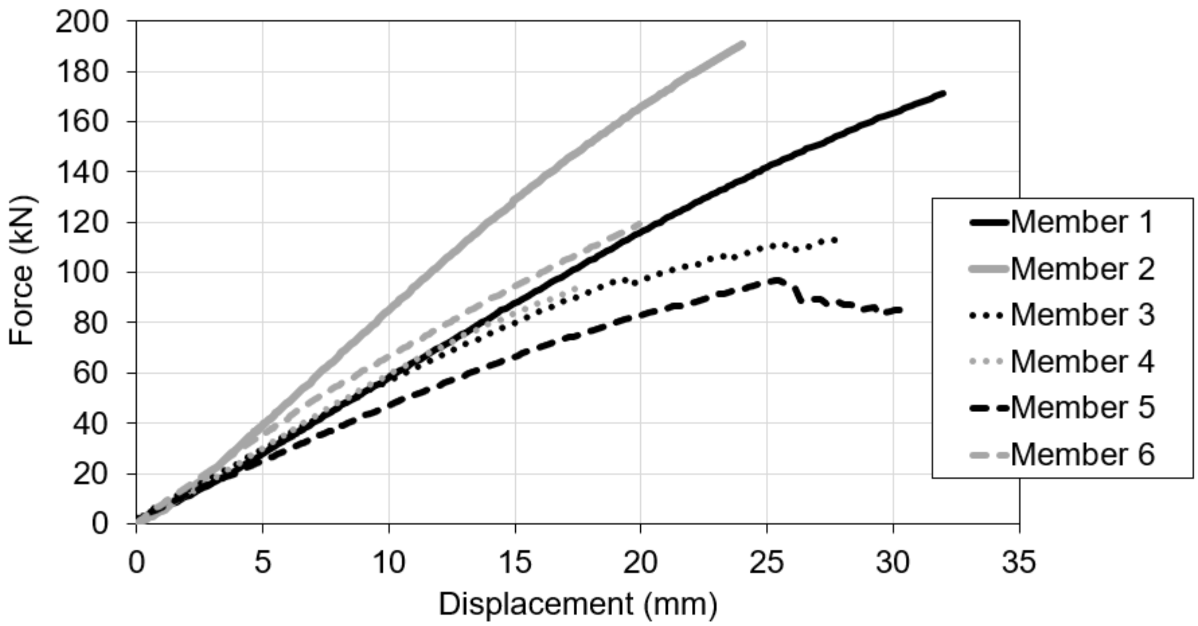


Figure B.7 Each member loaded to failure.

## B.4 Discussion

While none of the repaired members were able to achieve the strength capacity of the control members, all members were able to achieve well over the strength calculated by the CSA O86-14 procedure for Glulam bending members. Calculated and actual failure loads for all members (after repair) are seen in Table B.3. All members failed at a load of at least twice greater than predicted by CSA O86-14. Thus, even the repaired members that did not achieve the strength of the control members still held a considerable amount of strength relative to the predicted strength of CSA O86-14.

Table B.3. Calculated and experimental failure loads

| Member | Calculated Failure Load (kN) | Experimental Failure Load (kN) |
| --- | --- | --- |
| 1 | 31 | 171 |
| 2 | 45 | 191 |
| 3 | 31 | 113 |
| 4 | 45 | 93 |
| 5 | 31 | 96 |
| 6 | 45 | 119 |

One aspect that must be considered when analyzing results is the grade of the members, which was 16c-E. Typically this grade is used for compression members, however, in this instance the members were tested in bending. The grade of the members will therefore affect the overall performance, and members whose grades are meant to be loaded in bending may perform better in this test setup. Members were loaded in bending as opposed to in compression, however, as through the bending test setup information about elasticity could be deduced as opposed to information solely about axial performance. Moreover, lateral loads can be present in real structures which will induce bending in the columns.

### B.4.1 Members 3 and 5

From Figures B.5 and B.6, it is seen that in all cases, the repaired members were able to recover some stiffness compared to the carved members, although to varying degrees. The repairs of the members which were smaller in cross section (Members 3 and 5) both resulted in significantly less deflection compared to the carved members. Member 3 was able to regain sufficient stiffness such that the deflection of the repaired member was less than the deflection of the carved, and even control member. Maximum deflections of all members are seen in Table B.4. The relatively strong performance of Member 3 may be due in part to the notion that the carved member did not deflect significantly more than the control member. When the repair was performed, the increased stiffness was sufficient in enabling the member to deflect even less than the control member. Moreover, Member 3 was the repaired member that held the greatest percentage of the failure load of the control member of the corresponding size (66%). Thus, while the member regained a promising amount of stiffness when loaded to 45 kN, it still failed at a lower force than the control member.

Table B.4. Maximum deflections of members after carved (before repair), and after repair when loaded to 45 kN.

| Member | Maximum Deflection Carved, before Repair (mm) | Maximum Deflection after Repair (mm) | Difference between Carved and Repaired (mm) | Difference between Carved and Control (mm)[a] | Difference between Repaired and Control (mm)[a] |
|---|---|---|---|---|---|
| 3 | 8.9 | 7.7 | 1.2 | 0.8 | -0.4[b] |
| 4 | 8.0 | 7.3 | 0.7 | 2.9 | 2.2 |
| 5 | 14.5 | 9.4 | 5.1 | 6.4 | 1.3 |
| 6 | 8.7 | 7.0 | 1.7 | 3.6 | 1.9 |

a- Members 3 and 5 with respect to control Member 1 (deflection 8.1 mm), and Members 4 and 6 with respect to control Member 2 (deflection 5.1).
b- Repaired Member had less deflection than control.

Member 5 also experienced significantly less deflection (35%) when repaired versus at its carved state. This large recovery in stiffness could be due to the relatively lengthy area of repair, as 1128 mm was carved away and repaired along three sides of the member. The repair therefore comprised of a significant amount of material, allowing for a significant regain of stiffness.

The failure load of Member 5 was 57% of the control failure load. This is less than the capacity of the other repaired member of the same size (Member 3 that failed at 66% of the control load). One factor that could have played into the low failure load of Member 5 (relative to Member 3) was cracks that were present along the side of the member (primarily along the adhesive lines). These are seen in Figure B.8 and were present after the fire exposure of the member (before any mechanical loading). While this crack or delamination may have a different effect on the structural performance of the member if loaded in compression (as is typically done for Glulam members of 16c-E stress grade, where cracking can impact the moment of inertia reducing buckling capacity of some columns), it will also impact the member tested in bending. The presence of these cracks may have reduced the capacity of the member and made it more difficult to achieve composite action. The effect of cracks and delamination in Glulam members is also something that needs to be considered with regards to repair. Cracks occur in many timber structures, both historic structures as well as structures that were constructed relatively recently. Cracking and delamination in the column of a contemporary timber structure in Toronto, Canada is seen in Figure B.9, where the structure was constructed in 2015, with the photo taken four years later. The column seen in Figure B.9 shows both delamination along the adhesive lines as well as within the timber itself. The presence of cracks and delamination in timber members complicates both the structural and fire performances of the member, as well as the repair procedure. The effect of cracks and delamination in timber should be addressed in future research, with regards to the structural fire performance as well as how they may impact the repair.

Figure B.8 Side of Member 5.

Figure B.9 A timber column in a contemporary structure.

### B.4.2 Members 4 and 6

As for the members that were larger in cross section, Members 4 and 6, both were able to regain at least a portion of their stiffness. Both these members had a similar char depth (27 mm along the bottom of Member 4, and 23 mm along the bottom of Member 6), though Member 6 had a more extensive damaged length (1110 mm) than Member 4 (582 mm), where the large repaired area could account for variations in performance (Member 6 deflecting less, and sustaining more load than Member 4).

One aspect which could have impeded on the performance of Member 4 (relative to Member 6) is that while the other members auto-extinguished soon after the fuel of the pool fire was consumed, a smouldering fire occurred underneath the gypsum board layer of Member 4. The procedure of the fire exposure included a thirty-minute heating period followed by a thirty-minute cooling period, at which time the fuel had been consumed but the member continued to be observed without intervention. After thirty minutes, the gypsum boards were removed, and light amounts of water were used to extinguish any smouldering. Therefore, although the visible damage was therefore comparable to that of the other members, at least one side of the member was exposed to high temperatures well past the heating period due to the smouldering fire. This additional heating of the member could have caused increased material degradation beyond the char front, such as degradation due to the heating of the adhesives. It is therefore possible that Member 4 may have had additional degradation relative to the other members, resulting in the lower recovery of stiffness and strength.

As seen in Figure B.6b, the repaired trials of Member 6 had the greatest amount of standard deviation. This occurred because in the first of the three trials, the member deflected almost 1 mm more than the second and third trials (which were near identical) and returned to an unloaded position of 1 mm below the initial position. Because the member returned to a position slightly below it's original position, this suggests that during the first loading cycle, the member adjusted slightly in the loading apparatus causing it to move downward by about 1 mm. If this is the case, then the deviation of Member 6 would be greatly reduced once this slight adjustment is considered.

### B.4.3 Improvements to the Repair Procedure

The members tested in this study were loaded in bending after fire exposure. This procedure varies from what would occur in a real structure, where the members would be loaded during fire exposure. When subject to changes in temperature and moisture content, loaded timber members have been found to be affected by creep [17, 20], an effect that would not be observed in members that are heated and then loaded afterwards. This difference is important to note in interpreting the results of this study.

While the repair did somewhat improve the performance of the members, further improvements could be made to the repair procedure in order to fully attain composite action. It is possible that the thermomechanical degradation of the timber contributed to the larger deflections of the repaired members relative to control, however previous studies that have looked at fire-damaged timber beams have not seen as significant of reduction in failure load or increase in deflection in damaged members, relative to control members [21]. The differences in performance between the repaired and control members is therefore largely attributed to the adequacy of the repair procedure. In these tests, the area removed corresponded to the maximum damaged length and depth, however in order to fully achieve composite action, more area may need to be removed. In particular, it may be beneficial to repair a greater length than is charred in order to better achieve composite action. Furthermore, the spacing of the screws followed that of the requirements for built-up compression members from CSA O86-14 (guidance on bending members was not found by the authors, and therefore engineering judgement needed to be used). Additional screws could help to achieve a more developed connection between the main timber members and the added panels. Different types of screws, or different screw embedment lengths could also be investigated. The test series presented in this paper was somewhat limited by the number of members available. If a greater number of members were available, it would have been beneficial to experiment with the effect of different aspects of the repair, such as changing the repaired length, screw type, screw embedment length, and even investigating different fasteners such as adhesives. Each of these aspects needs future research. In addition to improvements to the mechanical repair, there is also a need to fully understand the thermomechanical degradation of engineered timber to accurately determine how much strength has been lost due to the fire exposure. In a real application of the repair of a building post-fire, this may be challenging as the fire exposure may be difficult to quantify in the first place. While the visible damage could be quantified visually by assessing the extent of the charring, degradation beyond the char front may also have occurred including the further breakdown of the adhesives. While zero-strength layers are present in code procedures (such as CSA O86-14) to account for heated wood beyond the char front, previous studies have shown that these allowances may not be conservative [21–23]. This uncertainty makes it difficult to assess the area of timber in need of repair. Moreover, engineered timber and solid timber sections (such as heritage timber) will degrade differently in fire (due to the presence of adhesives in engineered timber), and so the damage induced on a timber section will vary based on if engineered timber or heritage timber is considered. To have an effective method of repairing a fire-damaged timber member, a further understanding of the thermomechanical degradation of engineered timber is still needed. Due to the differences between engineered timber and solid heritage timber, improved repair procedures are needed for both these timber types.

The fire performance of the repaired member must also be considered should another fire occur in the presence of a member that had been previously repaired. The configuration of the repaired members examined in this test series consisted of timber panels secured into the main member via structural screws. Future research is needed regarding the fire performance of the timber panels and main member, as it has been seen that fire may be able to penetrate seams of other materials fastened to timber (as per Chapter 4). Evidently, future testing is required to understand the potential for fire to reach the main member before the side panel has completely charred through. Furthermore, metal screws have the potential to conduct heat into the timber. It has been suggested that exposed steel as a part of a connection can transfer heat into the timber and increase the char rate [24]. Future research is needed to better understand the effect of heat transfer between the screws and the timber.

### B.4.4 Cost Analysis of Hypothetical Building Repair

In addition to practitioners needing guidance regarding how the repair of a timber structure might be carried out, insurance companies also need information concerning how to appropriately balance their premiums for these timber structures. A cost analysis has been carried out on the hypothetical repair of an exposed timber structure if it were to experience char damage from a fire – but also conducted to evaluate research needs required to make an accurate cost assessment. It will be found that due to the assumptions that are needed in this hypothetical example, this example serves primarily as a case study pointing to the research needs regarding what should be done next to improve the repair procedure and determine an associated cost to repair.

For the purposes of this hypothetical example, the assumptions made regarding the setup of this case study include that the columns considered in this case study will be similar to the columns tested, Douglas Fir species of 16c-E stress grade. It will be assumed that the columns will be square and slightly larger than the columns tested, at 415 x 415 mm. One level within a building will be evaluated, assuming a floor height of 3 m. A hypothetical floorplan is considered, consisting of a square column grid with 80 columns in total. This hypothetical floorplan is seen in Figure B.10 (for illustrative purposes only and not to be construed as what is permissible by building codes).

While some columns will be corner and perimeter columns and are therefore likely to have one or more sides not exposed directly to fire, it will be assumed that charring occurs on all four sides of the column. This will be done to be conservative, as previous studies have shown that gypsum board is not always effective at protecting timber from fire (see Chapter 4, [25–27]).

Furthermore, all interior columns are assumed to be unencapsulated and exposed to the fire. This setup is not meant to necessarily reflect what is currently permissible by current code allowances, but to reflect the architectural desire to have exposed timber within tall structures.

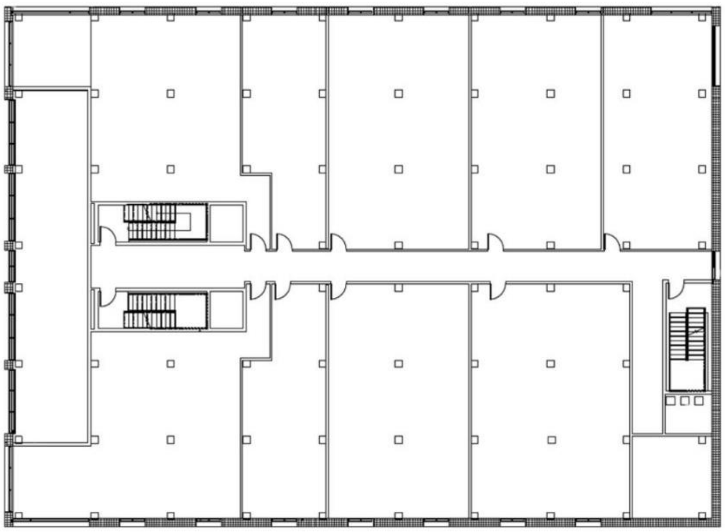

Figure B.10 Hypothetical building floor plan (for illustrative purposes only).

Nine damage cases will be examined. The first three where the fire has been limited to one single column, for durations of 30 minutes, one hour, and two hours. In all cases, it will be assumed that charring has occurred along the entire surface, but the char depth with time is reflective of the standardized charring rate. The charring rate with time is considered arbitrary as a standardized fire is not indicative to a real fire. A standard fire charring rate was chosen for simplistic illustrative purposes. Cases 4-6 will expand the hypothetical fire to one compartment, containing eight columns (taken as the average number of columns in the compartments of Figure B.10, for illustrative purposes) for durations of 30 minutes, one hour, and two hours, respectively. The Cases 7-9 will consider the entire floor of the building (considering 80 columns), for the same heating durations as the previous cases. In this case study, it is assumed that the fire auto-extinguishes and water suppression is not used. If water suppression were to be needed, the damage to the timber may be altered potentially requiring different repair strategies and altering the cost of repair.

The charring rate used will be 0.7 mm/min, as per CSA O86-14 notional charring for Glulam, as well as a zero-strength layer of 7 mm [4]. This charring rate is not necessarily reflective of the charring that would occur in a real structure, which is highly dependant on several factors unique to the fire, the compartment, and the timber itself. Moreover, the zero-strength layer of 7 mm (which as previously mentioned) has raised concerns that it may not always be conservative will nevertheless be considered herein in order to follow CSA O86-14. The charred depths are taken as 21 mm for Case 1 (30 minutes), 42 mm for Case 2 (1 hour), and 84 mm for Case 3 (2 hours), as per the CSA O86-14 charring rate of 0.7 mm/min [4]. A zero-strength layer of 7 mm brings the total depths that would be removed and repaired to 28 mm for Case 1, 49 mm for Case 2, and 91 mm for Case 3. These char depths are thicker than the panels used in the test series in the previous sections of this paper. Thus, for a repair to be carried out at these damage states, future research is needed using panels of these thicknesses. If thicker panels are needed, the beam may have been exposed to a higher severity fire which along with increasing char depth may also increase the thermal degradation beyond the char layer. Thicker panels will be needed to replace a larger area of timber that would be removed, and evaluation would be needed to see if the main member and thicker side panels act as a composite and are able to achieve desired capacity, or if the members are acting separately.

Preliminary costs are seen in Table B.5 (note that no taxes are considered in this analysis). The factors considered in the following cost analysis include the materials, the cost of engineering, and the cost of labour. Not included in this analysis is the time and cost it may take to temporarily support the column’s load while it is being repaired. The floor also may need to be propped up to unload the column for repair. Capital lost due to business discontinuity is also not considered and will vary greatly between specific structures. Engineering and labour hours noted in Table B.5 are based on the length of time taken by the researchers to carry out the experimental test programme described in the Experimental Methodology section of this paper. Material costs are also extrapolated from the repair costs of the test programme described above. Engineering costs per hour have been derived from fee guidelines published by the Ontario Society of Professional Engineers (2015), and construction labour costs per hour have been taken from Statistics Canada (2019) data [28, 29]. Cases 4, 5, and 6, as well as Cases 7, 8, and 9 were identical to Cases 1, 2 and 3, respectively, but were multiplied to consider all columns in the hypothetical compartment or on the hypothetical floor. At this larger scale, it is possible that the cost per unit of the materials may be altered from what is listed. Costs are reflective of a repair conducted in Toronto, Ontario, Canada in late 2019 (costs will vary in other regional jurisdictions and with time).

The costs listed in Table B.5 are the lowest possible costs for repairing timber members using replacement timber panels and structural screws. Since these costs correspond to the test programme described in the previous section which indicated that while some stiffness was regained, an enhanced repair procedure was needed to achieve composite action and regain full strength capacity. More extensive repairs are needed, necessitating increased materials, raising engineering and labour costs, as well as potentially increasing the time it takes for the repair to be completed (further disrupting business continuity). Furthermore, the engineer would need to check that the capacity of the connection is sufficient for the specific situation, which may necessitate a more extensive connection than is accounted for in Table B.5.

Table B.5 Cost of the hypothetical column repair.

| **Case Number** | **Item** | **Quantity** | **Cost per unit ($ CAD)** | **Total Cost ($ CAD)** |
|---|---|---|---|---|
| 1 – 30 minutes, single column | Structural Screws | 216 screws | 4.49 | 969.84 |
| | Timber panels | 0.13 $m^3$ | 3 285.61 | 427.13 |
| | Engineering Cost | 2 hours | 215.00 | 430.00 |

| Case Number | Item | Quantity | Cost per unit ($ CAD) | Total Cost ($ CAD) |
|---|---|---|---|---|
| | Labour Cost | 6 hours | 23.80 | 142.80 |
| | Total Cost | -- | -- | 1 969.77 |
| 2 – 1-hour, single column | Structural Screws | 216 screws | 4.49 | 969.84 |
| | Timber panels | 0.21 $m^3$ | 3 285.61 | 707.09 |
| | Engineering Cost | 2 hours | 215.00 | 430.00 |
| | Labour Cost | 8 hours | 23.80 | 190.40 |
| | Total Cost | -- | -- | 2 297.33 |
| 3 – 2 hours, single column | Structural Screws | 216 screws | 4.49 | 969.84 |
| | Timber panels | 0.42 $m^3$ | 3 285.61 | 1 388.51 |
| | Engineering Cost | 2 hours | 215.00 | 430.00 |
| | Labour Cost | 12 hours | 23.80 | 285.60 |
| | Total Cost | -- | -- | 3 073.95 |
| 4 – 30 minutes, all columns in compartment | Total Cost | -- | -- | 15 758.15 |
| 5 – 1 hour, all columns in compartment | Total Cost | -- | -- | 18 378.64 |
| 6 – 2 hours, all columns in compartment | Total Cost | -- | -- | 24 591.62 |
| 7 – 30 minutes, all columns on floor | Total Cost | -- | -- | 157 581.50 |
| 8 – 1 hour, all columns on floor | Total Cost | -- | -- | 183 786.40 |
| 9 – 2 hours, all columns on floor | Total Cost | -- | -- | 245 916.20 |

Other aspects that may also increase the cost of a building repair but may not be directly related to the structural performance of the timber include the extent of the smoke damage. The structure is likely to need significant cleaning for the smoke damage, which will be dependant on the extent of the fire. A fire investigation may also be necessary which would further increase the repair cost. Finally, as previously mentioned, the repair cost considers the repair of the columns only. Should repair of other members be required, the cost will further increase.

In some cases, it is possible that replacement of timber members may be more economical than repair of timber members. Utilizing the same price per cubic meter of timber as in Table B.5, the cost of a replacement column (materials only) would cost approximately $1700CAD. Even accounting for materials only (not including increased labour costs that would be required to repair), the replacement option is still less expensive that the hypothetical 1-hour and 2-hour exposure repairs. Thus, for severely damaged columns, replacement may be more economical than repair. In some cases, a repair may still be preferred however, which may be due to environmental considerations or instances where the fire damage is mild.

**B.5 Conclusions and Future Research Needs**

Given the motivations for tall timber construction, with these structures becoming increasingly taller, matched with the desire to leave timber structural members exposed, now more than ever there is a need to understand the potential for the repair of fire damaged structural members. Currently, there exists little to no guidance in Canada (and limited guidance internationally) directing practitioners on potential repair strategies, and the lack of existing information makes it very challenging for insurance companies to appropriately balance their premiums for resilience consideration. The experimental test programme and corresponding hypothetical cost analysis presented in this paper provided a first-look at a possible repair technique to be built upon by other researchers, and from which several research needs were identified.

From the experimental test programme, some clear trends were observed across all samples regarding the recovery of strength and stiffness by the repaired members. While the objective of this repair relied on achieving composite action between the main members and the panels installed during repair, which was not entirely achieved as seen by the lower strengths and capacities of repaired members compared to control members, the repaired members still showed some improvement in stiffness. When brought to a load meant to represent a serviceability limit state, all of the repaired members deflected less than when they were carved. One of the repaired members (Member 3) even had less deflection than its corresponding control member. Another example of a significant recovery of stiffness is Member 5, deflecting over 5 mm (35%) less than the carved member after it was repaired. These trends showed that overall, the repair was able to regain a portion of the stiffness lost during damage. With regards to overall strength capacity, none of the members reached the ultimate strength that was carried by the control members, with each member failing at only between 49-66% of the load of its corresponding control member. This indicates the need to further examine possible alterations which may improve this repair procedure, to the point where composite action is fully enabled, and a larger portion of the original strength is recovered.

A hypothetical cost analysis provided a baseline as to what the repair of a fire damaged member might cost, however costs found were an absolute minimum of what might be expected as the costs reflected the experimental test programme, which showed that more extensive repairs may be needed. However, both the experimental test programme and cost analysis were successful in identifying many areas where research still needs to be done to inform a more accurate analysis. Several steps should be taken to further develop the effectiveness of timber repairs post fire and determine the corresponding cost. To develop a possible procedure for repairing fire-damaged timber members, the following research needs should be considered:

- Future studies defining the heat damage done to engineered timber beyond the char layer, such that residual strength can be accurately determined, and the extent of any required repair will be well understood,
- Methods of achieving composite action, including extending the length of repair or altering the connection,
- Different repair configurations, including using thicker replacement panels that may correspond to more severe fire exposures, as well as using different fasteners including adhesives,
- Testing of repaired members through a variety of mechanical loading test setups (including loading in compression), as well as creating induced fire damage through a variety of heat exposures,
- The possibility of heat transfer between the timber and the screws (or other metal connections) which may alter the charring or damage to the timber,
- The effect of pre-existing cracks as well as delamination on both the structural and fire performances of timber member,
- Once a repair procedure is established, the fire performance of the repair configuration should be studied.

Further research on each of these elements would be beneficial in the development of an effective repair procedure, and consequentially the determination of the associated cost would then follow.

**Acknowledgements**

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## Appendix C: The Effects of Radial Cracks on the Fire Performance of Heritage Timber

### As Submitted for Journal Publication:

Harun G, Chorlton B, Richter F, Gales J (2021)

## C.1 Introduction

Timber is a common building material found in historical buildings in Canada and across the world. The value of heritage buildings comes from historic, scientific, aesthetic, cultural, social, or spiritual importance which are physically represented by their character defining elements [1]. In Canada, historical buildings with value are protected from major changes with heritage designations which classify them as heritage buildings. The original timber elements within heritage designated buildings are often character defining elements due to their representation of historic building techniques (having both historic and scientific value), their cultural association with Canadian architecture and their aesthetic value. Therefore, retaining the timber structure of a building with minimal intervention in turn preserves the value of the heritage buildings.

A number of heritage structures have experienced losses due to fire. A recent example of this is the fire of the Notre Dame Cathedral in Paris on April 15, 2019. The timber attic (which dated back to the 13th century [2]) and the spire (which dated to the 19th century) collapsed and were destroyed in the fire [3]. Further illustrating the vulnerability of heritage structures to fire is the fire at the National Museum of Brazil on September 2, 2018. In addition to the loss of invaluable artifacts, the structure itself was historically significant as previously serving as royal and imperial residences [4]. The fires at the Notre Dame Cathedral in Paris and the National Museum of Brazil exemplify the intangible value that can potentially be lost to fire and demonstrate the high-level of community support for heritage structures, not to mention the €300-600 million [5] (US$330-670 million [6]) and US$125 million [7] estimated costs for rebuilding the Notre Dame Cathedral and the National Museum of Brazil, respectively. The aforementioned fires were high profile events, but data collected by Historic England noted that in 2018 in England, over 350 fires occurred in heritage structures with 40 causing serious damage [8].

There is limited guidance available in standards and codes on heritage timber in fire. Comprehensive guidance on the overall protection of a heritage building is provided in the NFPA 914: Code for the Protection of Historic Structures, however there is little information regarding material performance [9]. The NFPA 914 references the Guideline on Fire Ratings of Archaic Materials and Assemblies report by the National Institute of Building Sciences (U.S.) for material performance in fire [10]. The report provides fire ratings of archaic assemblies, however the number of assemblies listed is limited, and it is therefore difficult to accurately extend these results to other scenarios. Another available document is the Institution of Structural Engineers' Appraisal of Existing Structures (U.K) which applies to all existing buildings, therefore not limited to heritage buildings [11]. To determine the fire properties of timber, it suggests referring to Eurocode 5: Design of Timber Structures which targets contemporary timber products [12]. To the authors' awareness, there is no direct guidance regarding fire performance for practitioners who deal with heritage timber.

This lack of guidance coupled with conservation guidelines that value minimal interventions leads to practices that are unproven. For example, a key factor that effects the fire performance of all timbers is the presence of radial cracks. Radial cracking from shrinkage (checking) occurs with significant reductions in the moisture content of timber. These cracks can penetrate deep within the cross section of the timber member. Significant changes in moisture content usually occur when there are changes in use or occupancy of the building, or during renovations when the building is not conditioned as usual. There is little information currently available regarding how these radial cracks within timber will affect a timber structural element's fire performance. Often one fills the crack in-situ to negate any potential reductions in fire resistance, as seen in Figure C.1. Products known as wood filler and wood putty are readily available and advertise the ability to repair cracks and surface defects on wood. These attempted repair practices have insufficient evidence to support their use for fire performance purposes and can unduly compromise the architectural appearance of a timber structure.

Figure C.1 Partial attempted sealant repair on a radial crack present on a column (author's photo).

A limited number of studies have previously investigated heritage timber, including the studies outlined in Chapter 3 and Chapter 5. Improving the understanding of the fire performance of heritage timber members is a key step to conserve heritage timber structures. The purpose of this study is to evaluate the effect of existing radial cracks on the fire performance of heritage timber. Full scale timber members were removed from a historic building and subjected to a pool fire. Charring around pre-existing radial shrinkage cracks was considered, as well as the extent of the cracks change in size during testing. Further, small scale Cone Calorimeter tests were examined in which charring around pre-existing cracks was also considered, as well as time to ignition and heat release rate relative to solid (non-cracked) samples. The results of this study will provide an understanding of the impact of radial cracks on the fire performance of heritage members, such that when encountered in practice, stakeholders can make informed decisions to ensure that timber members are meeting the required fire performance, while at the same time avoiding unnecessary intervention.

## C.2 Background

### C.2.1 Cracks in other Structural Materials

Ervine et al. (2012) considered thermal propagation through tensile cracks in reinforced concrete, by loading concrete beams in four-point bending to induce tensile cracks of varying severity, and then using a radiant panel at 35 $kW/m^2$ to heat the beams which had embedded thermocouples [13]. Two damage states were induced, minor damage cracks (surface and rebar level crack widths of approximately 1 mm and 0.5 mm respectively) and major damage cracks (surface and rebar level crack widths of approximately 5 mm and 3 mm respectively). Ervine et al. (2012) noted that temperatures around cracks were only marginally higher than in uncracked regions, and attributed temperature differences to the curvature of the beams caused by loading, concluding that cracks up to 1 cm at the surface did not significantly change thermal propagation in concrete but larger cracks may potentially contribute to more rapid heating [13].

Studies regarding the effect of cracks on the fire performance have not reached a consensus, however. Liu et al. (2021) tested four concrete beams with embedded thermocouples and with manually induced mechanical cracks of 0.5 mm, 1 mm, and 3 mm [14]. Furnace testing was carried out following a temperature-time heating curve, and it was found that the temperatures were higher in cracked concrete. Liu et al. (2021) attempted to characterize heat transfer across the crack, attributing heat transfer in the cracked region to be primarily of conduction. Liu et al. (2021) also concluded that the moisture content affected the temperature field, with water absorbing a large amount of heat, the mechanism to which Liu et al. (2021) credited the varying results of different researchers [14].

From the above literature related to tests of cracks in concrete, differences in methodology included the heat source (radiant heat vs furnace testing), as well as the crack creation (through bending vs manually created).

**C.2.2 Thermal Degradation of Timber**

When timber is heated, it begins the processes of dehydration, pyrolysis, and oxidation. During pyrolysis, the timber polymer chains are broken to form char and flammable volatiles, with the volatiles diffusing towards the surface where they ignite. The ignition of the timber can cause further charring of the timber, to the point at which either the char layer becomes thick enough to slow the heat transfer from the fire to the remaining timber to a point where the rate of charring becomes insignificant or the material has completely charred [15]. Cracks within the charred region have been shown to alter the heat transfer mechanisms of timber, for example that cracks allow volatiles to escape more readily [16].

Moisture content of the timber begins to evaporate around 100°C, with some water moving further into the sample and recondensing, and bound water is freed later [17]. A review by Friquin (2011) concluded that most studies correlated increased moisture content with decreased charring rates [18]. Moisture acts a heat sink and slows the temperature rise of timber as well as cools the pyrolysis zone through convective transport of water vapour [19].

Timber’s performance in fire varies from that of concrete in that when it is exposed to severe enough thermal exposure, it will begin charring. Thus, there is the potential for the shape of the crack to widen and/or lengthen during thermal exposure, a property unique to timber. To the authors' awareness, there are no currently published studies conducted with the primary purpose of understanding the effects of radial cracks on the fire performance of timber.

## C.3 Methodology

It should be noted that while the timbers tested are from historical buildings, not designated (listed) heritage buildings, they are representative (having similar age and conditions) of the timbers found in heritage buildings. Therefore, the historical timber discussed herein will be referred to as heritage timber for the purposes of this study.

The testing presented herein is separated into two phases. The first phase considers full scale heritage timber members, and the second phase considers small-scale Cone Calorimeter tests. Prior to testing, material collection of historic samples was needed, which presents specific challenges with heritage testing therein a detailed methodology for collection is provided.

The novel research in this publication builds upon preliminary work initially presented at a conference by Harun et al. (2020), that covered only observations made during full-scale fire testing of the heritage members. Post-fire analysis of the full-scale members and the small scale test programme were not included at that the conference stage in the study [20] and are discussed herein.

### C.3.1 Material Collection

The timber material was collected from a former industrial building in Toronto, Canada, built in 1905. The material acquisition occurred during the partial deconstruction of the building to accommodate a new high rise on the site that will incorporate a small portion of the original façade. The building was a 6-storey brick masonry structure with interior elements made of timber and steel, the timber elements tested herein were found on the upper (5th and 6th) floors as seen in Figure C.2. Its original use was industrial but had been converted to commercial office space for contemporary use. The timber members were encapsulated at the time of deconstruction, as observed by the authors, which is common with heritage timbers. The first National Building Code in Canada, published in 1941, limited combustible construction to 4 storeys which terminated the construction of high rise timber structures [21]. For the 6-storey building, it can be assumed that the timber on the upper levels was encapsulated sometime after 1941 to comply with building codes of the time, hypothesized by the authors after the change from industrial to commercial use.

Figure C.2 Material acquisition from industrial building in Toronto, Canada (by permission).

Collecting viable heritage materials for destructive testing presents unique challenges concerning limited access to materials and their conditions. The larger timber members used in high rise construction (between 5-8 storeys) can only be found in buildings built before 1941 in Canada, which contributes to their rarity. Additionally, they are often found in designated heritage buildings that are protected from removal or demolition. The heritage materials must also be in serviceable condition, so any materials from buildings being demolished due to deterioration are not representative of heritage timbers in use, and therefore cannot be used. Members that have been stored outside during renovation or deconstruction projects can also be subjected to damage from moisture and/or pests and become structurally compromised after removal. Figure C.3 shows unsuitable storage of materials of a different site found in Canada where the authors rejected other samples. These considerations exemplify the difficult to study nature of procuring in-situ testing of older material specimens and the need to provide guidance on material collection for other practitioners.

Figure C.3 Improper storage of heritage timber materials (by permission).

The deconstruction of this building for redevelopment, not due to structural issues, was vital to the collection of sound heritage materials that are representative of materials in service in other heritage buildings. The deconstruction allowed for the authors to coordinate with the demolition company to safely remove the timber elements in serviceable condition and not induce any structural cracking of the members. The proper handling of the timber after collection was ensured as not to foster additional crack formation due to abrupt and sudden moisture changes or mechanical damage. The members were not exposed to the elements before they were removed from the structure, and they were stored inside a humidity conditioned space after procurement. Members were documented on arrival to the lab to ensure any shrinkage effects caused by handling and transportation were documented. In this case there were no visible differences.

Three heritage timber members collected from site were considered in this test programme, two that were subjected to heating (described in the next section), and one as control. The three members had identical dimensions, as presented in Table C.1, and were used as columns in the original building. The timber was of Pine species, commonly found in heritage stock in Ontario, with a density of 657 kg/m$^3$ and a moisture content of 6.6% as measured from oven-controlled heating. This equilibrium moisture content corresponds to the low end of accepted relative humidity [22]. Charring rate has been shown to have a general downward trend with increasing moisture content (where the degree of correlation has not seen agreement among researchers [18,23,24]), though other parameters such as density and species are thought to have much greater influence on the charring behaviour of the timber [17].

Table C.1 Timber members tested.

| **Member ID** | **Initial Dimensions (mm)** | **Description** |
|---|---|---|
| Heritage 1 | 185 x 185 x 4280 | Charred |
| Heritage 2 | 185 x 185 x 4280 | Charred |
| Heritage 3 | 185 x 185 x 4280 | Control |

### C.3.2 Full Scale Tests

Heritage 1 and 2 were tested in a 30-minute methanol pool fire with soffit temperature in excess of 800°C and allowed to cool for another 30 minutes. The test setup is seen in Figure C.4. Narrow spectral illumination (as described in [25,26]) was used to filter out the flame in photographs that were taken throughout the test so that visual observations regarding changes in the cracks along the surface of the timber could be made. Methanol was chosen as a fuel as the authors considered other fuel types (including acetone and kerosene), but the soot in the fires of the alternative fuels obstructed the view of the specimens when using narrow spectral illumination. For each 30-minute fire exposure, 14.3 L of fuel in a 0.48 m x 0.6 m pan was used to create the desired fire exposure.  The process for determining the most suitable fuel type and volume is detailed in Chapter 4. At the end of the 30-minte cooling period, the members had auto-extinguished with no external flaming. Light amounts of water were used at the end of the 30-minute cooling period to extinguish residual smouldering.

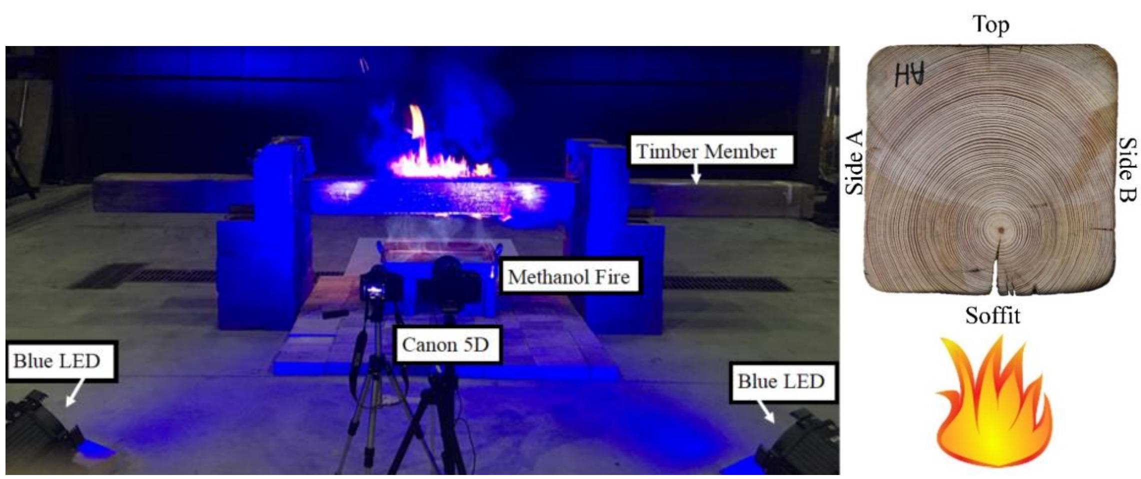


Figure C.4 Experimental test setup for pool fire, view of beam Side B.

A pool fire was selected instead of a radiant heater for this phase of testing. The primary purposes of using a pool fire over a radiant heater include inflicting both a radiative and convective heating component that could be seen in a real fire as opposed to just predominantly radiation. This was also to avoid thermal bowing effects that would influence the degree of exposure that could be seen if a radiant heating panel had been used. The thermal exposure would have mostly been inflicted on the side of the member facing the heater only. If only one face of the member was heating up and dehydrating, a bowing effect could have been created where the timber member bows away from the heater, making it more difficult to characterize thermal exposure over time as the radiation is proportional to the distance from the source. A pool fire was used in part to allow more sided exposure but is acknowledged not standard nor of a real exposure. The chosen exposure, however, allows for controlled observational study of heat induced damage.

A furnace test [27] was also not practical for this type of study as one of the aims to using a pool fire with narrow spectrum illumination was to create a repeatable thermal exposure in which the changes to the material deformation can be tracked during the test. This test setup has also been seen previously in Nicoletta et al. (2020), where narrow spectrum illumination was used to monitor strain in steel stay-cables during a 30-minute methanol pool [28]. Chapter 4 used a similar test setup consisting of a methanol pool fire and narrow spectrum illumination technology to monitor material changes of fire-rated gypsum board as applied to timber. Both previous studies used this technique to discuss heat induced damage during a fire, and this technique has provided repeatable and effective results in creating a representative fire exposure of up to 800 °C. These previous applications establish the basis for the test setup and parameters herein, where a similar objective is set out (examining the damage induced on heritage timber during a fire, and in particular the effect of cracks).

While the members were used as columns while in-service, they were exposed to fire while rotated horizontally. The purpose of this orientation for the fire exposure was to create a localized fire exposure in one region of the member, without creating a thermal gradient as could be done if the member were oriented vertically with a pool fire at the base. The primary purpose of this fire exposure was to examine charring around the crack, and this orientation provides a consistent fire exposure along the exposed region. Moreover, this setup ensures that the heat transfer and charring will be perpendicular to the grain which is more likely to be seen in a real structure fire (rather than charring along the grain).

Following the pool fire tests, the members were then subjected to a four-point bending test until failure, in accordance with loading rates from ASTM D143 of 2.5 mm/min [29]. The loading rate is also inline with ASTM D198 [30]. An MTS 244 actuator with a 250 kN capacity was used for loading, and the actuator was calibrated to verify its accuracy post testing. Members were not loaded while simultaneously being heated as the primary goal of this research was to understand the effect of radial cracks on charring, not to determine the in-fire strength of heritage members. Thus, the members were loaded after fire testing. The loading of the members after being exposed to fire provides some insight as to the fire performance of heritage members as well as the effect of pre-existing cracks. Moreover, these tests give insight as to the post-fire strength of a heritage timber member, critical to understand in the recovery of a heritage timber structure that had previously experienced a fire.

While the members were used as columns while in service, they were loaded in bending. This allowed for information about elasticity to be deduced from the bending tests, rather than axial performance only (if they had been loaded in compression). In addition, lateral loads (earthquakes and wind) can be present on real structures columns, therefore loading these columns in bending was practical.

The test setup and char depth on the member at different points can be seen in Figure C.5. In addition to the members tested in fire (Heritage 1 and 2), one uncharred heritage member (Heritage 3) was included in the test program as a control member. From Figure C.5, it can be seen that the charred portion of the member is not always centred within the loading apparatus. This is because the charred portion was not always centred along the length of the member, even though the pool fire was centred. During the heating of Heritage 1, the center of the ignited portion of the beam deviated from the center of the pool fire by 194 mm. Figure C.5 also shows the camera set up and black and white speckled pattern along the member, used for monitoring deflection through digital image correlation. A Canon EOS 5Ds camera was used to take photos at five second intervals throughout the loading of the members, and the black and white pattern provided high-contrast points. Deflection was then computed using digital image correlation software (GeoPIV RG) [31], a technique shown to be accurate for monitoring displacement in wood specimens [32].

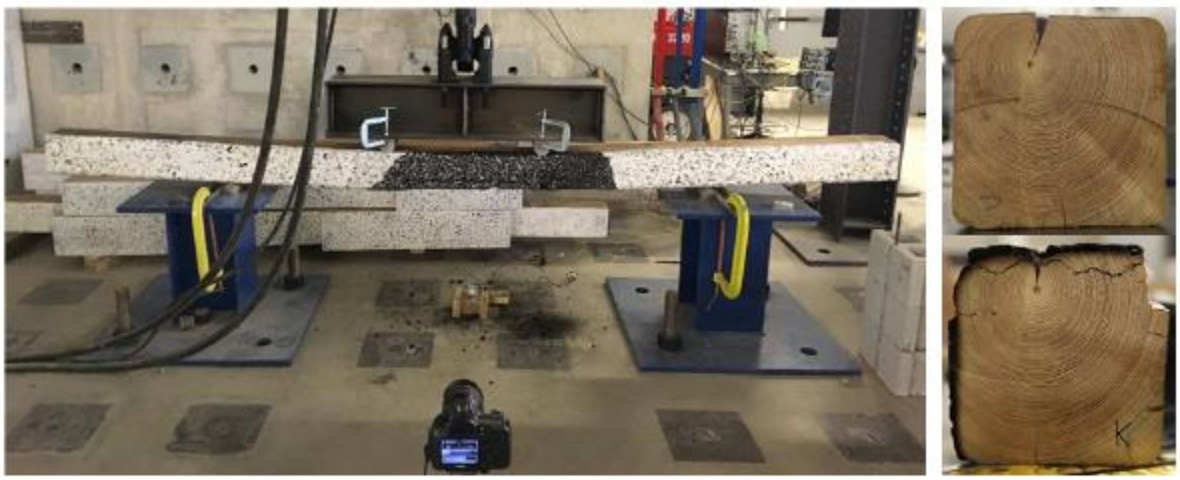

Figure C.5 Loading test setup (left) and member cross section slices (right, top- towards the end of the member, bottom- towards the centre of the member).

After the timber members were loaded until failure, they were cut into 50 mm segments along the length of the member, so that the char depth could be measured along the length of the member. Char depth was determined by measuring the portions of the cross section that were not visually black by colour and subtracting those dimensions from the initial dimensions of the member. Two of these slices, showing the cross-sectional area of the heritage timber including a radial crack propagating from the top of the member towards the pith, are shown in Figure C.5.

The cross sections are vital to evaluating the char penetration into the crack present in the timber as a result of the fire test.

### C.3.3 Cone Calorimeter Tests

Using the same heritage timber from the testing program described above, Cone Calorimeter tests were conducted to further study the effect of radial cracks present in heritage timber. The Cone Calorimeter utilizes a coiled radiant heater for thermal exposure. As previously mentioned, in larger members, using radiant heaters to create a radiant heat flux along one face of a timber member can create an upwards bowing effect through de-hydration of the material. The sample holder and small size of the Cone Calorimeter minimizes this effect, and thus the Cone Calorimeter offers an opportunity to consider radiant heat only where the bowing effect will not significantly affect the results.

Rectangular prism samples of 100x100x80 mm were cut from the end of Heritage 2, which would have seen minimal to no thermal exposure and minimal mechanical degradation. Half of the samples (four) contained a radial crack, and half (four) had no or very minimal cracking (maximum crack widths of less than 2 mm). The Cone Calorimeter tests are summarized in Table C.2. The number of samples that could be tested was limited to the available quantity of undamaged timber, where a sample could be cut with a crack down the centre. This reinforces the challenges and uniqueness of testing heritage timber, as tests are largely limited to the availability of acceptable timber samples.

For specimens with a radial crack, the initial crack width along the surface of the member varied from 8-11 mm and the crack depth was 45-46 mm (extending from the surface of the crack to the timber's pith). Exact crack width was not identical across all samples as the cracks were pre-existing radial shrinkage cracks on the timber, such that the specimen would be representative of what would be found in practice as opposed to mechanically creating a crack within solid timber. The specimens were exposed to heat using a Cone Calorimeter apparatus, according to a modified ASTM E1354 procedure [33] shown in Figure C.6. The ASTM E1354 procedure was modified in that no pilot burner was used, and that the samples were removed from the apparatus after the desired heat duration and extinguished with light amounts of water. All samples were exposed to a heat flux of 50 $kW/m^2$, for varying exposure durations. The cracked and solid samples were exposed to the heat flux for 6, 15, and 30 minutes respectively (with duplicates of the 6-minute tests to confirm test repeatability). The primary purpose of the Cone Calorimeter tests was to induce a repeatable thermal exposure on the timber, such that the effect of the crack on the fire performance of the samples could be assessed. As such, 50 $kW/m^2$ was therefore chosen as a heat flux that was great enough to induce significant char depths, but not so high as to run the risk of charring through any specimens completely at 30 minutes [34]. Test times were selected as 30 minutes to induce a reasonably deep char depth that would be certain not to char through (considering the sample height, crack depth, and charring seen in similar tests [35]). 15 minutes was selected as half of 30 minutes to provide a moderate point of comparison, and 6 minutes was selected as an even milder point of comparison, in line with the methodology of Chapter 5, as to be able to compare data from both studies.

Following heat exposure in the Cone Calorimeter apparatus, each of the eight samples was cut in half, perpendicular to the direction of the crack. Char depth was then determined by measuring the depth of undamaged timber, determined visually by colour as the region that had not turned black or brown, and subtracting the undamaged depth from the initial depth of the sample. Char depth was measured at quarter and mid spans of the samples.

Table C.2 Summary of Cone Calorimeter tests, where “Solid” samples are characterized as having a maximum crack width of 2 mm.

| Sample ID | Description | Heat (mins) | Duration |
|---|---|---|---|
| C1 | Cracked | | 6 |
| C2 | Cracked | | 6 |
| C3 | Cracked | | 15 |
| C4 | Cracked | | 30 |
| C5 | Solid | | 6 |
| C6 | Solid | | 6 |
| C7 | Solid | | 15 |
| C8 | Solid | | 30 |

Figure C.6 Cone calorimeter test setup.

### C.3.4 Limitations

Limitations include that the sample size, and additional as well as repeat tests could have been performed if material availability had allowed. The number of tests was limited by the availability of materials with pre-existing shrinkage cracks in acceptable condition. If a greater quantity of materials had been available, additional testing could have included longer duration testing at a lower thermal exposure, potentially altering the temperature distribution across the sample creating a more uniform profile across the member. Moreover, the effect of moisture content should also be explored in future testing. In this study, moisture content was not the variable in consideration and expansion of the test program was limited due to material availability. However, variation in moisture content could also impact the temperature and charring profile of the timber. Testing for longer durations and at differing moisture contents should be addressed by future research.

### C.4 Results

The results presented herein are separated into the two phases described in the previous section, the tests considering the full-scale heritage timber members, and those considering small-scale Cone Calorimeter tests.

#### C.4.1 Full-Scale Tests

The largest existing cracks on each of the timber members were measured before and after exposure to the pool fire and presented in Table C.3. The table also presents the average char depth excluding the crack region, and the maximum char depth (at the crack region) of each member on the side with an existing crack larger than 2 mm. The char depth was calculated by subtracting the dimensions of the residual undamaged timber from the initial dimensions of the member. The average char depth away from the crack was determined as the average of four measurements equally spaced away from the crack region, cracks included in consideration of Table C.3 include the existing cracks on the soffit for member Heritage 1 and side A for Heritage 2. Figure C.7 shows the 5.4 mm cracks on side A of member Heritage 2 before exposure to the pool fire, and then after with a thermal camera and regular camera where the maximum crack width is 10.4 mm.

The char depth measured at each 25 mm slice for the soffit of Heritage 1 and 2 were recorded and presented in Figure C.8, note that for Heritage 1 there was a pre-existing crack, and for Heritage 2 there was no crack present on the soffit. The existing radial crack on Heritage 2 was present on the side of the member with respect to the pool fire, and those char measurements are shown in Figure C.9. It should be noted that the members charred primarily on the soffit and two sides, with little to no char on the top of the members. Therefore Figure C.8 represents the char measured on the soffit of the member, while Figure C.9 represents the sum of the char depths measured on both of the sides. The char depth represented in these figures was determined by subtracting the measured undamaged depth of timber post testing from the initial dimensions.

Table C.3 Timber member crack width before and after fire.

| **Member ID** | **Maximum Crack Width before Fire** | **Maximum Crack Width after Fire** | **Average Char (Excluding Crack)** | **Maximum Char (at Crack)** |
|---|---|---|---|---|
| Heritage 1 | 6.2 mm (Soffit) | 12.6 mm (Soffit) | 14.2 mm (Soffit) | 29.0 mm (Soffit) |
| Heritage 2 | 5.4 mm (Side A)<br>0.9 mm (Side B) | 10.4 mm (Side A)<br>11.5 mm (Side B) | 16.9 mm (Sides) | 39.0 mm (Sides) |
| Heritage 3 | 2.0 mm (Soffit and sides) | NA | NA | NA |

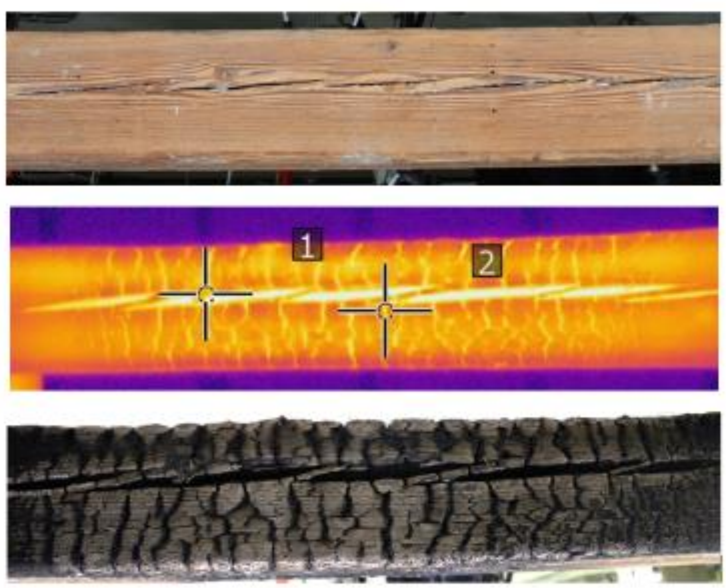


Figure C.7 Side A crack progression before (top) and after fire (middle and bottom) on Heritage 2 (identifiable markings were recorded temperature markers).

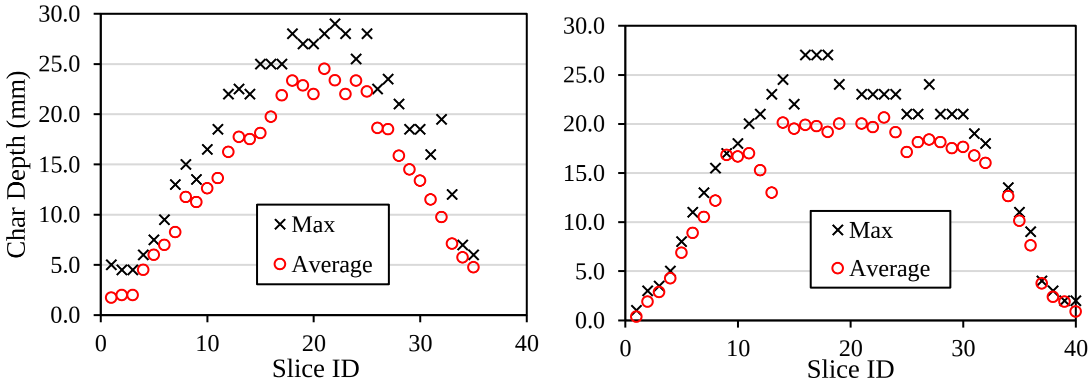


Figure C.8 Char depths after loading on soffit of Heritage 1 (left) and Heritage 2 (right), where Max is the maximum char depth around the crack, and Average is average char depth away from the crack.

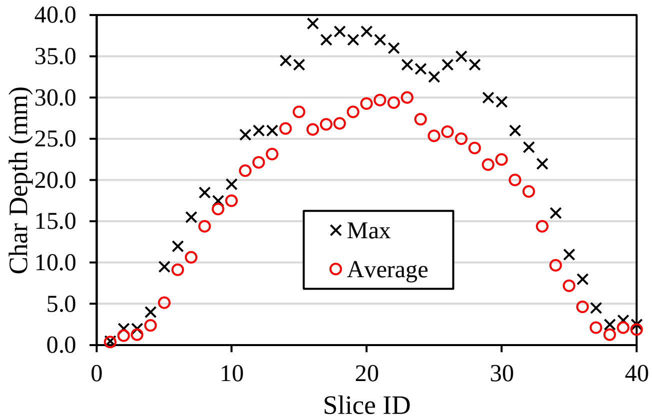


Figure C.9 Char depths after loading on the sides of Heritage 2, where Max is the maximum char depth around the crack, and Average is average char depth away from the crack.

The deflections computed during the loading tests for the two heated members, Heritage 1 and 2, and the control member, Heritage 3, are presented in Figure C.10. The deflections measured in millimeters are plotted in relation to the force applied in kilonewtons, until failure.

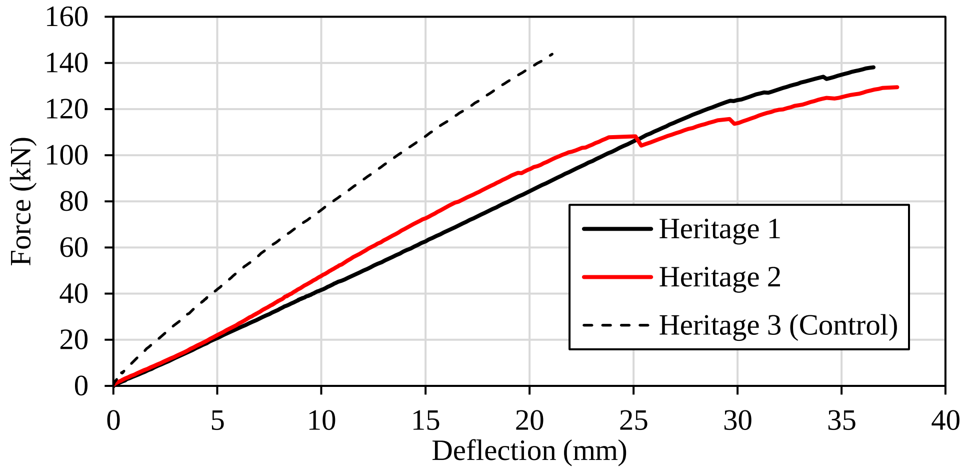


Figure C.10 Force vs deflection for the charred heritage and control members.

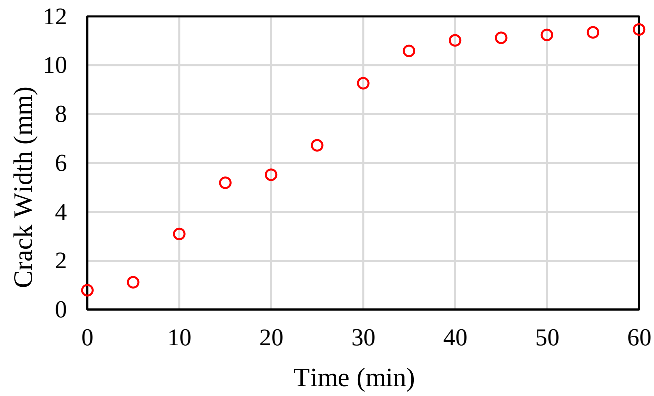


Figure C.11 Crack expansion over time during the 30 minute pool fire and 30 minute cooling phase on Side B of Heritage 2.

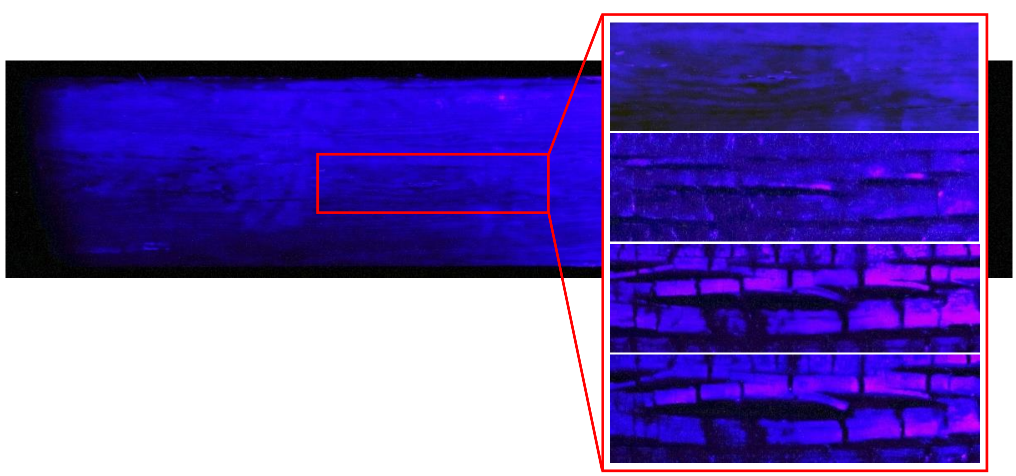

Figure C.12 Crack expansion during heating at 0, 15, 30, and 60 minutes on Side B of Heritage 2.

In terms of crack expansion during testing, Heritage 1 initially had a crack on the soffit of 6.2 mm in width, which grew to 12.6 mm after fire exposure, meanwhile Heritage 2 had a crack on side A with an initial width of 5.4 mm and a final width of 10.4 mm. In both these cases, the crack width more than doubled during the thermal exposure. Moreover, Heritage 2 had only very small initial cracking along side B, and by the end of the thermal exposure one crack grew from less than 1 mm in width to 11.5 mm in width. This expansion over time is plotted in Figure C.11 and shows that the crack expansion occurs relatively linearly during the heating phase (the first 30 minutes), and the expansion rate slows to near zero during the subsequent 30 minute cooling phase. Figure C.12 shows the capabilities of the narrow spectrum illumination technology allowing for this analysis, as the images seen would otherwise be obscured by the presence of flames. The crack that is shown in Figures C.11 and C.12 that began at less than 1 mm is depicted as it exemplifies the trends seen in other cracks (i.e., it was the crack with the greatest change in width, allowing for trends to be more clearly observed). The lack of pre-existing radial cracks indicates minimal exposure to severe moisture changes (and therefore shrinkage) before thermal exposure, unlike the opposite side of the member which had not experienced previous shrinkage cracks, therefore there was more potential for shrinkage crack formation during fire test. While this crack widened more than 10 times its initial size, versus the doubling of the existing cracks, the final crack widths after exposure were comparable, within 9% difference of each other.

Figures C.11 and C.12 show that the crack did continue to increase in width after the heating phase was complete. Figure C.11 shows that during the heating phase (the first 30 minutes of testing), the crack width increased by 8.5 mm, while during the cooling phase (the second 30 minutes of testing), the crack width increased by 2.2 mm. The continued increase in crack width during the cooling phase of testing could be attributed to continued heating and moisture evaporation of the timber even after the pool fire had been consumed.

### C.4.2 Cone Calorimeter Tests

Figure C.13 shows the cross section of each of the samples tested, showing the char depth at the center of the cracked samples at the top, and solid samples at the bottom in order of exposure duration. Samples labelled “solid” were characterized to have no crack exceeding 2 mm in width before exposure. The char depth of each sample, both cracked and solid, is shown in Figure C.14 at the three exposure durations tested. The value at 6 minutes is an average of the two samples tested at that exposure duration for the cracked and solid samples. The second graph shows the heat release rates from the 30-minute exposure test of the cracked and solid samples.

Table C.4 presents the maximum width of cracks present in all samples before and after exposure, as well as the time to ignition in seconds.

Figure C.13 Char depth of cracked (top) and solid (bottom) timber samples at various exposure durations.

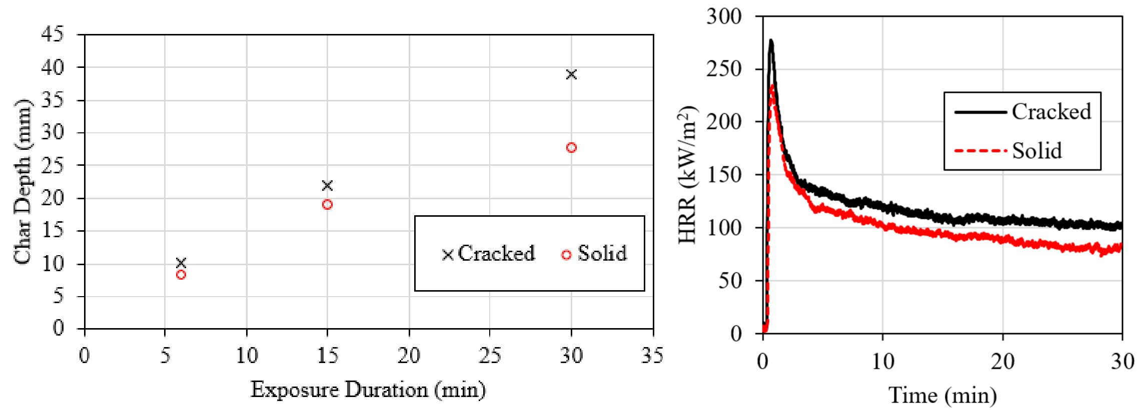


Figure C.14 Maximum char depth of cracked and solid specimens, and heat release rates of cracked and solid samples tested to 30 minutes.

Table C.4 Changes in Crack Width of the Cone Calorimeter Samples

| **Sample ID** | **Initial Density ($kg/m^3$)** | **Initial Maximum Crack Width (mm)** | **Maximum Crack Width Post-Heating (mm)** | **Time to Ignition (s)** |
|---|---|---|---|---|
| C1 | 647 | 8 | 9 | 29 |
| C2 | 667 | 8 | 10 | 25 |
| C3 | 619 | 10 | 13 | 29 |
| C4 | 630 | 11 | 15 | 19 |
| C5 | 648 | 1 | 1 | 19 |
| C6 | 633 | 1 | 1 | 32 |
| C7 | 632 | 2 | 2 | 21 |
| C8 | 635 | 2 | 2 | 23 |
| Cracked Average | 641 | 9.25 | 11.75 | 25.50 |
| Solid Average | 637 | 1.50 | 1.50 | 23.75 |

The results of the Cone Calorimeter tests showed some notable differences between the cracked and solid samples. First, the presence of the crack did seem to affect char depth and heat release rate. Around the crack, the maximum char depth was 29% greater for the cracked samples than the solid samples after 30 minutes. Similarly, for the heat release rate, the peak heat release rate of the cracked samples was 18 $kW/m^2$ (6.7%) higher than the average peak heat release rate of the solid samples. Charring around the crack could have been facilitated by the relatively large initial crack widths, which ranged from 8-11 mm (with variation being due to natural crack formation). These results suggest that under the thermal exposure observed in these tests, pre-existing cracks of at least 8 mm in width did increase the overall char depth and heat release rate.

The results of the Cone Calorimeter tests differed from the results of the full-scale tests as the small cracks did not expand during heating, which could be attributed to a size effect. Differences in scale may potentially play a role in observed differences in crack expansions, particularly with respect to moisture content. When timber is heated, moisture evaporates or migrates deeper into the timber and the dehydration process causes shrinkage cracks. The smaller samples may have smaller amounts of water, with therefore less potential for shrinkage crack formation. Overall, the effect of moisture content on crack expansion and charring around the crack should be considered as a future research need.

## C.5 Discussion

### C.5.1 Full-Scale Tests

Charring around the crack was greater than charring away from the crack. On average across the two samples, the average char depth away from the crack was over 18 mm (64%) less than the maximum char depth at the crack. Liu et al. (2021) attributed heat transfer through the cracks in concrete members to be primarily due to conduction [14]. This theory seems to be in agreement with the full-scale test results, as the areas of greatest damage correlated with the areas of direct flame impingement, and considerable crack expansion occurred in initial crack widths of less than 1 mm where the radiation configuration factor would be minimal.

When comparing char depths on the soffit and sides, the char depths are on average 11% greater on the sides than on the soffit. This is due to the fire exposure, while the soffit was closest to the pool fire, the sides were exposed on both faces, making the total char depth in that direction larger.

The charred region on Heritage 1 was off centered by 194mm, as discussed in the methodology (Section 3.2). Although the pool fire was centered along the member, the off-centered charring was due to an uneven fire spread once the beam ignited, spreading to one side of the beam over the other. This could have been caused by ventilation in the room, or a heat channel caused by the existing crack on the soffit. It did not have a significant effect on the loading results however, with Heritage 1 and 2 performing similarly.

The loading tests revealed a similar ultimate capacity between the control and charred members, where the ultimate capacity of the control was only 7.2% larger than the average of the charred members. The most significant difference was in the stiffness, where the control member was much stiffer than the charred members, with the charred members experiencing a maximum deflection of 43% more than the control members on average.

**C.5.2 Cone Calorimeter Tests**

Volatiles are credited with the ignition of timber, by either coming into contact with a spark or flame, or by reaching the temperature needed for unpiloted ignition [17]. The presence of cracks would allow for the more ready escape of volatiles, however in the Cone Calorimeter tests, the time to ignition did not appear to be affected by the presence of the cracks when comparing the solid and cracked members. It is possible that sufficient volatiles were available for both the solid and cracked members, and once they reached the temperature threshold, they ignited at around the same time, leaving time to ignition largely unaffected by the dimensions of the surface cracks.

Previous research by Ervine et al. (2012) on concrete noted that thermal propagation is not significantly impacted by cracks up to 10 mm at the heated surface [13]. In the timber Cone Calorimeter tests, it was noted that charring was increased around the crack, implying that the presence of a crack is altering the thermal profile of the timber member. Notable differences between the timber Cone Calorimeter results and the study by Ervine et al. (2012) include variations in heat flux and duration. Ervine et al. (2012) considered a thermal exposure of 1 hour with and incident radiant heat flux of 35 $kW/m^2$, creating a longer thermal exposure at a lower heat flux. The duration and heat flux of the thermal exposure can potentially change the temperature profile of timber [15], and a longer fire duration may result in a more even temperature distribution and char depth across the sample. Moreover, it is notable that the tests by Ervine et al. (2012) considered a non-combustible material, whereas even though the timber was exposed to an external radiant heat flux, all timber samples ignited quickly and flaming was present on the surface of the timber throughout the durations of the tests. Thus, the presence of flaming on the surface of the timber further explains the difference in test results as compared to Ervine et al. (2012). Future research could explore the effect of a longer fire duration to examine if charring becomes more uniform across the member.

**C.6 Conclusions**

Given the immense value of heritage timber structures combined with their vulnerability to fire, it is important to understand the fire performance of heritage timber members, including the effect of often-observed radial shrinkage cracks. To date, little research has been conducted on the effect of a crack on the heat transfer and fire performance of a material, and to the authors' awareness, there are no previous studies explicitly looking at the effect of shrinkage cracks on the fire performance of timber. This study provides an evaluation of the effect of radial cracks on the fire performance of heritage timber, by considering changes in crack dimensions and charring depth around pre-existing cracks on small- and large- scale samples.

Results of the experimental program showed that there was significant crack expansion in the large-scale member with a pre-existing crack, with the crack width more than doubling from

6.2 mm to 12.6 mm throughout the test duration. Moreover, Heritage 2 had an initial crack of less than 1 mm in width that expanded to be 11.5 mm in width upon conclusion of the fire exposure. The cracks present did appear to impact the char depth of the member, with the char depth away from the crack being an average of 18 mm (64%) less than the maximum char at the crack.

In assessing the impact of the fire exposure and the cracks on the load carrying capacity of the members, the heritage members were loaded in bending until failure. The ultimate capacity was only reduced by 7.2% compared to the undamaged control member, however, the control member was much stiffer than the damaged members, deflecting 43% less than the charred members.

The Cone Calorimeter tests similarly showed that the presence of cracking affected the final char depth, with the maximum char depth of cracked samples being an average of 29% greater than solid samples after 30 minutes. Expansion of crack width was also seen in the Cone Calorimeter samples, though only in cracks with an initial width of 8 mm or greater and not in cracks with initial widths of 1-2 mm. This discrepancy from the large- scale pool fire tests could be attributed to the radiant heating, where the radiant heat is less able to penetrate cracks of small initial widths.

The results of this study give a look at the fire performance of these members and suggests that the presence of these cracks do impact the total char depth of the member under the thermal exposures examined. The results emphasize the importance of properly maintaining and conditioning heritage timber buildings to minimize the formation of the radial cracks, as well as the need for heritage conscious fire protection strategies.

These results can help to inform practitioners who encounter heritage timber members with radial shrinkage cracks in more accurately assessing the fire performance of the member, such that they can make informed decisions on the level of fire protection required.

**Acknowledgments**

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**Appendix D**: **Incorporating Timber Education into Existing Accredited Engineering Programs**

**From:**

Chorlton B, Mazur N, Gales J (2019) Incorporating Timber Education into Existing Accredited Engineering Programs. In: 2019 Canadian Engineering Education Association (CEEA-ACEG19) Conference. Ottawa, ON

## D.1 Introduction and Background

Timber construction is becoming increasingly popular across Canada. Coast to coast, buildings such as the Brock Commons building in Vancouver have been constructed, and numerous others such as Toronto's Arbour Building are in progress. Moreover, the proposed changes to the upcoming National Building Code of Canada (NBCC) 2020 includes allowances for taller and more exposed timber structures [1]. With this growing demand for timber construction, there is a need for timber education in engineering programs, which is currently lagging behind the industry demand and momentum. Timber is a building material with many unique properties not typically considered in reinforced concrete or steel construction, often resulting in a highly complex design. In order for practitioners to keep up with the requests for these timber structures, timber design needs to be taught broadly across accredited civil engineering programs.

There are a number of methods which may be carried out to ensure that students have the required knowledge to fulfil the industry demand. While some schools have already successfully been able to offer a timber design course or other means of timber education to their students, a significant number have not yet been able to. This appendix will discuss methods of educating students on timber at schools which have not yet implemented these courses or programs.

One option to educate students regarding timber is to introduce a timber course into undergraduate engineering programs. There are a number of teaching resources to facilitate the creation of a timber course provided by the Canadian Wood Council (CWC), including a series of free presentations that an instructor could adapt and deliver to their students [2]. The timber design handbook is also easily attainable and would further facilitate structuring a timber design course. A course outline for a typical undergraduate timber design course has also been developed by the

CWC and is summarized in Table D.1. A drawback of this method is that it can take many years to introduce a new engineering design course at a university, and graduates who can design timber are needed in industry immediately. Further, the addition of another design course can overload students, whose curriculums have already been rigidly constructed to meet existing Canadian Engineering Accreditation Board (CEAB) requirements.

Table D.1 Outline of an undergraduate timber design course.

| **Topic** | **Description** |
|---|---|
| Introduction | *Wood as a green building material; History of wood structures* |
| Physical and mechanical properties of wood | *Molecular and cell structure; Physical properties; Mechanical properties* |
| Structural Wood Products & Structural Forms | *Dimensional shapes; Engineered wood products* |
| Strength and modification factors | *Specified strength of wood, size, use, species and grade; Modification factors; Shrinkage calculation* |
| Design Process | *Limit states design – ultimate & serviceability limit states* |
| Design of tension members | *N/A* |
| Design of compression members | *N/A* |
| Design of bending members | *Solid lumber beams, joists, planks; Glulam – straight prismatic beams, tapered straight beams* |
| Fire safety | *Mechanics of wood in fire; Code procedures; Encapsulation* |
| Combined bending and axial load | *N/A* |
| Connections | *Nails and spikes*<br>*Bolts and lag screws* |
| Lateral loading and design | *Shear walls/diaphragms* |

This raises the question of how universities can educate their civil engineering graduates on timber design quickly, without overloading students and still meeting CEAB accreditation requirements. The purpose of the research herein is to provide an overview of an alternative method to educate civil engineering students on timber design, by implementing a series of timber modules into existing civil engineering courses. This method has been implemented at one accredited university, where the learning modules have been introduced within the Structural Steel

Design Course on a trial basis. Furthermore, in this course, a number of different trial teaching methods were used (some of which are beyond the scope of the paper to describe), allowing for not only the attainment of the required graduate attributes but also the inclusion of attributes beyond those required.

## D.2 Motivation

### D.2.1 Integration of timber learning modules into existing courses

In order to be integrated into existing courses within the civil engineering curriculum, the course outline presented in Table D.1 has been broken down into two learning modules. The first learning module (Module 1) consists of the first four topics listed in Table D.1, beginning with the Introduction and ending with Strength and Modification Factors. The second learning module (Module 2) covers the remaining topics, focusing therefore primarily on timber design. Once these learning modules have been outlined, the question then becomes where these modules can be presented in the curriculum. One course that offers a prime opportunity for the integration of timber is Structural Steel Design. A sample course outline for an undergraduate Structural Steel Design course is seen in Table D.2. This is a common outline used for the Structural Steel Design course. From comparing both Table D.1 and Table D.2, it becomes clear that there is significant overlap between the two courses in design methodologies and themes. Many of the skills and topics students are learning about in their steel design courses become easily transferrable to timber design, allowing for a quicker introduction to the topics than if they were introduced in two separate courses.

Other courses also present opportunities to implement timber learning modules. An example of this would be a Civil Engineering Materials course. Both the Structural Steel Design course and the Civil Engineering Materials course are nearly universally offered in civil engineering programs across Canada.

Table D.2 Outline of an undergraduate steel design course.

| **Topics** | **Subtopics** |
|---|---|
| Introduction | *Background into structural steel; Limit states design – ultimate & serviceability limit states* |
| Design of tension members | *N/A* |
| Design of compression members | *N/A* |
| Design of bending members | *N/A* |
| Design of beam-columns | *N/A* |
| Corrosion | *Causes, effects and prevention of corrosion; Case studies* |
| Connections | *Welds; Bolts and rivets* |
| Composites | *Composite beams; Composite decks* |

These courses show that there are many opportunities to integrate timber design within existing engineering courses. One method of presenting the timber modules could be to present Module 1 in the Civil Engineering Materials course, and to present Module 2 in the Structural Steel Design course. An advantage of this approach is that Civil Engineering Materials is often a lower year course (while Structural Steel Design is often taught to upper years). This gives lower year students an introduction to the material. Module 1 also coincides well with the existing topics in Civil Engineering Materials, as does Module 2 with the existing topics in Structural Steel Design. This method would necessitate having the Civil Engineering Materials course as a pre-requisite to the Structural Steel Design course, so that students learn the modules sequentially. Alternatively, both learning modules could be presented in the same course. In this case, the course would likely be an upper year course, such as Structural Steel Design, so that students would already have a strong background in materials and structural design.

### D.2.2 Graduate Attributes

In developing engineering courses at CEAB accredited institutions, the graduate attributes are carefully considered for each course (see [3]). While each course must meet their required graduate attributes, additional graduate attributes may also be met. There are a number of simple ways in which additional graduate attributes may be met. Within the Structural Steel Design course, many different teaching methods were used to meet and even exceed the required graduate attributes. This can be seen in Table D.3. While these methods touched on a number of different graduate attributes, these graduate attributes were largely unmeasured and unassessed. The teaching methods described below were largely introductory and exploratory procedures, many of which could easily be assessed in future installments of the course.

Table D.3 Graduate attributes required and met or explored for the Structural Steel Design Course.

| **Graduate Attribute** | **Required (Yes/No)** | **Met or Explored (Yes/No)** |
|---|---|---|
| Knowledge base | Yes | Yes |
| Problem analysis | Yes | Yes |
| Investigation | No | No |
| Design | Yes | Yes |
| Engineering tools | Yes | Yes |
| Individual and team work | No | Yes |
| Communication skills | No | Yes |
| Impact on society and the environment | No | Yes |
| Ethics and equity | No | Yes |
| Economics and project management | No | Yes |
| Life-long learning | No | Yes |

Students were required to research a steel building of their choosing and self-record a presentation. The requirements of this presentation allowed for many additional graduate attributes to be met, including communication skills, and economics and project management (to name just a few). Additionally, experiential learning took place through the form of site visits. The sites that were visited included new construction, heritage buildings, and buildings undergoing demolition. This allowed students to see the full life cycle of a steel structure and touched on graduate attributes such as impact on society and the environment as well as lifelong learning.

Due to the importance of equity, diversity and inclusivity within engineering, a guest speaker, who focuses on these topics, was asked to present a lecture on the current state of diversity within the engineering education system and profession, and to suggest skills that students can use to help create an inclusive environment. This addressed the graduate attributes of ethics and equity, and impact on society and the environment, for example. Finally, students also worked in groups for their mid-term evaluations, which is representative of what may occur when they enter the workforce. This incorporated the communication skills and individual and team work graduate attributes.

### D.3 Methodology

The two timber modules previously outlined were integrated into the Structural Steel Design course at an accredited engineering institution in Ontario during the Winter 2019 semester. 32 students were enrolled in the course, all within the civil engineering program. The learning modules were introduced to the students over two, three-hour sessions. Most of the topics outlined in Table D.1 were presented within these sessions, however, where the content was extremely similar or identical content already covered within the steel lectures, students were expected to transfer their knowledge to timber applications. To the authors' knowledge and based on feedback from the students, the students had never previously been introduced to timber as a building material within their undergraduate education. At this particular institution, the timber Module 1 was also introduced into the Civil Engineering Materials course in the same academic year, however, the fourth-year students enrolled in the Structural Steel Design course did not have this previous exposure (necessitating both timber modules to be introduced in the same course, until the students who learned Module 1 in the Civil Engineering Materials course progress to the Structural Steel Design course).

Students were surveyed both before and after the learning modules were presented. Participation of the students was voluntary. Students were provided with a link to an online survey platform, where they could complete the survey using a laptop or mobile device. Of the 32 students enrolled in the course, 29 chose to participate in the surveys (91%). Students were not penalized for not filling out the survey. The survey was meant to gauge student motivations, level of interest, and knowledge. The full 15 question survey is presented at the end of this appendix.

### D.3.1 Graduate Attributes

Several survey questions align with the graduate attributes. The purpose of the survey was not to evaluate graduate attributes, but many of the survey questions reflect these areas nevertheless. More formal assessments were used in the course to measure graduate attributes.

'A knowledge base for engineering' is one graduate attribute that was addressed by the survey. Several questions asked students to use their specialized engineering knowledge. Questions 9-13 (see end of appendix) are all based on the students' engineering fundamentals and specialized engineering knowledge, as they ask knowledge-based questions about timber products, industry trends, and timber design.

Next, 'impact of engineering on society and the environment' is another graduate attribute dealt with in the survey. Construction materials have a significant impact on the environment, and they impact society through social, health and safety, and cultural means. These considerations apply to timber as it is a material that can be harvested and manufactured relatively sustainably. Further, in a social and health context, it has been shown that there are psychological and physiological health benefits of occupying a timber building [4, 5]. There are also several unique challenges that must be addressed in timber construction to assure life safety - for instance, its combustible nature requires significant considerations for its fire design. Several of the survey questions solicited responses from the students regarding these topics. Questions 5-6 and 12-13 (see end of appendix) all asked students to reflect on the impact of timber construction on the society and the environment.

The final graduate attribute that will be discussed is ‘economics and project management’. As a building material, timber is typically characterized as being expensive but fast to construct (relative to reinforced concrete and steel). Survey questions 5-6 and 12-13 asked the students to reflect on these economics and project management principles.

### D.4 Results and Discussion

A number of survey question results showed differences before and after the learning modules were presented; however, other questions showed no difference. The following subsections will examine some of the findings.

#### D.4.1 Thoughts of Industry and Trends

Students were surveyed to evaluate their knowledge and opinions of the timber industry. The results of one question, gauging student support of more tall and large timber buildings, is seen in Figure D.1.

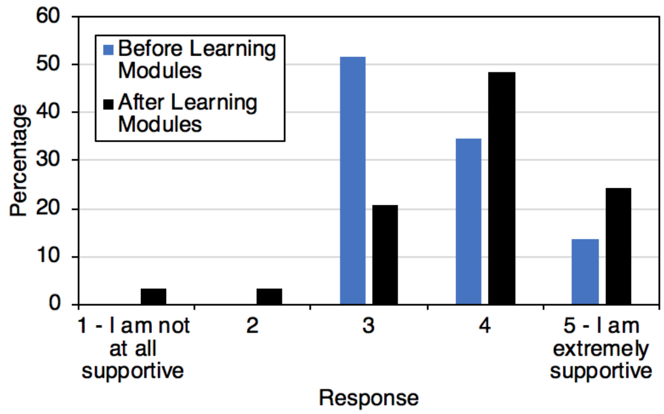

Figure D.1 Distribution of responses to the question, "How much do you support the construction of more tall and large timber buildings?"

From Figure D.1, it can be seen that before the learning modules, 52% of students selected a neutral response. This neutral response reflects the little knowledge students had regarding timber construction prior to the presentation of the learning modules. After the presentation of the learning modules, students were more opinionated. Only 21% were neutral, with the rest of the students indicating that they were either supportive (72%) or not supportive (7%). This indicates that the learning modules were successful in providing the students with knowledge regarding timber construction, and this knowledge was sufficient for them to form an opinion where they were previously neutral.

As a follow up, students were asked why they supported/did not support the construction of more tall and large timber buildings. There were no significant differences in their reasoning before and after the presentation of the learning modules. The most common reasons students were in support were sustainability and architectural reasons. The most common reasons students were not in support were concerns about fire, pests, sustainability, limited guidance available, deterioration, and architecture.

Students were also asked about their predictions regarding the construction of more tall and large timber buildings, in both Toronto and Canada. For both questions, students predicted significantly or slightly more large and tall timber buildings, more frequently after the learning modules had been presented. The student's responses regarding the construction of tall and large timber buildings in Toronto is seen in Figure D.2.

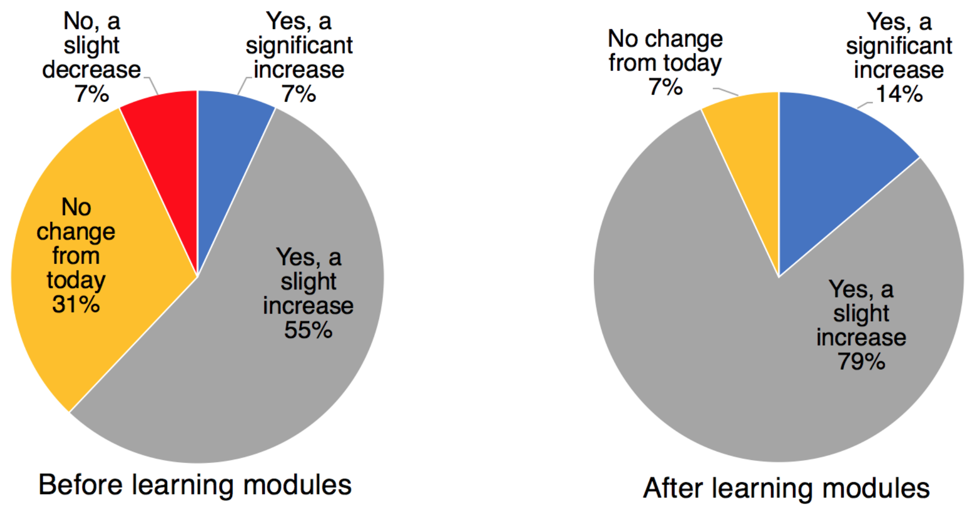


Figure D.2 Distribution of responses to the question, "Do you think we will see an increase in the number of timber buildings being constructed in the next few years in Toronto?" before the learning modules, left, and after the learning modules, right

Students were also asked to name any engineered timber buildings in Toronto or Canada. 16 students (55%) were able to name a building before the presentation of the learning modules, compared to 21 students (72%) afterwards. The most common buildings both before and after the learning modules were Brock Commons, Origine, 80 Atlantic Ave, and the Arbour building. These results suggest that the timber learning modules helped students to become more familiar with Canadian applications of timber design.

### D.4.2 Level of Knowledge

The survey asked questions with the intention of gauging how much knowledge students had regarding timber before and after presentation of the learning modules. These were not meant to be difficult questions for the students but were simply meant to give an idea of the level of understanding.

Students were asked how familiar they were with existing engineered timber products. The distribution of responses is seen in Figure D.3. It is clear that before presentation of the learning modules, there was little knowledge of engineered timber products, with 45% of students responding that they were not familiar at all. Only 24% of students rated their knowledge at a 3 or higher (with 1 being not at all familiar, and 5 being very familiar) before the presentation of the learning modules. After the learning modules were presented, 86% of students rated their knowledge as a 3 or more. In addition, students were also asked “What is engineered timber?” as an open-ended question. Responses were classified as correct relatively generously, if students were able to at all describe what constitutes engineered timber. Before presentation of the learning modules, 8 students (28%) answered correctly, and afterwards 18 students (62%) answered correctly.

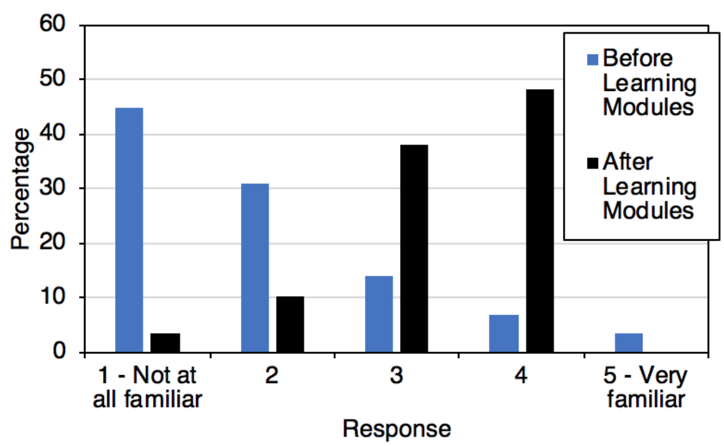


Figure D.3 Distribution of responses to the question, “How familiar are you with different timber products, for example, Cross Laminated Timber, Glued Laminated Timber, etc.?”

The level of student knowledge was also assessed by asking students to explain two or three advantages and disadvantages of timber construction. 69% of students were able to explain two or more advantages before the presentation of the learning modules, compared to 83% afterwards. The most common advantages listed included lightweight, sustainable, architecturally pleasing, and fast construction. After the learning modules were presented, there were additional answers regarding material durability. In terms of disadvantages, 69% of students were able to correctly identify two or more before the learning modules, compared to 79% afterwards. The students listed a wide variety of disadvantages, with the most common being concerns about fire, moisture, vibration, sustainability, maintenance, material defects, acoustics, pests, and fungi/rot. After the learning modules were presented, student answers also included strength perpendicular to the grain and high cost. Overwhelmingly in both surveys, fire and moisture control were the largest sources of concern.

Student responses to all of the questions assessing level of knowledge give indication that the learning modules were successful in providing the students with some general knowledge of timber. Every question asked showed an improvement in quantity of correct answers, or an improvement in students' self-assessment of their own level of knowledge.

### D.4.3 Level of Interest and Motivation to Study Timber

A number of questions were asked to assess the interest levels and motivations of the students to study timber design. First, students were asked why they were interested in or disinterested in timber design. There were no significant differences before and after presentation of the learning modules. Mostly, students were interested because they think it aligns with industry trends and will be useful as they enter the workforce. Some students also mentioned that they like the sustainability aspects, and others noted that they were simply curious because they had not yet learned about timber. Students were asked to quantify how interested they would be in learning more about timber within their civil engineering education, on a scale of 1-5 (with 1 being not interested and 5 being extremely interested). Before the learning modules, 86% of students ranked their interest level as a 4 or a 5, and after the learning modules 97% of students ranked their interest level as a 4 or a 5. This shows that students are highly interested in learning more about timber design even with no prior introduction, and that the learning modules only sparked a further interest in the students.

Students were then asked, if given the option to take one of either steel design, timber design, or a hybrid steel and timber design course, which would they select. Their responses are seen in Figure D.4. Both before and after the learning modules, students were very keen on a hybrid steel design course. Before the learning modules, the second most favoured course was steel design. After the learning modules, while the hybrid course remained the favourite, the timber design course became the second most chosen option. This may show that the learning modules helped the students to see the importance and applicability of timber design. The fact that in both surveys students favoured the hybrid course reinforces the student desire for timber education.

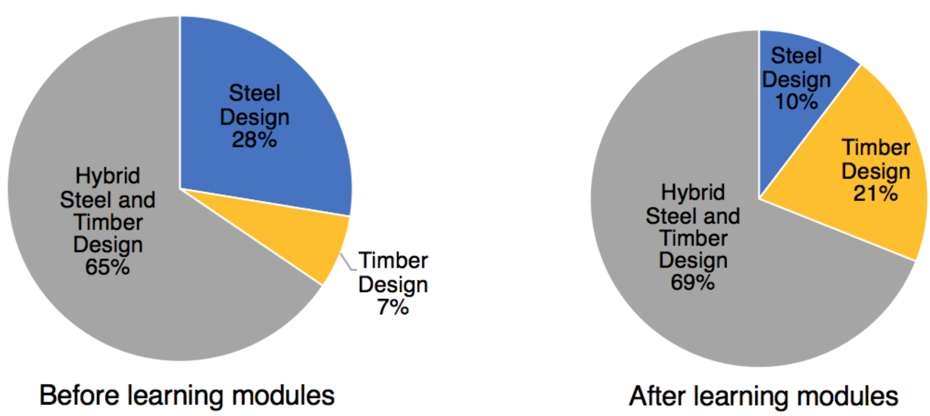


Figure D.4 Distribution of responses to the question, "If you had the option of taking one of the following courses, which one would you choose?" before the learning modules, left, and after the learning modules, right

### D.4.4 Other results

Other miscellaneous topics covered include student self-confidence in contributing to the design of a timber building upon graduation. The results of this question are seen in Figure D.5. Students were able to rank their confidence level from 1 to 5, with 1 being not confident at all and 5 being very confident. Before the learning modules, only 55% of students ranked their confidence as a 3 or more, compared to 76% of students after the learning modules. Furthermore, 28% of students initially indicated that they were not confident at all. After the learning modules, no students selected this response, indicating that all students had at least some level of confidence.

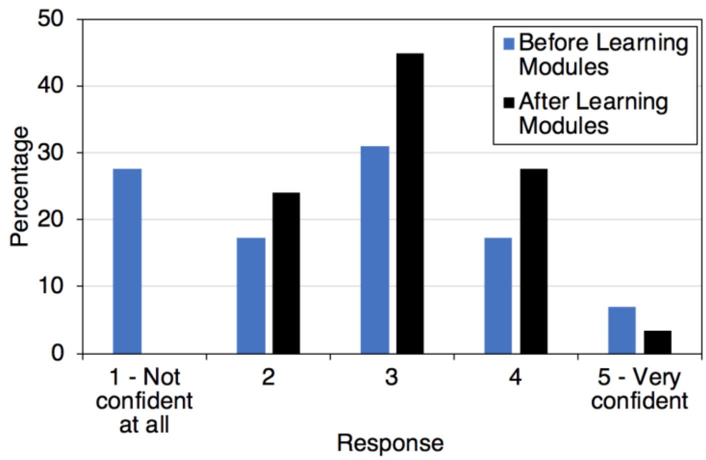


Figure D.5 Distribution of responses to the question, "Upon graduation, how confident would you be contributing to the design of a timber building?"

The final question that will be discussed gave the students the chance to state any remaining thoughts. The question asked, "Do you have any other opinions about timber education or the timber industry in Canada that you would like to share?". This question was asked only after the learning modules were presented. Largely, students took the opportunity to re-express their interest in further learning opportunities. A summary of their responses is seen in Table D.4.

Table D.4 Responses to the question, “Do you have any other opinions about timber education or the timber industry in Canada that you would like to share?”

| Response | Count |
|---|---|
| Stated an interest in a separate timber course or further integration into the engineering curriculum | 15 (52%) |
| Stated an interest in learning more about timber without mention of an additional course or the engineering curriculum | 4 (14%) |
| Discussed sustainability | 1 (3%) |
| Stated a disinterest in learning more about timber | 1 (3%) |
| No further opinions | 8 (28%) |

### D.4.5 Graduate attributes

The results of the survey also showed that the learning modules were useful in helping to convey several of the graduate attributes. The knowledge base for engineering was largely addressed by Section D.4.2 - Level of Knowledge. In this section, students were asked specific questions regarding timber products, the timber industry, and timber design. Each of the questions posed showed an improvement in the level of knowledge after the learning modules were presented to the students.

The impact of engineering on society and the environment was also addressed by Section D.4.2 - Level of Knowledge, as well as Section D.4.1 - Thoughts on Industry and Trends. The results of the survey questions associated with these sections indicate that students gained a better understanding of the impact of timber construction on the environment and have begun to think about factors they had not thought about previously. As an example of this, sustainability factors were one of the most commonly discussed topics when students were asked why they were in support (or not in support) of the construction of more large and tall timber buildings. As well, when students were asked to name two or three advantages of timber construction, the students discussed durability of the material only after the learning modules had been presented. This shows that not only have students learned about the unique properties of timber, but they have also expanded their thought processes regarding factors that contribute to the sustainability of a material.

Finally, several survey questions addressed the economics and project management graduate attribute. The questions that covered this graduate attribute are discussed in Section D.4.1 - Thoughts on Industry and Trends as well as Section D.4.2 - Level of Knowledge. An example of this would be the questions that asked students to list two or three advantages and disadvantages of timber construction. Many aspects of economics and project management were referenced in the student responses, including the construction time and material cost.

## D.5 Recommendations and Conclusions

There is a growing demand for civil engineering graduates who are knowledgeable about timber design and construction, and the method described in this paper offers an efficient means of providing students with the required knowledge without overloading them with additional courses. By integrating timber learning modules within the existing civil engineering curriculum, students are able to graduate in the next few years with some knowledge of timber design, in the time required for entire timber design courses to be developed widely across Canadian universities.

Organizations such as the Canadian Wood Council have provided many materials which significantly facilitate the creation of a timber design course, or even simple timber learning modules such as the ones described above. Lecture slides, course outlines, and design guides are all available for free or are easily accessible to instructors and students. The open stance on resources is extremely helpful to instructors in developing their course content. Continued access to the existing and improved resources will help instructors develop the learning materials they require to educate students.

The survey outlined above showed that the timber learning modules were successful in providing at least some foundational knowledge of timber design. One of the most telling questions is the question that asks students how confident they would be in contributing to the design of a timber building upon graduation, which saw that students gained significant confidence after the learning modules had been presented. This question exemplifies that even though the learning modules presented were short and concise, they were sufficient in providing students with the required skill set to begin to understand timber design problems.

The results of the survey also showed the success of the learning modules at meeting a few of the graduate attributes. A knowledge base for engineering was developed as students expanded their structural engineering knowledge to a material that was entirely new to them. The learning required them to consider the impact of timber construction on the environment and society as well as the economics and project management of a timber design, as timber has many unique properties that must be considered within these various contexts.

Eventually, more civil engineering universities across Canada are likely to begin offering entire courses on timber design. Until that is the case, the method proposed in this paper can be used to allow students to gain basic knowledge. Guest lectures and site visits would be other methods which allow students to further their knowledge of timber design. These methods would complement the learning module method described above but could also be implemented on their own where instructors at a university may not have a background in timber design (and therefore teaching timber learning modules would be challenging).

In order for the learning module method to be completed in two installments (the first in Civil Engineering Materials and the second in Structural Steel Design), Civil Engineering Materials needs to be a pre-requisite to Structural Steel Design. Having Civil Engineering Materials as a pre-requisite to design courses in general would be beneficial to the students, as it would give them background to the material mechanics and properties, allowing students to better understand material performance and design. It is therefore recommended that the Civil Engineering Materials course be a pre-requisite to the Structural Steel Design (and other design) courses.

The students have clearly indicated that they are highly interested and motivated to study timber design. This very much aligns with industry demand, as educators it makes sense to provide students with the skills they desire.

**Acknowledgements**

Funding provided by York University, through the York University Initiation research grant. Additional thanks to the Canadian Wood Council for providing teaching resources.

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**Survey Questions**

The survey questions are presented below. Note that where no options are offered, students were able to input text in a short answer format.

1. How would you rate your interest level in learning about timber design?
- 1 – Not Interested
- 2
- 3
- 4
- 5 – Extremely Interested

2. Why are you interested in timber design?
3. How interested would you be in learning more about timber within your Civil Engineering education?
- 1 – Not interested
- 2
- 3
- 4
- 5 – Extremely Interested

4. If you had the option of taking one of the following courses, which one would you choose?
- Steel Design
- Timber Design
- Hybrid Steel and Timber Design

5. How much do you support the construction of more tall and large timber buildings?
- 1 – I am not supportive of all
- 2
- 3
- 4
- 5 – I am extremely supportive

6. Why do you support/not support the construction of more tall and large timber buildings?
7. Do you think we will see an increase in the number of timber buildings being constructed in the next few years in Toronto?
- Yes, a significant increase
- Yes, a slight increase
- No change from today
- No, a slight decrease

- No, a significant decrease

8. Do you think we will see an increase in the number of timber buildings being constructed in the next few years in Canada?
    - Yes, a significant increase
    - Yes, a slight increase
    - No change from today
    - No, a slight decrease
    - No, a significant decrease

9. What is engineered timber?
10. Can you name any engineered timber buildings in Toronto or Canada?
11. How familiar are you with different timber products, for example, Cross Laminated Timber, Glued Laminated Timber, etc.?
    - 1 – Not familiar at all
    - 2
    - 3
    - 4
    - 5 – Very familiar

12. Please explain 2-3 advantages of timber construction.
13. Please explain 2-3 disadvantages of timber construction.
14. Upon graduation, how confident would you be in contributing to the design of a timber building?
    - 1 – Not confident at all
    - 2
    - 3
    - 4
    - 5 – Very confident

15. Do you have any other opinions about timber education or the timber industry in Canada that you would like to share? (Asked only after learning modules had been presented)

**Appendix E**: **Comparing the Experiences of Women in Engineering Across Different Schools**

**From:**

Mazur N, Chorlton B, Gales J (2019) Comparing the Experiences of Women in Engineering Across Different Schools. In: 2019 Canadian Engineering Education Association (CEEA-ACEG19) Conference. Ottawa, ON

## E.1 Introduction

The percentage of students enrolling in undergraduate engineering programs in Canada who are women has been very slowly increasing over the past 10 years [1]. However, this statistic does not hold for all engineering disciplines, with some disciplines seeing decreases in women's representation in those fields [1]. Almost 22% of engineering undergraduates are women - a proportion that drops to 17% for newly licensed engineers [2]. This issue of retention continues throughout women's career trajectories in engineering. This necessitates greater research focus, to understand the factors that may be influencing women to leave the engineering profession. Although there have been many efforts on the recruitment end, if women are not staying in the field, then these efforts will have been ineffective. Tackling recruitment alone is not enough to encourage increases in diversity [3, 4].

Numerous studies have shown that women face more obstacles than men throughout their careers; this retention issue has often been termed the "*Leaky Pipeline*" [5–7]. A key variable that has been responsible for perpetuating these obstacles is what has often been called a "*Chilly Climate*" - a hypermasculine, male-dominated, and sexist environment [5, 8–11]. Women have consistently reported being intimidated, being targets of subtle sexist humour, and being regarded as 'tokens' or 'diversity hires' who have been hired to fill a quota as opposed to because of their abilities. The chilly climate is not something unique to the workplace. It is introduced and perpetuated by undergraduate institutions [12], leaving women in undergraduate programs disillusioned and excluded [5, 13, 14]. Most of this highlighted research has been done in the United States, but little to none exists on the Canadian cohort. The Canadian schooling systems and licensing laws differ from those of the United States, so it is necessary to begin understanding the local situation. There may be cultural variables responsible for retention issues in Canada that are unique. Without accounting for those, we run the risk of relying on unrepresentative data and recommendations that are irrelevant or ineffective for our situation.

A previous study by the authors on the experiences of different genders in engineering programs in Canada indicated significant differences in men's and women's experiences throughout their engineering programs [15]. That first-stage study highlighted that the causes of Canada's low retention of women in the field are at least partially attributable to women's negative experiences at the beginning of their careers, in their undergraduate education. The research done thus far has been explorative; there is now a need to begin identifying where and when students are experiencing negativity, and if it is correlated to their gender. Furthermore, previous results were based on a single school; different schools have different policies and climates that could contribute to student experiences in different ways [16]. Especially considering the fact that education decisions are made provincially as opposed to nationally in Canada, it is important to understand student experiences from many different contexts before making any sweeping generalizations and recommendations.

Understanding how specific behaviours and practices of professors, teaching assistants, peers, and other personnel in the classroom affect students will have significant consequences for what inclusive pedagogy in engineering should look like. A significant retention drop, or "leak in the pipeline," occurs between women's graduation from university and the years in which they prepare for licensure. If women have more negative experiences in their undergraduate programs than men, they have already overcome challenges that may further make resilience and retention difficult. Furthermore, if students at particular schools have more negative experiences than students at other schools, some graduates may enter their careers at a great disadvantage. Lessening negative experiences for all students, and allowing women to have an equal experience, is of utmost importance to ensure that engineers begin their careers strong and motivated, and that all have engineers have equal opportunities to move forward.

### E.2 Methods

The purpose of this research is to identify factors in engineering students' undergraduate education that may be contributing to their retention beyond the undergraduate degree. The primary target of this research is to identify challenges that affect genders and institutions in different ways. A 17-question survey was distributed to undergraduate engineering students at four accredited universities - three in Canada and one in the United States. All universities surveyed are public. The survey was made up of both multiple choice and open-ended questions. These questions were selected based on issues identified in previous research.

#### E.2.1 Participants

A total of 282 students completed the study - 68 from Institution A, 117 from Institution B, 36 from Institution C, and 61 from Institution D. Institution B is an American public university, while Institutions A, C, and D are Canadian. The Canadian institutions were not the same institution as in the previous pilot study [15]. Participants were recruited via email and social media posts directed by administrative contacts at each institution. About 7% of all invitees participated. Of the 282 respondents, 55.9% identified as women and 40.47% identified as men. The remaining 3.63% identified as another gender or preferred not to indicate their gender. The respondents represented more than 18 streams of engineering and all four years of study (1-4). The average age of participants was 21.8 years old. All participants were invited to complete the survey over three to four weeks in December 2018. The email and social media posts explicitly stated the purpose of the survey and students of all genders and backgrounds were invited to participate. The survey obtained ethics clearance from the researchers' home university as well as the institutions being surveyed. The authors have chosen not to disclose the universities involved in publication.

### E.2.2 Materials

The survey was made available online through Qualtrics Experience Management, a data collection platform. Each institution had a slightly different survey, with appropriate changes made to the name of the institution and the programs offered. Participants used a personal computer or other device connected to the internet to answer the questions. The survey was intended to be completed independently. The survey itself consisted of an informed consent form, given at the beginning of the survey, and 17 questions divided into four blocks according to theme (e.g., demographics, experiences). Questions were presented one block at a time (see end of Appendix). All participants received the same questions in the same order. Where there were multiple possible answers in multiple choice questions, the order in which the answers were presented was randomized for each participant.

### E.2.3 Procedure

Once participants navigated to the survey link on their device of choice, they read through the informed consent form. If they accepted the terms of their participation, they clicked the navigation button to give their consent to begin the survey. If they declined participation, they were free to close the browser.

The first block of questions in the survey related to demographic items such as engineering program, age, gender, and year standing. The next block asked questions related to student experiences. The final block consisted of an optional comments box if participants wanted to share any further information related to the survey. After completing the survey, participants' answers were submitted to the Qualtrics database.

## E.3 Results

Survey answers differed between genders and institutions. Chi square tests were used to determine whether significant relationships existed between responses to demographic questions and responses to educational experience questions. Results with p values less than 0.05 (i.e., a confidence level greater than 95%) were considered to be statistically significant, as per common research standards [17].

In general, women showed similar trajectories of discouragement between all schools. Discouragement increased in middle years and dropped in fourth year. Figure E.1 shows that the fourth year drop is slightly more prominent for women than for men, and that on average a significantly higher proportion of women (63%) than men (50%) reported being discouraged or intimidated in their program ($\chi^2$ (1, $N$ = 228) = 76.44, $p < 0.001$).

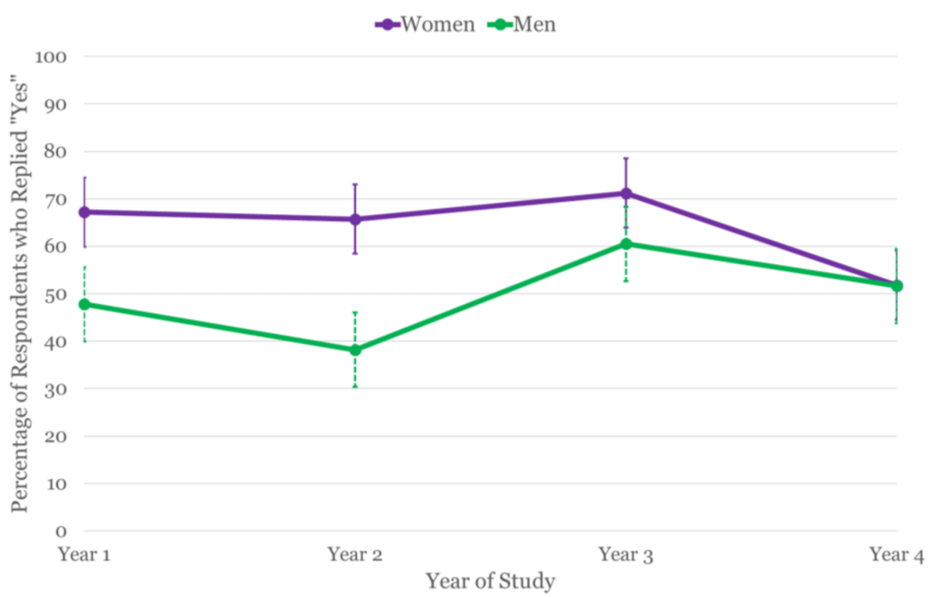


Figure E.1 Responses to the question, “Have you ever been discouraged or intimidated in your program?”, averaged across all institutions. (Note: Error bars indicate standard deviation).

About half of all respondents who identified as men had been discouraged or intimidated in their program.

Peers and instructors were consistently indicated as primary or at least major sources of discouragement, for all institutions surveyed. Figure E.2 shows that an exception to this was Institution B, wherein the primary source of discouragement was indicated to be Other. Respondents did not specify who “Other” was.

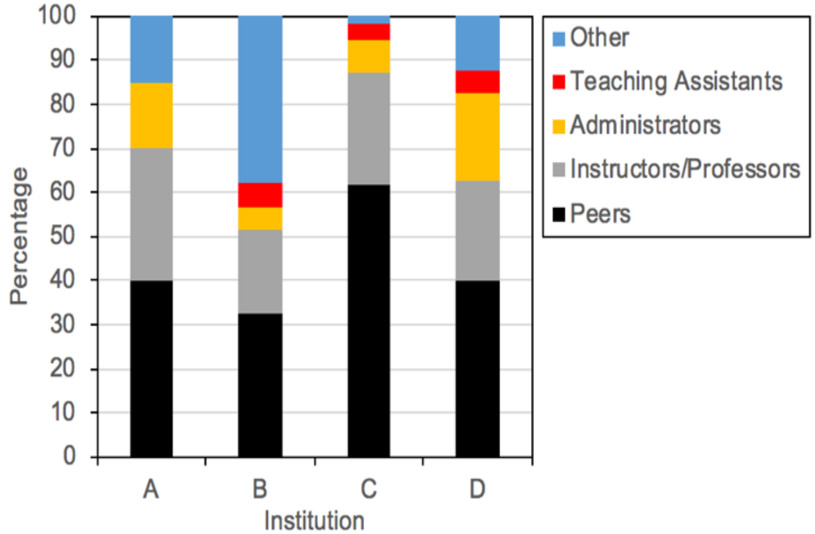


Figure E.2 Sources of discouragement and intimidation per institutions. (Note: Data for Teaching Assistants was not available for Institution A.)

Respondents indicated that they engaged their instructors through e-mail or online means most of the time (averaging 37%, ranging from 35-39%); through talking to them before or after class (averaging 27%, ranging from 23-39%); and through meeting them in office hours (averaging 20%, ranging from 18-24%). Men and women generally interacted with their instructors in similar ways, although women were more likely than men to interact with their instructors through online means or through someone else. Men were more likely than women to interact with their instructors through talking to them before or after class and to not interact with instructors or Teaching Assistants (TAs) at all. Men and women were equally likely to meet their instructors in office hours and to not interact with their instructors but still interact with TAs.

Women self-reported having less of a chance of securing opportunities in their program more often than men did. Men reported having more of a chance of securing opportunities in their program more often than women did. Furthermore, Figure E.3 shows that significantly more men than women reported having much more of a chance, and more women than men reported having much less of a chance ($\chi^2$ (1, $N$ = 293) = 17.36, $p < 0.05$).

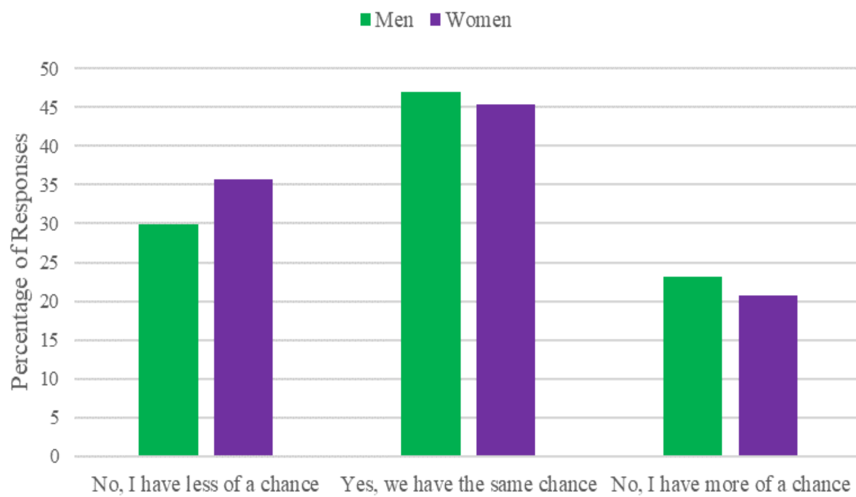


Figure E.3 Responses to the question, "Relative to your peers, do you feel that you have the same chance of securing opportunities in your program?", averaged across all institutions.

Students were presented with a gender balanced list of comparable female and male exemplar engineers. When asked to select the names of engineering exemplars they recognized as having made contributions to the engineering field, in general, men tended to choose male exemplars and women tended to choose female exemplars, showing minor bias for their own gender. The exception to this trend was Institution C, whose male respondents greatly preferred their own gender while female respondents showed no significant bias. At Institution C, recognition of exemplars was also related to year of study. Figure E.4 shows the distribution of male and female exemplars that were identified by students at Institution C, across the years of study ($\chi^2$ (1, $N$ = 293) = 39.54, p = 0.01).

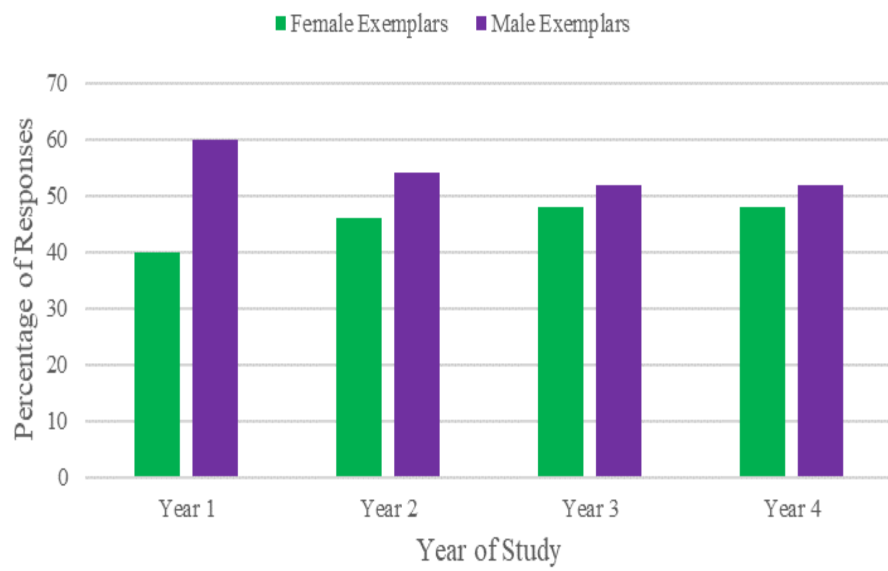


Figure E.4 Recognition of exemplars across all years of study and gender, for Institution C.

Generally, women (60%) at all institutions reported having difficulty finding group members Sometimes or Often or Always, more often than men (45%), with the exception of Institution D. At Institution D, men reported having difficulty finding group members more often than women. For pre-designated groups, women (78%) at Institutions A and C reported having issues working in their groups Sometimes or Often or Always, more often than men (56.5%). In contrast, men (70.5%) at Institutions B and D reported having issues working in their groups Sometimes or Often or Always, more often than women (61.75%). The most commonly cited reasons for tension were poor communication, unfair delegation of workload, poor time management, and lack of motivation. Some women, in their comments, noted overt sexism present in pre-designated groups. Men, in their comments, did not address discrimination or gender.

Women (47.5%) were slightly more likely than men (40.25%) to have someone who gives them career advice, with the exception of Institution A, where men (54%) were more likely than women (40%) to have someone who gives them career advice.

In terms of student profile, women (36%) were more likely than men (24%) to have a family member who is a practising engineer. Women and men did not generally differ in their career intentions, except in the area of pursuing further education. More men (23%) than women (17%) indicated that they intended to pursue further education beyond undergraduate studies. Women (8.5%) at Institutions C and D were more likely to pursue non-engineering jobs than men (3%).

## E.4 Discussion

The purpose of this study was to expand on the findings of a previous study on the experiences of women in engineering [15]. Of particular interest in this study were sources of reported discouragement, intimidation, and discrimination as well as institutional differences.

### E.4.1 Similarities

In terms of similarities to previous research, it is clear that women are experiencing more discouragement and intimidation in undergraduate engineering programs than men are, especially in their middle years. This trend is consistent across all institutions studied thus far and is therefore likely a facet of larger engineering culture [5, 12–14]. This chilly climate evidently alienates a significant portion of men as well, as their reports of discouragement and intimidation average around 50% across all years of study - an exceptionally high number. The decreases in reported levels of discouragement by fourth year seen in the pilot study have also been replicated in this study. The reasons for this are unclear, but a few comments from respondents revealed that this may be due to the development of “an uncaring attitude” or “thick skin,” where the student has become desensitized to negativity around them. Alternatively, students know that the end of their program is near and may be “eager to leave, seeing the end in sight” or have developed an adequate support system by this time. This attitude change may begin in third year, as evident from the increased variability in responses to the question of discouragement for women.

Women's and men's interactions with their instructors are similar, except for within the classroom. Many female respondents reported that their professors would either "put [them] on the spot," or routinely let others interrupt them or repeat them without validating their contributions. This may account for why women prefer to have others approach their professors for them (i.e., to avoid discomfort) and why they prefer to meet their professors at scheduled office hours (i.e., to avoid being interrupted by peers).

Perhaps related to how often women interact with their instructors and their issues with men in their classes more generally, women more often reported having lower chances of securing opportunities in their program, as compared to their peers. The differences between men and women on this item are particularly noticeable at the extremes (i.e., Much Less Of A Chance, Much More Of A Chance). It is possible that because women feel more alienated than men in their programs, they are less likely to form wide expansive networks that could be useful when applying for jobs or participating in interesting projects. Women reported instances of sexism, including harassment, in their comments, stating that many of the peers in their program did "not take [them] seriously". Women also reported that they did not want to report others for disconcerting behaviour against them, for fear that they would be found out and ostracized by their peers or others for speaking up about the issue. It is possible that the general competitiveness and chilly climate associated with engineering is responsible for this trend.

Like the previous study, men and women did not generally differ in terms of career intentions and goals, with the exception that this sample had institution-dependent gender differences in the proportions of students intending to pursue graduate studies and non-engineering work. This shows that women and men both aspire to do similar work. Nevertheless, many women reported being assigned administrative duties instead of technical work when in project groups with their peers, much to their frustration.

It is notable that all respondents surveyed across the four institutions had similar things to say when asked about the most frustrating and favourite parts of their programs. Participants most often cited interest in subject matter, hands-on practical experiences, and team building as their favourite aspects of their programs, regardless of gender. Next to workload and disorganized program management, chilly climate was the most commonly reported frustration of students, regardless of gender. Similar to previous research, women reported instances of sexism (both specific events and general occurrences) that they faced on a daily basis during their program in both their frustrations with the program and in additional comments sections of the survey. Men did not report on discrimination against them, except in a couple of isolated instances, where these respondents felt that the number of women around them (when at an equal 50/50) intimidated them. No women made negative or critical comments about equity initiatives at their schools, including women who reported that they personally did not experience discrimination. Several men in the study made comments about the inappropriateness of equity initiatives, of this study itself, and of women being allowed into engineering.

These results all seem to point to meta-institutional issues in engineering culture (i.e., a chilly climate) that may be responsible for women’s comparatively worse experiences in their undergraduate engineering programs.

### E.4.2 Differences

In terms of differences between the present and previous research, men and women both tended to choose their own gender when given exemplars to choose from in this sample, while women in the previous study showed no significant bias. The exception to this trend was Institution C, whose results replicated the previous study's. Furthermore, it was discovered that year of study may influence students' knowledge of exemplars, with first years being the most biased against women. This suggests that different institutions - particularly, different student groups - may create an atmosphere more or less sensitive to diversity issues in representation of exemplary engineers.

Women reported having more trouble finding group members than men, with the exception of Institution D, which showed the opposite trend. Previous research found no trend. With these new results, it is probable that this particular item is dependent on institutional and student culture. Institution D, in particular, is well-known in the wider community for being committed to the inclusion of women and diverse peoples in their STEM (Science, Technology, Engineering, and Math) programs. Additionally, its engineering programs are newer than those at Institutions A, B, and C. Previous institutional biases and policies that may have been unfavourable to women do not exist to as great an extent at this institution. It is possible that peer culture, representation of women, and inclusive climate at this institution affect students' interactions with each other. The fact that men at this institution found it more difficult to find group members, compared to women, may be attributable to a mismatch between a meta-institutional chilly climate and the institution's inclusive climate. Going into engineering, men may have made assumptions based on societal stereotypes regarding engineers and, when those stereotypes were challenged by their school and their peers, they had trouble navigating the social elements of their program. Alternatively, because Institution D's programs are relatively new, students have trouble working with others simply because there are fewer students to choose from. Cohort-specific effects may contribute to this trend.

In this study, women were more likely than men to have someone who gives them career advice, with the exception of Institution A, where the trend was reversed. This is in opposition to previous research, which found no trend. These findings may point to institutional or cohort differences. It is unknown who the sources of advice are for the respondents. If they are institutionally affiliated, there may be institutional-level differences in how women are engaged by their peers, instructors, and program staff. If they are extra-institutional, such as family members, these results may be specific to the sample.

In terms of women who reported the most discrimination, Institution C had the greatest proportion. This result is interesting because this institution has many programs and initiatives for supporting women and minorities. It is possible that these initiatives are not well advertised (Institution D advertises its programs and initiatives consistently very well, for example, and Institution C may not have this kind of coverage). Alternatively, Institution C's initiatives may not be well-targeted or impactful enough for students. In any case, every institution that was part of this study had issues regarding the inclusion of women in their programs, despite every one of these institutions having programs combating stigma and a chilly culture. This suggests that these programs may not be effective. They may be underfunded, disorganized, not well targeted, not well advertised, and/or not strong enough to combat the meta-institutional chilly climate of engineering.

**E.4.3 New Revelations**

This study uncovered that peers are the largest source of discouragement, intimidation, and discrimination against undergraduate engineering students, for all genders. Next to peers, instructors and professors were significant sources of negative experiences, followed by administrators, others, and TAs. It is clear that the issue of including women in engineering is not unique to an "old generation", but is something that extends to the current generation of aspiring engineers. This is further underscored by many of the young (male) students' comments about their exclusionist views on women in engineering.

The exception to the pattern of source of discouragement was Institution B, the American public university. This may be a facet of that specific institution, but it also implies a possible difference between Canadian and American issues of the inclusion of women in undergraduate engineering. This difference warrants separate study of the Canadian context, as well as further investigation into the Other category that was indicated as the primary source of discouragement in the American context.

This study also uncovered many small-scale differences between Canadian institutions, showing that at least some issues regarding the inclusion of women in engineering can be addressed at the level of the institution. There has been limited literature on the topic of institutional differences accounting for differential gender-related experiences in engineering, but what exists [16] is supported by this study.

**E.4.4 Limitations**

Women's backgrounds were different from men's in this sample (e.g., they were more likely to have a family member who is a practising engineer). There were fewer background differences present in previous research than in current research and it is not clear whether this presents a sample bias or whether this highlights institution- or cohort-level differences.

Genders other than male and female were not explicitly represented in this study. Although respondents could indicate whether they fall into a gender identity group apart from male or female, this group was treated as one single Other category. There were not enough respondents in this category to qualify for significant statistical analysis. Additionally, exemplars given in this survey did not include persons in this category.

Other intersectional identities were not significantly targeted and explored, but comments about race, ethnicity, and age came up in the results. These likely did not significantly impact the results, but it is possible that the sample studied was biased in such a way that one group contained more people with marginalized identities than the other.

There were not enough participants from each respective stream of engineering to make conclusion about program-specific or stream-specific experiences.

Experiences related to work terms will be covered in future work and were not covered in this study, despite programs such as co-op being highly integrated into the general engineering program experience. Participants were instructed to refer only to their experiences in the academic context and to exclude experiences with co-op, but comments about co-op and work terms still occurred.

Recruitment and data collection times for this study were very short - over a one-month period in total. This resulted in few participants. Consequently, the experiences reported in this study may be biased. However, it is notable that many similarities between samples and to previous research were found.

With future work, many of these limitations may be overcome.

### E.5 Conclusions

This study found that women experience more negativity in their undergraduate engineering programs than their male peers. Furthermore, these peers appear to be the primary source of women's discouragement, discomfort, discrimination, and intimidation.

Furthermore, this study found that institutions differ in how inclusive they make their climate to women. It is clear that, despite all institutions under study having clear guidelines and initiatives for equity and diversity, certain institutions are doing better on certain aspects of inclusion than the others.

It is clear that better equity programs and initiatives are needed to target all sources of discouragement.

### E.5.1 Recommendations

Preliminary recommendations for all institutions include:

- survey or engage students of all genders for feedback about their undergraduate experiences, so that priorities for improvement can be identified,
- continuously monitor the successes and failures of existing and new initiatives, so that resources are used effectively,
- target peers and instructors for education such as bias eradication training, and make this education mandatory and repeated (i.e., crucial to cultivating institutional culture).

If every institution does their part in creating a community culture wherein equity is critical foundation, significant improvements in all students' experiences in engineering education will be made. As well, the retention of women in engineering beyond the undergraduate degree may improve.

### Acknowledgements

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**Survey Questions**

Please answer the following questions keeping in mind your academic experiences in the classroom and at your school. **If you are on a work term (co-op or internship)**, please focus on your experiences at school and not at the workplace. We hope to look at work experiences in a separate study.

1. Which engineering program are you in?
2. Which year are you in, or will be entering when you return from your work term?

3. Are you taking a voluntary 5th year in addition to your core degree program? (Note: This does not include students who take co-op and are in their 5th year of studies but have 4th year standing.)
- Yes
- No

4. What is your gender?
- Male
- Female
- Other / Prefer not to say

5. How old are you?

6. Do you have a family member who is a practising engineer?
- Yes
- No

7. Do you have someone who provides you with career advice?
- Yes
- No

8. Of the following, choose the people that you recognize as having made contributions to the field of engineering. [Multi-select]
- List of ten randomized names, 5 female and 5 male, recommended by engineering professor contacts

9. How do you typically interact with your professors? [Multi-select]
- E-mail and/or online
- Meeting them in office hours
- Talking to them before/after class
- Through someone else (e.g., asking a friend to talk to the professor)
- I don’t interact with my professors, but talk to Teaching Assistants (TAs) instead
- I don’t interact with my professors or my TAs

10. Have you ever been discouraged or intimidated in your program?
- Yes
- No

11. Please rank how much each of the following sources contributed to your discouragement or intimidation (where 1 is the source that most significantly caused your discouragement or intimidation): [Displayed if Yes to 10]
- Peers (other students)
- Teaching Assistants (TAs)
- Professors
- Administrators
- Other

12. Relative to your peers, do you feel that you have the same chance of securing opportunities in your program?
- No, I have much less of a chance
- No, I have a little less of a chance
- Yes, we have the same chance
- No, I have a little more of a chance

- No, I have much more of a chance

13. Have you ever had difficulty finding group members when assigned group work?
    - Never
    - Rarely
    - Sometimes
    - Often
    - Always
14. Have you ever encountered difficulties when working in a pre-designated group whose members you did not get to choose?
    - Never
    - Rarely
    - Sometimes
    - Often
    - Always
15. Can you tell us about what kinds of difficulties you encountered? [Optional]
16. What are your plans after graduation?
    - Working in an engineering field
    - Working in another field (non-engineering)
    - Pursuing further studies in an engineering field
    - Pursuing further studies in another field (non-engineering)
    - Taking time off
    - Other
17. Additional comment [Optional]
18. What is the most frustrating part of your program?
19. What is your favourite part of your program?
20. If you have any further comments about your educational experience that you wish to share, enter them below. Otherwise, click the Next button to finish the survey. [Optional]