Heritage Considerations in Fire Safety Engineering

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This thesis is dedicated to my grandfather, Pierre Harun.

Abstract

The objective is to initiate a framework of guidance for fire safety engineering and heritage conservation, where there is a dearth between the disciplines. The human factor of emergency egress is evaluated through the pedestrian modelling of a case study heritage cultural center that underwent many interventions. Their effectiveness on egress is evaluated and found to have a 17.7% improvement on total egress time. The residual properties of heritage timber and masonry after fire are also evaluated. The timber testing considers the effect of existing radial cracks on charring of timber through pool fire exposure and cone calorimetry. The radial cracks were found to increase char depth by 64% and 29% for both tests respectively. The masonry testing compares compressive strengths of heritage and contemporary masonry units after 800°C furnace heating. Provisional results show no significant reduction in strength and a framework for testing heritage masonry materials is presented.

Acknowledgments

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Declaration

The contents of this thesis are the work of Georgette Harun, with the supervision of Dr. John Gales at York University. Some of the chapters presented are written with the influences and input from several colleagues and co-authors, which are acknowledged and described below.

Chapter 3 continues on experimental data collected by René Champagne and presented in the following publication:

> Gales., J., Ferri, J., Harun, G., Young, T., Jeanneret C., Kinsey, M., Wong, W. (March 2020) Contemporary Anthropometric Data and Movement Speeds: Forecasting the Next Ten Years of Evacuation Modelling, SFPE Performance Based Design Conference. 7 pp. New Zealand.

It also is based on preliminary research presented in the following conference paper, written by the author:

> Harun, G., Huang, L., Young, T., and Gales, J. (2020) 'Heritage implications in egress and modelling', in *Fire and Evacuation Modeling Technical Conference*. FEMTC, 9 pp.

Chapter 4 is based on research conducted with the help of Bronwyn Chorlton and submitted as a journal article written primarily by the author that is currently under review.

> Harun, G., Chorlton, B., Richter, F., and Gales, J. (2021). The Effects of Radial Cracks on the Fire Performance of Heritage Timber. Fire and Materials (John Wiley). Submitted.

And preliminary results were presented here:

> Harun, G., Gales, J., Weckman, B. (March 2020) Fire Performance of Heritage Timber Buildings in Toronto Canada, SFPE Performance Based Design Conference. 6 pp.

Chapter 5 presents research that was introduced in the following conference presentation by the author:

> Harun, G., Gales, J, Kotsovinos, P. (September 2019) Heritage Masonry Structures in Fire. CONFAB Fire and Blast. London, UK. (Abstract).

Chapter 6 provides a summary of findings and recommendations, while is not based on any existing research, summarizes findings from the sources outlined above.

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Chapter 1: Introduction

1.1 General

The fire that erupted at the Notre Dame Cathedral (Notre Dame de Paris) on April 15, 2019, illustrates the vulnerability of heritage buildings to fire, and their worth and significance beyond their physical form. A fire erupted in the timber roof of the cathedral, nicknamed "la forêt", "the forest" in English, for it's impressive timber stock, some dating from the 13th century (*La Charpente*, 2021). The fire began at 6:20pm in the attic, but firefighters were only notified 30 minutes later when guards finally discovered which attic the fire detection system had identified. The fire spread and ultimately consumed the timber roof, and the spire collapsed through the vaulted masonry ceiling. The fire was contained after several hours with no fatalities, and the majority of the Cathedral was saved (Peltier *et al.*, 2019). The fact that the Notre Dame Cathedral Fire is considered a tragedy, even though no lives were lost, emphasises the value that heritage buildings can hold to a community, whether local or international.

Before the Cathedral can be rebuilt, an assessment of the effect of fire must be considered for the surviving materials, as fire temperatures in the Notre Dame Cathedral fire were frequently above 900°C, and above 1200°C at its hottest according to experimental data from 2020 (Deldicque and Rouzaud, 2020).

Investigations after the fire showed that the fire detection system was quite sophisticated, and the 30 minute delay to alert the fire department was more so the outcome of improper response plans and training, human behaviour issues, then the detection system (Bateman, 2019). The subject of this research is not the events or outcomes of the Notre Dame Cathedral Fire, but the case study highlights several topics addressed in the research presented herein. These topics include fire protection strategies, human factors in fire, and heritage timber and masonry materials after fire.

Fire is a common risk to buildings, therefore fire protection strategies are considered to mitigate risk to life safety of occupants during fires. Heritage buildings hold value in their materials and often house important artifacts (artwork, records, books, etc.), therefore have extra safety considerations beyond life safety.

Though fire prevention is ideal, even the most highly valued heritage buildings, such as the Notre Dame Cathedral, can succumb either partially or fully to fire. When that occurs, there is a great interest in rebuilding and reusing as much of the original building materials as possible, therefore their residual properties after fire must be evaluated before they can be re-used. Research is needed to have confidence in the residual properties of heritage materials after fire, so they can be accurately evaluated and safely reused where possible.

The desire to rebuild after fire also applies to heritage buildings without world renown, such as the St. John's Anglican Church in Lunenburg, Nova Scotia, which was rebuilt after a fire resulting the loss of over 50% of its heritage fabric in 2001 as seen in Figure 1.1 (Canada's Historic Places, 2006).

Figure 1.1. St. John's Anglican Church in 2001 after the fire ((St. John's Anglican Church, Lunenburg, before and after November 1, 2001, 2001)*) and the rebuilt church as seen in 2017.*

The reason the Notre Dame Cathedral would have such an intricate fire detection system, but no sprinklers or fire walls in the roof structure is due to its heritage status, as well as the value of the contents of the building. Common fire protection strategies, such as sprinklers, are often avoided in heritage buildings to mitigate the damage risks to the valuable parts of the building, such as water damage in the case of sprinklers

(Gibbon and Forbes, 2001). Conservation guidelines promote limited interventions to preserve heritage value (Canada's Historic Places, 2010).

This illustrates how conservation guidelines and fire protection strategies are sometimes at odds, and special (careful) considerations must be made to meet safety standards while mitigating risks to heritage value.

There are a number of standards, codes, and guidelines that address fire safety engineering and heritage conservation in Canada and internationally (discussed below), but without extensive overlap between the two topics.

First considering conservation guides, the *Standards and Guidelines for the Conservation of Historic Places in Canada* (Canada's Historic Places, 2010) provides examples of fire safety measures for each guideline in the "health, safety and security" section, with some examples relating to fire escapes or sprinklers, but mostly a general emphasis on minimizing impact on heritage value while providing adequate fire safety measures. This leaves the interpretation up to the practitioner. No specific information about material properties of heritage materials is presented. *Protecting Our Heritage: Fire Risk Management Manual for Historic Places in Canada* (Richardson and Algie, 2011) is a useful guide for property owners, but only serves as guidance for those managing heritage properties and not necessarily for engineers.

Considering fire guides, the *Guideline on Fire Ratings of Archaic Materials and Assemblies* (National Institute of Building Sciences, 2000) is a useful U.S. based resource that provides fire ratings for older materials that are not included in modern fire rating lists. While this is a useful guide for the materials listed in the dimensions included, the timber materials included are limited to two species of softwood (Pine and Douglas fir), and there is no guidance on how to evaluate any that are not included. The *NFPA 914: Code for the Protection of Historic Structures* (NFPA, 2019) is an extensive guide that touches on many topics related to historic structures from fire prevention to construction and inspections, but relies heavily on the data from the NIBS Guideline above, with limited materials listed and first published in 1980 and updated in 1999.

In the *SFPE Handbook of Fire Protection Engineering (5th Edition)* (SFPE, 2016) there is no specific section on heritage materials or human factor considerations related to heritage in this handbook, though heritage implications are mentioned occasionally. For example, in the sections discussing fire suppression systems, some are recommended for heritage buildings due to their minimal visual appearance which makes them more compatible with conservation guidelines.

Canadian timber and masonry standards, CSA O86 and CSA S304, the materials discussed herein, include sections on fire resistance that make no mention of heritage materials.

1.2 Motivation

The motivation for this research is to contribute to heritage conservation guidelines regarding fire safety engineering, from both a human and material standpoint, considering human factors in fire and material fire resilience. The lack of detailed guidance regarding heritage conservation and fire safety engineering outlined above reflects the dearth of experimental data on heritage and fire, which will be detailed in the next section. This contributes to generalized fire protection strategies being applied to heritage buildings, without considering the impact on heritage value or exploring any alternatives. The research will investigate the efficiency of emergency egress strategies applied to heritage buildings, and heritage material behaviour in and after fire.

In both the cases of structural and human factor analysis, special considerations are needed for heritage buildings, and guidance is currently lacking to address these needs. This research addresses how to create appropriate framework for making guidance for fire safety engineering regarding heritage buildings, and contributes to the gap in experimental data on the subject. Many changes made to heritage buildings have a negative effect on their heritage value, therefore identifying the best conservation strategies with minimal interventions is ideal to achieve a code compliant, fire safe, and intact heritage buildings. Additionally, a lack of confidence in heritage materials performance in fire, due to a dearth in experimental data, results in fire protection strategies that potentially lower the heritage value, but have an unquantified effect on the fire safety of the building.

1.3 Research Scope and Focus

The research addresses heritage considerations in fire safety engineering, which is a broad topic in itself. Fire safety engineering consists of fire dynamics, structural behaviour, and human factors. This research addresses the former two branches of study within fire safety engineering, presented below.

1.3.1 Human Factors

The human factors involve the egress analysis of heritage buildings, and the interventions that effect emergency egress negatively or positively. A case study of the factors affecting the emergency egress of a heritage cultural center that underwent code compliant interventions is included. Pedestrian modelling software is used in conjunction with movement profiles previously created from real evacuation events, and a new analysis considering heritage interventions is presented. The software is used to evaluate egress times in the case study building throughout history and after major code compliance renovations.

1.3.2 Material Factors

The material factors involve structural fire resilience testing of both heritage timber and masonry samples. Both the timber and masonry test programs involve the same general procedure of exposure to a heat source, followed by mechanical testing until failure to determine the residual strength. The timber tests will consider the resilience of full-scale heritage timber members, as well as the effects of existing radial cracks on charring rate. The masonry tests will consider clay masonry bricks from four eras of history from the 1840s until today, heated and then tested for residual strength. Methods and considerations for testing heritage masonry will be included.

1.4 Research Objectives

The research objectives are as follows, to:

1. Identify the gaps in research regarding fire safety of heritage buildings, and the conflicts between fire safety engineering and heritage conservation;

2. Evaluate the effectiveness of code-compliant interventions on a heritage case study building based on egress time, so the benefits of interventions can be quantified against their potential detriments to heritage value;
3. Determine the effect of pre-existing radial cracks on the charring rate of heritage timber, and evaluate the residual properties of heritage timber after fire; and
4. Determine heritage clay masonry unit's residual properties after heating and develop a framework for testing heritage masonry units and assemblies fire resilience and repairability after fire.

With the information and experimental data gathered from research objectives 1-4, the overarching objective can be met, which is to:

5. Initiate a provisional framework for creating guidance for fire safety engineering regarding heritage buildings.

1.5 Thesis Outline

The organization of this thesis is manuscript style, chapter 2 provides a theoretical background on all the topics discussed herein, chapters 3-5 all represent a different topic of study related to heritage buildings in fire, and chapter 6 ties them all together. A visual outline of the thesis is presented in Figure 1.2 below.

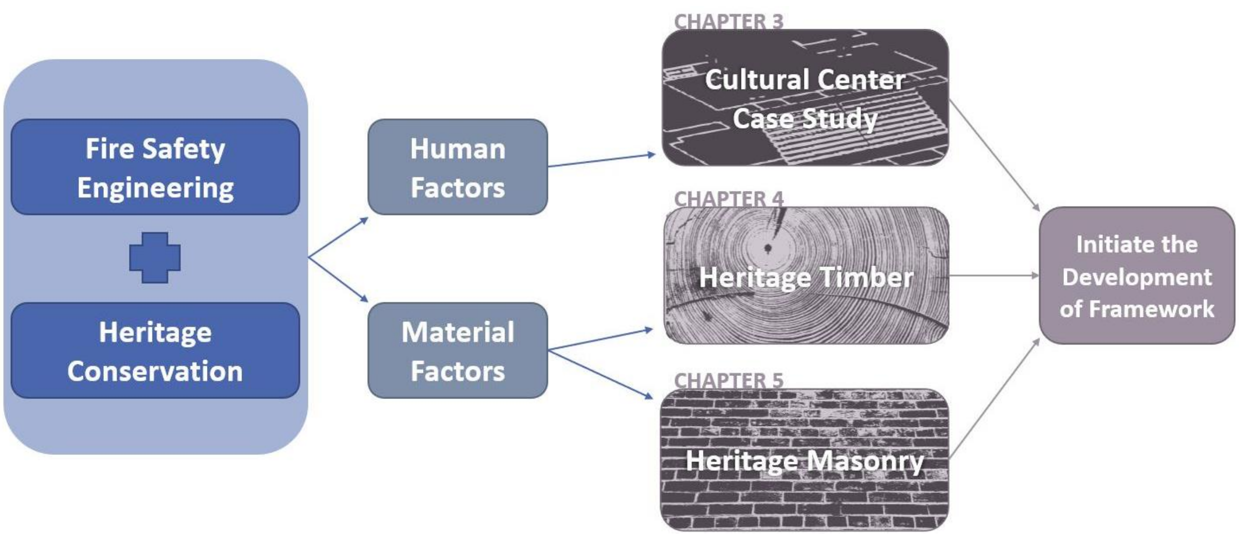


Figure 1.2. Visual outline of thesis.

Chapter 2 – Review introduces key concepts regarding the various subjects of this research. These include fire behaviour, human factors in fire, heritage conservation, and heritage materials in fire (timber and masonry). The chapter will explore key concepts and terminology, how the subjects interact with each other, and existing relevant research on their intersections.

Chapter 3 – Human Factors, presents a case study of the emergency egress of a heritage cultural center. The egress is studied using pedestrian modelling software to generate total egress times under various scenarios, based on real emergency egress data and movement profiles generated previously. The new modelling considers the efficiency of the code compliant interventions on the building, to evaluate their efficacy in improving egress. The egress performance of the building over various configurations over its 100+ year lifespan will be compared, and the most efficient interventions will be identified, as to limit interventions while improving emergency egress performance. This modelling introduces novel considerations for the improved egress performance of heritage buildings through interventions, beyond simple code compliance.

Chapter 4 – Timber Material Factors presents material testing research on heritage timbers, with a special interest in the effect of existing radial cracks on the charring rate. The results are published in a journal article and are modified to suit the thesis format, and to maintain flow and coherence. The author is the first draft author of the journal. The experiments consist of large-scale heating of pine timber members using a pool fire, and then loading in a four-point bending test until failure. This will determine the charring rates of heritage timber under real fire conditions, and the after-fire properties. The loading test is conducted on an unheated heritage member for comparison. Existing radial cracks from shrinkage are present in the heritage timber, and their effects on the charring rate are isolated using Cone Calorimeter testing. The results of the testing, and subsequent implications on preserving heritage timber with existing radial cracks is presented.

Chapter 5 – Masonry Material Factors presents preliminary masonry tests on fired clay bricks from four time periods in Toronto, the 1840s, 1900s, 1920s, and today. The clay masonry bricks are heated in an annealing oven, and then tested in compression to determine their compressive strength after heating. A framework for testing the fire resilience of masonry units and assemblies follows the preliminary experimental results. The framework will address the repairability of masonry assemblies after fire, aiming to identify how each of the component's properties change after fire exposure, and potentially how the materials can be reinforced.

Chapter 6 – Conclusions and Recommendations summarises all the theoretical and experimental data collected in previous chapters, and presents framework for new guidance for fire safety engineering of heritage buildings. This framework can be used by both practitioners to implement heritage conservation conscious fire protection strategies, and researchers to continue to fill the dearth of information regarding the intersection of the two disciplines.

Chapter 2: Review

2.1 Introduction to Fire Safety Engineering

2.1.1 Realistic Fire Behaviour in Rooms

The main components that make up a fire are fuel, heat and oxygen, and combustion is initiated by some form of ignition. Fuel can refer to any material that is burning, most commonly a solid (for example, a piece of furniture or a structural element) but can also be a liquid or gas (Drysdale, 2011). Ignition can be piloted, initiated by a spark or another flame, or spontaneous, and external heating is required for the combustion of solids and liquids (Drysdale, 2011). The figure below represents a typical room fire. There are four main periods of a fire, the incipient period where the fuel is being heated. After ignition (the start of combustion) is the growth period, followed by burning and then decay (Buchanan and Abu, 2017). The growth period is dependant on the available fuel, the combustible materials burn until the compartment reaches a critical temperature referred to as "flashover", which signifies the beginning of the burning period. The burning period is dependant on the available ventilation and is characterized by the whole involvement of a compartment in a fire. And the decay occurs when available fuel is used up (Buchanan and Abu, 2017).

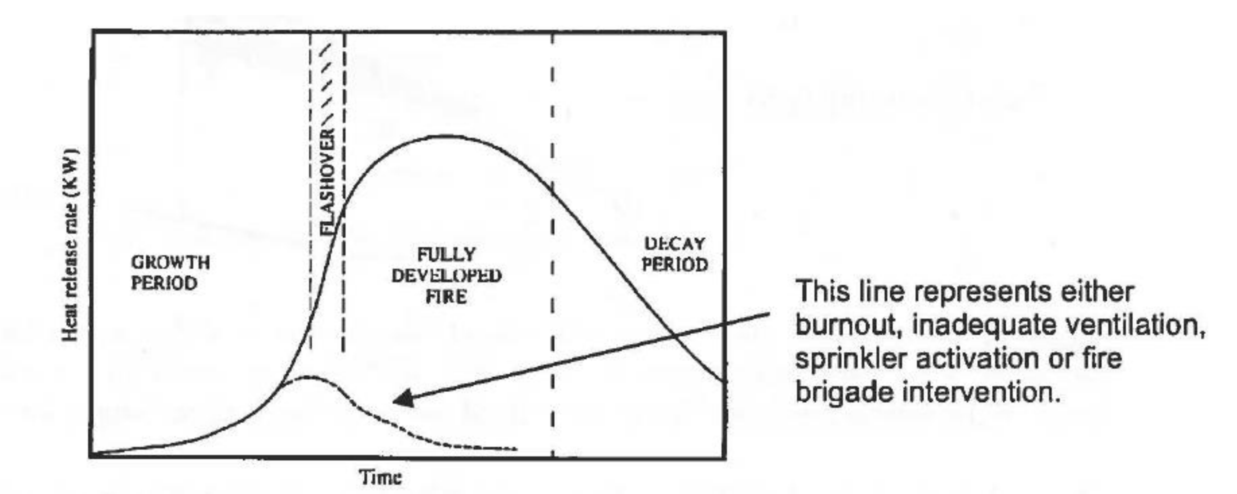


Figure 2.1. Phases of a fire associated to the release of heat (adapted from Buchanan and Abu (2017)).

Heat in a fire is transferred through all three methods of heat transfer, conduction, convection, and radiation. Conduction occurs through solid surfaces, and depends on the thermal conductivity of the material, therefore different materials can act as barriers to heat transfer through conduction. Convection occurs through the movement of hot gasses and smoke, and contributes to flame spread and the movement of heat upwards through a building. Radiation is the mechanism most involved in heating fuels from radiative heat from flames or smoke (Buchanan and Abu, 2017).

2.1.2 Standard Fires and Fire Resistance

For the purposes of comparative testing of structural systems in fire, time temperature curves were introduced in 1916 based on early fire testing, which became the basis of the standard fire curve used in fire resistant standards in Canada called CSA ULC S101, and in the US called ASTM E119 (Drysdale, 2011; Underwriters Laboratories of Canada, 2014; ASTM International, 2019; Gales, Chorlton and Jeanneret, 2020). The curve from 1916, shown in Figure 2.2 below, is identical to today's curve. The earliest standard by ASTM common to today was published in 1918, and most international standards are based this curve (Buchanan and Abu, 2017). The standard fire curve rises quickly and continues to increase in temperature, which is not representative of real fires, which have a period of decay and eventual extinguishment (Fire Protection Committee, 2018). This implies burnout much to the illustration shown in the first figure of this chapter.

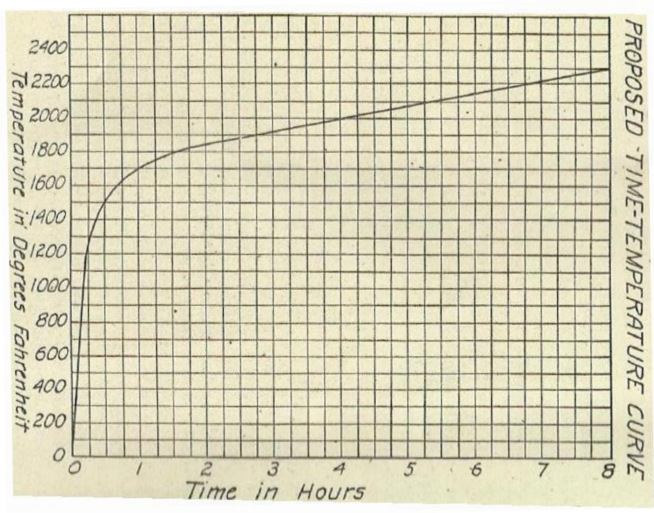


Figure 2.2. Standard fire as used in international standards first proposed in 1916 (Ingberg et al., 1916).

Fires also vary by duration and severity, depending on a number of factors, most notably ventilation, fuel availability, and fuel distribution (Drysdale, 2011). The Eurocode uses parametric fire curves which follow the growth and decay of fires more closely and vary in intensity based on fire load, ventilation conditions, and thermal properties of the compartment (Wang *et al.*, 2013). Yet even with these changing parameters, the dynamic nature of fires makes it difficult to capture in any mathematical curves. Standard fire resistance tests use the standard fire curve and are limited by the size of the furnace (which limits the size of members and assemblies tested) and the thermal expansion boundary conditions assumed during the tests (Fire Protection Committee, 2018).

Fire resistance is a measurement of time, before failure of a structural element or assembly to perform its function in fire (Drysdale, 2011). Fire resistance ratings are usually given in hours, and determined based on standard fire resistance tests (furnace tests using standard fire time temperature curves) (Buchanan and Abu, 2017). Fire resistance is a concept that touches on the structural performance of assemblies in fire. Fire resistance references the amount of time a structure will remain viable during a fire event. Many building codes require a 2 hour fire resistance rating on all materials and systems, therefore able to withstand 2 hours in a furnace following a time-temperature curve (ASTM International, 2019). The time before failure in a time-temperature furnace test is not necessarily representative of the time to failure in a real fire event, due to the variability of fire behaviour and the interactions between the entire structural system (that can't be captured in standard fire tests due to the size limitations of furnaces - see below figure for illustration) (Drysdale, 2011; Fire Protection Committee, 2018).

Figure 2.3. A standard fire furnace of fixed dimensions (photo by John Gales used with permission).

The concept of fire resistance only considers the structural performance of materials and assembly during fire (or more specifically during a furnace test following a standard time-temperature curve) and doesn't consider the cooling phase or after the fire/heating altogether. Repairability and serviceability after fire is not considered with fire resistance ratings, and not in most prescriptive or performance-based codes (Buchanan and Abu, 2017). Alternatively, resilience encompasses the ability to withstand shocks or stresses and return to normal with minimal interruption to building operation (Cimellaro, Reinhorn and Bruneau, 2010; Smith and Gales, 2017). Fire resilience refers to the resistance during fire and the repairability after fire.

2.1.3 Fire Protection

Fire protection systems are designed by engineers to meet the goals of the design. The goal is always to protect life safety, but other goals could include the protection of property, continuity of business operation, limit environmental impacts of the fire, or even protecting cultural heritage (Meacham *et al.*, 2016; SFPE, 2016). These systems are considered active or passive, depending on their activation during fire. Passive systems are inherently included in the building design, such as encapsulation, and active systems only operate during a fire event, such as sprinkler systems (Buchanan and Abu, 2017). A material's fire resistance rating is also considered a passive system. Fire protection is also approached from a human perspective, which will be discussed in the next section (2.2). Passive fire protection methods include compartmentation to limit smoke, intumescent paints and encapsulation to delay ignition of combustible materials. Active fire protection methods include fire detection and alarm systems, fire suppression (sprinklers), and staff training (Buchanan and Abu, 2017).

Fire protection engineering is about understanding fire, understanding building's response to fire, understanding human's response to fire, to meet the fire protection goals discussed above.

2.1.4 Material Behaviour in Fire

The thermal properties of a material can determine their performance during fire. Some properties of note are density, coefficient of thermal expansion, thermal conductivity, emissivity, and specific heat. These properties help to determine the insulating effects of materials and determine their behaviour in fire, for example thermal expansion creates additional stresses and bending moments in structural systems. Some of these properties and heat-dependant, such as specific heat, and change from ambient temperatures to heated conditions (Fire Protection Committee, 2018).

Structural systems can be subject to loss of stability and load-bearing capacity from fire exposure, due to the loss of strength and stiffness at high temperatures. These effects are caused or exacerbated by thermal expansion/contraction creating stresses, nonuniform heating creating thermal gradients, and cooling phase effects creating deformations. Materials can also experience a loss of cross section, for example charring on timber (Fire Protection Committee, 2018). Cooling phase observations are especially important to consider when evaluating fire resilience, as any permanent deformations may need to be mitigated to continue building operations.

The SFPE Handbook includes a chapter on Data for Engineering Analysis, outlining the data required to conduct deterministic or probabilistic engineering analysis. The data needs for analysis of "burnable product fire hazard or risk analysis" for the phenomena of "contribution to other harm – environmental impact, impact on heritage" are "laboratory test results (of characteristics and effects of fire conditions produced when product burns)" (Ahrens and Hall Jr., 2016; SFPE, 2016). This highlights the need for laboratory analysis of heritage materials in fire, to fill the dearth of information outlined in the last chapter.

Research on the specific material behaviours in fire for timber and masonry will be discussed in Chapters 4 and 5 respectively.

2.2 Human Factors

Human behaviour in fire is influenced by dynamic factors of influence, both physical and psychological. The physical contributions involve architectural layout, available exits, and signage. The psychological aspects involve decision making, group behaviour, familiarity with the building or attachment/affiliation with the space, and the influence of authority (Bernardini, 2017). The topic of study presented herein touches on some of the psychological aspects explored in previous research but focusses on the physical architectural details of heritage buildings on human behaviour in fire.

2.2.1 Emergency Egress and Wayfinding

Emergency egress is one of the main considerations for human factors in fire, and considers the protection of occupants by moving them to a safe place (usually outside of the building) (Bukowski and Tubbs, 2016; SFPE, 2016). Wayfinding is one of the main systems that support egress, especially in buildings like cultural centers, where occupants are not familiar with the building's egress routes and emergency procedures. Wayfinding is aided by signage, familiarity with the building, and the role of authority (staff preparedness), to help occupants make their way to emergency exits (Proulx and Sime, 1991; Galea, Hui and Lawrence, 2014)).

There are two main periods of an emergency evacuation, the pre-evacuation period and the movement (or evacuation) period. The pre-evacuation period encompasses from the ignition of fire (or other emergency) to the beginning of movement, and is further broken down into the pre-alarm phase, the evacuation decision-making phase, and the protective action phase (Kuligowski, 2016; SFPE, 2016). This pre-evacuation period is important to consider, and takes into account occupants gathering information, making decisions, and gathering belongings or assisting others before beginning their egress (Kuligowski, 2016; SFPE, 2016). The movement period is characterized by the occupant's wayfinding and movement speeds.

There are both prescriptive and performance based approaches to improving emergency egress, either through applying the necessary building code requirements to a building (prescriptive), for example having the required amount of exits for the number of occupants, or a performance based approach that relies on the available and required safe egress time (ASET/RSET) (Gwynne *et al.*, 2017). Modelling allows for the quantification of the required safe egress time, as in the amount of time needed for occupants to safely exit the building (Gwynne *et al.*, 2017). The available safe egress time is determined by the tenability conditions in a building, based on smoke and heat from a particular fire scenario, initially calculated by the time available before the smoke layer had descended to head height of individuals. In practice, the tenability conditions vary greatly between fire scenarios, and can be improved by occupant behaviour (opening doors, activating ventilation, etc.) which is a shortcoming of this concept (Schröder, Arnold and Seyfried, 2020).

2.2.2 Heritage Considerations in Human Behaviour

For egress in the historic building specific code by the NFPA (NFPA, 2019), where buildings cannot comply with prescriptive approaches, performance based approaches can be used as long as they comply with NFPA 101: Life Safety Code (NFPA, 2019, 2021). The prescriptive based approaches only reference the life safety goals set out in the general section (chapter 4) that states that an egress system should be designed and implemented, therefore there is no heritage specific approach to egress outlined in the NFPA 914: Code for the Protection of Historic Structures, which is to be expected since the code is meant to protect the buildings themselves and the other NFPA codes address life safety more directly, though without heritage considerations. The SFPE Handbook also does not have any heritage related human behaviour considerations (SFPE, 2016). Despite the lack of acknowledgment in the codes, there are many unique challenges with regards to heritage and human behaviour to be considered.

Heritage buildings are often visited by those who are unfamiliar with the layout, such as museums or theatres (frequently visited by tourists), which contributes to the pre-movement times during the evacuation as the occupants seek more information before egress and rely on specific verbal cues from staff or voice alarm systems (Bernardini, 2017). Human behaviour considerations, such as decision making, wayfinding, and movement speeds can also be affected by social and cultural backgrounds of occupants, in which heritage cultural centers host a diverse group of occupants compared to other buildings (Chattaraj *et al.*, 2013). Additionally, the diverse occupants have diverse linguistic abilities which also affect movement times based on verbal evacuation cues (Mazur *et al.*, 2019). Heritage buildings tend to have more complex layouts then contemporary buildings, as well as relying on fewer main entrances, with many secondary exits for egress that are unfamiliar and often ignored by occupants.

Heritage buildings tend to have narrower passages and doorways, which are more likely to lead to occupant overcrowding and bottlenecks. Position and visibility of egress routes are not always ideal in heritage buildings because they were not considered in the original design intent, and often the egress routes were not included entirely (they are added in through prescriptive code requirements) (Bernardini, 2017). This was evident during the study conducted on the cultural center (to be discussed in Chapter 3) during the first evacuation scenario, where the occupants pried open doors to the main atrium rather than walking a few meters to the available (yet unfamiliar) egress route (Champagne *et al.*, 2019).

2.3 Heritage Conservation

The value of heritage buildings comes from historic, scientific, aesthetic, cultural, social, or spiritual importance which are physically represented by their character defining elements. Character defining elements are the physical elements in a building (structural systems, facades, decorative elements) that hold the tangible and intangible value (Canada's Historic Places, 2010). When these character defining elements are conserved and not obstructed, the heritage value of the building is also conserved. In Canada, historical buildings with value are protected from major changes with heritage designations which classify them as heritage buildings. Not all historical buildings are classified as heritage buildings, but in this report all materials from historical buildings are referred to as heritage materials as they are representative of materials in heritage buildings (of the same age and mechanical properties).

The interest in conserving heritage buildings can come from a connection to history, but also from a sustainability or even economic perspective. When considering life cycle assessments (LCAs) of buildings, heritage buildings have an advantage due to both the durability and embodied energy of their original materials. This acknowledges the inherent sustainability of reusing existing building materials by conserving them in place. The implications on carbon, energy, and finances of replacing a historic building has to be carefully considered and often is not worth those costs. The importance of the embodied energy of the original building materials is also becoming more and more significant in LCAs as buildings become more energy efficient, so this advantage to conserving historic buildings will only appreciate over time (Menzies, 2011). Historic buildings, even vernacular architecture, also have many passive sustainability features in their design to conserve energy which was not as readily (and cheaply) available as it is today. Some examples of vernacular architectural details in colder climates include vestibules, interior and exterior shutters, smaller windows, and massive walls (Burns, 1982).

Heritage buildings contribute to the economy in many nuanced capacities, but also tangibly in rent, entry fees, and tourism. As historic buildings become increasingly rare, government fiscal incentives also contribute to their economic viability (Throsby, 2012).

2.3.1 Key Concepts

In Canada, heritage conservation is an umbrella term for three different types of conservation treatments: restoration, preservation, or rehabilitation. Rehabilitation projects, to adapt historic buildings for contemporary use, are the most likely to require updated fire protection strategies due to major renovations or changes in use (Canada’s Historic Places, 2010). Most heritage buildings in Canada were built before the first Canadian building and fire code in 1941, and therefore were not designed to comply to building codes. When major renovations or changes in use occur in a building, they are required to be updated to modern building codes. The NBCC is applied to existing buildings during a rehabilitation, change in use, or addition, or under special circumstances by an enforcing authority (cl. A-2.1.3.1.(1)) (Canadian Commission on Building and Fire Codes, 2015b).

> *"Some NBC requirements are most readily applied to new buildings and their retroactive application to existing situations as prescribed by this Code could result in some difficulty achieving compliance. It is the intent of the NFC that an equivalent level of safety be achieved rather than necessarily achieving strict conformance to the NBC. The application of this Code to the upgrading of existing facilities should be based on the judgment of the enforcement authority, who must deal with each case on its own merits." (NFC 2015 A-1.1.1.1.(1))*

Here the National Fire Code addresses challenges with applying prescriptive code clauses to existing buildings, and indicates that equivalent levels of safety (performance based approaches) can be used. The main goals in heritage conservation are to protect character defining elements and minimize interventions, so performance based approaches that respect heritage value are ideal solutions that satisfy both safety and conservation goals.

2.3.2 Fire Risk to Heritage Buildings

A number of factors unique to heritage buildings contribute to their fire risk. Arson is an important fire risk to historic buildings, and can be the principle risk according to the Canadian Conservation Institute (Baril, 1998). The layout of the buildings can contribute to their fire risk, often with narrow passages and low ceilings that could promote channelling of smoke or fire. There is usually an abundance of combustible materials housed in heritage buildings, from interior wooden elements, artwork and decorations such as carpets, wall hangings, and drapes. There is often an absence of both active and passive fire protection systems, such as sprinkler systems for active systems, and fire resistance ratings on materials and fire compartmentation for passive systems (no fire zones or fire doors) (Bernardini, 2017). Their layouts can limit access for firefighting, and they house unusual ignition sources (old electrical systems, or candles) (Carattin and Brannigan, 2012).

Heritage in considered in the SFPE (Society of Fire Protection Engineers) Handbook when considering Building Fire Risk Analysis, and in a few other spaces are mentioned when referring to active fire protection measures, such as sprinklers, that small-diameter piping are preferred to minimize impact on heritage character, or water mist systems (SFPE, 2016). It's stated that a fire safety goal of a building could be to "protect the heritage and cultural value of the property" but doesn't give much detail on how to achieve that specifically, and the heritage protection goals usually fall under the umbrella of property protection in the list of fire protection goals. Parks Canada put together a document on fire risk (titled "Protecting Our Heritage: Fire Risk Management Manual for Historic Places in Canada") that outlines fire risk to heritage buildings and defines related terms, but is meant to be a guide for heritage property owners, and doesn't provide in depth insight for engineers and practitioners (Richardson and Algie, 2011).

2.3.3 Fire Protection Engineering Conflicts

Heritage buildings were built before the building codes existed, so they were not built to comply with any building codes. When changes in use occur, or major renovations, the buildings must be brought up to modern safety standards, which prompt these considerations.

The NBCC Structural Commentaries address the challenges with regards to heritage buildings in Commentary L – Application of NBC Part 4 of Division B for the Structural Evaluation and Upgrading of Existing Buildings in the introduction:

> *"Many older buildings have structural systems, components or materials that are not addressed by the structural design standards referenced in NBC Part 4. When properly interconnected, however, older structural systems can be made to work effectively. Because information on their structural properties is lacking, the evaluation and upgrading of such*

systems is difficult. This difficulty is especially important for heritage buildings."(Canadian Commission on Building and Fire Codes, 2015a)

This statement applies to structural design, but as outlined in the previous chapter, the dearth of information on fire performance of heritage materials applies to this statement as well.

Tozo Neto and Ferreira (2020) reiterates that changes to historic fabric is undesirable for heritage buildings. Common passive fire protection strategies such as intumescent paints and encapsulation obscure heritage elements and are therefor not ideal from a conservation perspective (Canada's Historic Places, 2010).

Protection of property as well as life safety (structure, contents, and occupants) is important for rehabilitation projects. The contents of the buildings have value not only to the owners of the building, but often have heritage value themselves. Such is the case of the fire in the Brazil National Museum, where a scientific collection spanning two centuries and estimated at 20 million items was destroyed (Escobar, 2018). Therefore while life safety is always the top priority of any design,the safety of the contents of heritage buildings can compete with the safety of occupants (Carattin and Brannigan, 2012).

2.3.4 Existing Studies on Heritage Conservation and Fire Safety

Bukowski and Nuzzolese (2008) chronicles the detailed process (with lengthy approval times) of designing a fire protection system that respects heritage value for the rehabilitation of a historic Italian theatre using performance-based methods. They identify the main fire safety issues in the historic building to be the abundance of combustible materials, and insufficient egress capacity for occupant load. The extensive fire protection design included new compartmentation of the building, new staircases, high sensitivity fire detection systems, fire suppression systems, smoke control through HVAC, and a 24 hour operated security and control centre. For the exposed combustible structural elements that held heritage value, sprinkler systems aimed at the exposed combustible structural materials were used to delay ignition, rather than intumescent coatings which would obscure the elements. Redundancy was also added to the structural elements with heritage-compatible systems to improve their fire resistance while leaving them exposed (Bukowski and Nuzzolese, 2008).

Notably, during the design process some prescriptive solutions were found to fail the performance criteria, highlighting the need for unique fire protection strategies for heritage structures, and illustrating that compliance to prescriptive codes does not necessarily ensure safety (Bukowski and Nuzzolese, 2008).

Tozo Neto and Ferreira (2020) evaluated a number of intervention packages (groups of interventions) with increasing cost/square foot on their effect on lowering the fire risk index (FRI) value. These packages were based on the structure, detection systems, and occupant training. While the packages increased in intensity, the first one with very minimal intervention was successful at reducing the FRI to a low risk of nearly 95% of the population studied using only better signage and staff training (Tozo Neto and Ferreira, 2020). This highlights the fact that measures can be taken to improve fire safety outside of major prescriptive changes to a building, therefore without impacting the heritage value.

2.3.5 Testing Heritage Materials

The main reason for the dearth of information on the material properties of heritage materials in fire is the limited access to testing materials. Most testing conducted on heritage materials consists of in-situ non-destructive testing or small samples for chemical characterization due to the protected status of the buildings they come from. The existing documentation of heritage materials relies on historic material characterization, which may be unreliable and doesn't capture the performance of the materials after 50 years or more of service, or the characterization of equivalent new materials which also doesn't consider weathering or other deterioration over time.

Samples that can be used for destructive testing for mechanical characterization (compression testing, for example) are very difficult to source, as viable materials are usually found in heritage buildings in use (and that should continue to be protected). The historic buildings that are being demolished have usually been neglected and allowed to deteriorate to the point of no return, such as the case of the Red Path Mansion in

Montreal (National Trust for Canada, no date), in which case their materials are not representative of the heritage stock in use.

The city development of Toronto presented a unique opportunity to source heritage timber and masonry materials, due to the development of the historic area of town for high rises and the limited protection for heritage buildings outside of their facades. Many historic buildings are being partially deconstructed to make room for new high rise buildings that incorporate the historic facades of the original buildings. The original buildings being deconstructed are in good condition, therefore their materials are representative of those materials still in service. The material studies conducted herein are on masonry and timber due to the availability of those materials from industrial "brick and beam" buildings in Toronto (Koo, 2013), but also due to safety concerns about fire testing of heritage steels.

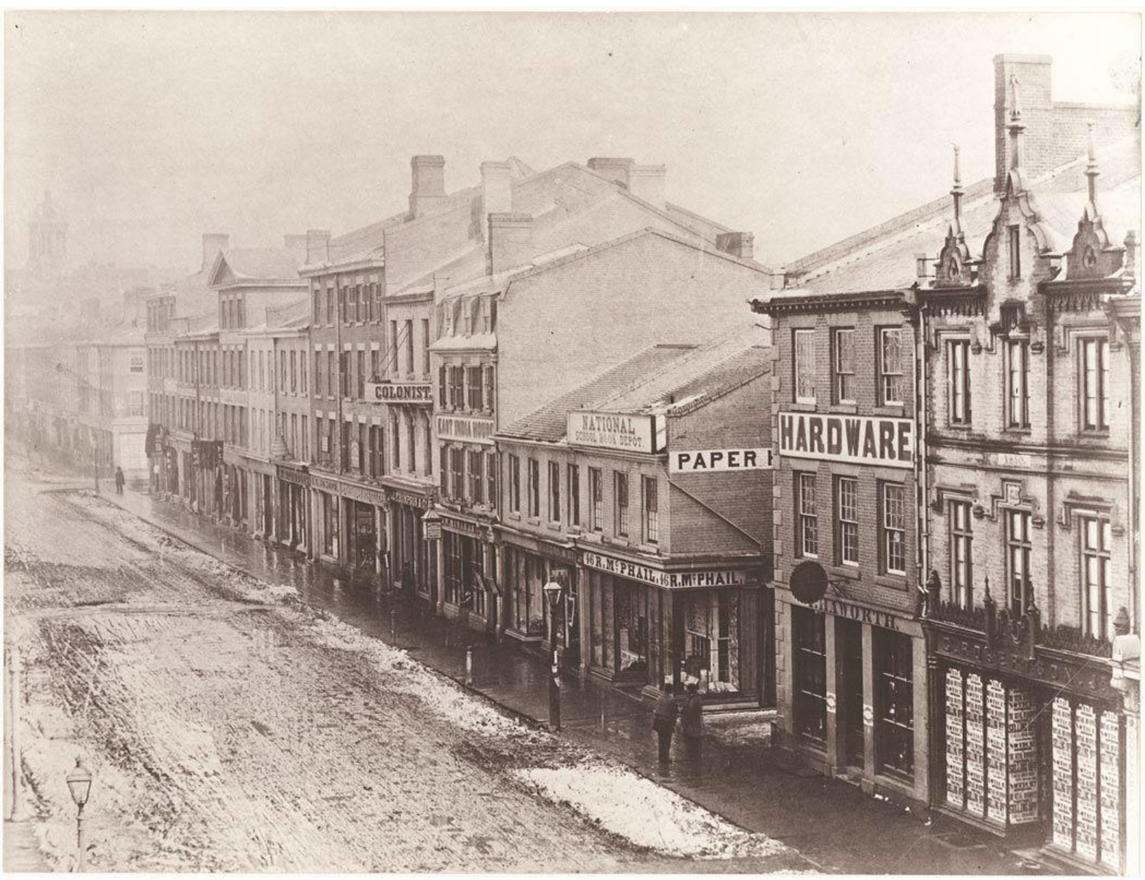


Figure 2.4. King Street East in Toronto 1856 (showing 1840s material source building) (City of Toronto Archives, 1856).

Figure 2.5. Historic facades as seen in 2019. Removed buildings are fifth, sixth, and seventh from bottom right in historic photo (Figure 2.4) (photo by John Gales used with permission).

The historic facades (seen in Figure 2.4 and 2.5) being incorporated into the new 65 King Street high rise are part of the St. Lawrence Neighbourhood Heritage Conservation District, designated in 2015 and currently under appeal to the Local Planning Appeal Tribunal (LPAT). In Toronto, the Heritage Conservation Districts are protected under Part V of the Ontario Heritage Act. The addresses of the buildings partially demolished were 71-85 King Street East, and they were all also listed under Part IV, yet they were deconstructed in 2019 for the new high rise due to a Heritage Easement Agreement. These agreements are reached to preserve some elements of the building, in this case only the façade, and to control the demolition of these protected buildings. Within the heritage conservation field keeping only the façade of a building, known as facadism, is a controversial practice that was popular between the 1970s-90s but is now seen to compromise the authenticity of the heritage site (Cheung Chin Yan, 2015). Alternately to facadism, interventions or adaptive reuse to facilitate the continued use of the building is preferred. The building's functionality holds heritage value (along with interior elements), and is more valuable than just the façade (Kyriazi, 2019).

Historic steels are often covered in a lead coating or lead based paints. The danger of studying heritage steel (and other metals) in fire is illustrated by the lead exposure from the fire at the Notre Dame Cathedral. The lead from the melting roof and spire not only affected the surrounding environment, but also had an effect on the firefighters at the scene. Moderate lead contamination was found in 10% of the firefighters with more than a 9 hour exposure, even with the use of respiratory protection. (Allonneau *et al.*, 2021). There are also risks identified in a study of the occupational exposures from lead-based paint abatement in structural steel demolition, that identified heavy demolition work involving acetylene torch curring or welding, all involving heat, had the highest exposures (Jacobs, 1998). Other safety concerns related to heritage materials for testing is the presence of asbestos.

2.4 Summary

This chapter covers the three areas of topics covered in the coming chapters. The subjects are introduced to provide background and context to the concepts discussed herein. The section (2.1) on fire behaviour covers the basics of real fires and fire resistance testing. It presents the additional concept of fire resilience that considers performance in fire and also operations and residual strength after fire. The section also covers fire protection systems, both active and passive, and an introduction to material behaviour in fire that is built upon in Chapters 4 and 5. The human factors section (2.2) covers emergency egress and wayfinding, prescriptive and performance based approaches to egress, and heritage considerations such as building layout and occupant familiarity with the building and fire procedures. The heritage conservation section (2.3) discusses rehabilitation projects and discusses fire risk considerations specific to heritage buildings like increased arson and material combustibility. The conflicts between the fields of fire safety engineering and heritage conservation are also discussed, the obscuration of character defining elements with fire protection systems for example, and an overview of the other studies considering these two fields is included. The challenges regarding collecting and testing heritage materials are also described.

Chapter 3: Human Factors

3.1 Introduction

Architectural interventions to heritage buildings need to comply with egress and fire codes, however these are often at odds with preservation standards and guidelines, obscuring or damaging character defining elements. There is need for these two aspects to mutually be considered when planning the appropriate rehabilitation of these heritage buildings, something that is not considered in prescriptive fire code requirements that are applied to all buildings regardless of heritage status.

Herein, an evacuation modelling study was recently conducted on an early 20th century historic cultural center in Ontario, Canada. The study collected movement data from real egress events to monitor exit usage and occupant behaviour, and gather modern occupant data relevant to cultural centers (Champagne *et al.*, 2019). Movement profiles were subsequently produced and validated to be used for modelling the egress of the building. The heritage designated building had undergone many changes in use, as well as a recent major renovation where many changes were made to update the structure and layout to comply with building code requirements in Ontario. New emergency exits, staircases, and structural elements were added to create alternate egress routes to comply with modern building codes to improve the fire safety of the building.

A model of the building has been created and the validated movement profiles (presented in Harun *et al.* (2020), attached in Appendix A) are used to simulate egress in Pathfinder, a pedestrian modelling software. The movement profiles are based on observed behaviour, which can inform issues that may arise with egress, even for code compliant buildings.

This research represents a novel use of human behaviour modelling being applied to heritage conservation, bringing heritage buildings into the future while minimizing changes to the character defining features that hold their value.

The prescriptive approach may not be ideal for heritage buildings, and a performance based approach may be more appropriate to consider solutions that improve fire safety while respecting conservation guidelines, and minimizing interventions.

3.2 Motivation and Research Objectives

Heritage buildings must meet modern fire safety standards when undergoing changes in occupancies or major renovations, two occurrences that are common for large public heritage buildings such as cultural centers (Canadian Commission on Building and Fire Codes, 2015a).

Data on evacuations (quantities and egress times) are limited for historical buildings, and the studies that are available are dated from (1950s-1980s) and are therefore not representative of modern populations (Thompson *et al.*, 2015). The dearth in real movement speeds/data was one of the main motivations of the original study on the cultural center and the motivation to collect this data (Champagne *et al.*, 2019; Harun *et al.*, 2020), and this dearth is even greater when considering heritage buildings.

Carattin and Brannigan (2012) points out some of the existing limitations on evacuation modelling in heritage buildings, and the need to consider the unique architectural features and their effect on human behaviour modelling. Features such as the complexity in heritage buildings slowing/impeding egress, which is seen in this study with the addition of new stairs.

Most of the research regarding heritage buildings and fire evaluate the unique fire risks associated to heritage buildings, but rarely does that risk analysis translate to design solutions (Torero, 2019). The research herein will explore the effectiveness of prescriptive designs in heritage buildings, and illuminate areas where design can be improved. The motivation is to improve the emergency egress of heritage cultural centers without unnecessarily compromising heritage value (by changing or obscuring character defining elements).

The research objectives are to evaluate the effectiveness of prescriptive code compliant changes in heritage buildings and to identify the most lucrative intervention, by measure of the reduction of total egress time.

The insights learned from this research will help create a framework for improving the fire safety of heritage buildings, and considers whether prescriptive code compliance adequately improves life safety. This objective is built upon through lessons learned from the critical evaluation of a real buildings' architectural interventions on simulated egress.

3.3 Case Study

3.3.1 Cultural Center

The cultural center that is the subject of this study is an early 20th century cultural center in Ontario. Though the building has gone through many changes in use throughout its service life, the original designed function is the same as it is today, as a cultural center. Though unlike the original design, which had intended to only be open to the public on the 1st and 2nd floors, all 4 levels above ground and one basement level are open to the public. The expected occupant load today is therefore much greater than the designed occupant load, and the building was constructed before the building and fire codes were formalised in Canada (National Research Council of Canada, 1941).

Nearly two decades ago, the cultural center underwent a major rehabilitation to serve its current occupancy and improve both structural and fire performance of the building. The interventions relevant to the egress of the building were the addition of 10 new emergency exits, and the closure of one the original exits. Therefore the total number of exits increases from 3 to 12 after the rehabilitation. New staircases were also added to connect the upper 3rd and 4th floors to the main circulation space, since they were originally not intended for public use and their access was limited. This new staircase is also a major structural addition to the building, and required columns to be installed in the foyer of the main entrance to support their weight. The columns sit in front of two of the three doors in the main entrance. During regular use, only the center door (unobstructed) is in use, but during emergency egress, the use of the additional two doors can be very useful in allowing faster egress and avoiding crowding in the main entrance.

All these interventions were implemented, illustrated in Figure 3.1, in an effort to improve the fire safety and emergency evacuation of the building and to comply with modern building codes. The ultimate goal of code compliance is to improve life safety in the building in the event of fire or other emergency egress situation, but code compliance doesn't necessarily equate with improved fire safety.

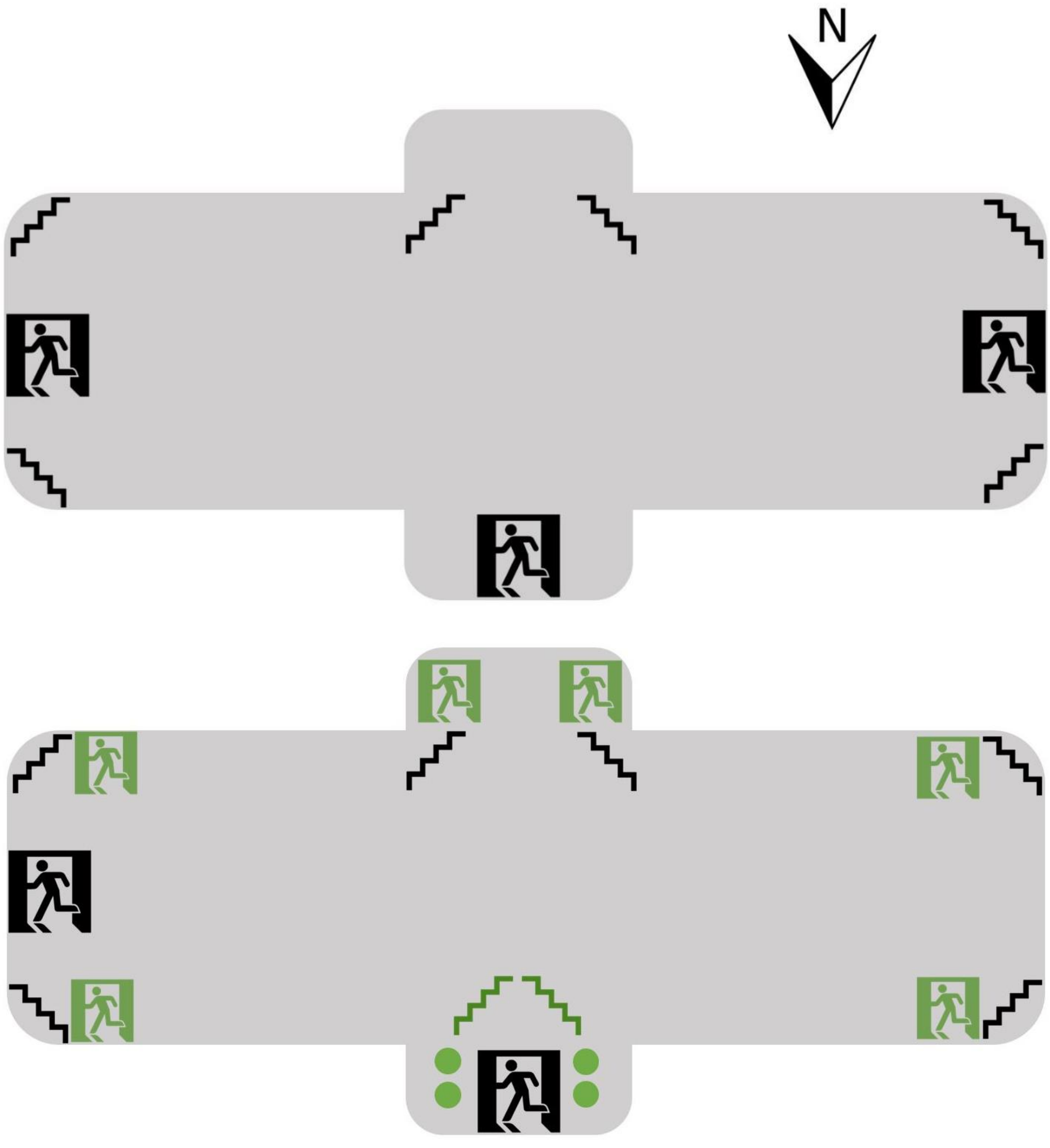


Figure 3.1. Simplified museum floorplan showing the historic exit and stair locations in black (top), and current layout with additional elements (stairs, exits, and columns) in green (bottom). Three new exits in back corners simplified to one exit on each side in diagram (seen at the top of the diagram).

3.3.2 Previous Studies

The previous study conducted on the museum by Champagne et al. (2019) and presented in Gales *et al.* (2020), which this data and modelling is derived from, was conducted using evacuation footage from three planned and unplanned evacuation scenarios (scenarios 1-3) over the course of two years. Video footage was recorded using CCTV (closed-circuit television) and a few additional cameras to cover blind spots to be able to monitor the occupants during the evacuation. Occupant behaviour was thoroughly tracked and noted, such as exit use, pre-movement time, and movement speeds. Scenario 1 was an unplanned evacuation triggered by the accidental trigger of the alarm by a child. Scenario 2 was a planned yet unannounced drill to evaluate the evacuation performance of the cultural center. Scenario 3 (also planned and unannounced) was conducted after some (non-structural) improvements were made to the emergency evacuation plan, such as staff training and improved exit signage (Champagne *et al.*, 2019).

Some important events to note from the scenarios are as follows. In Scenario 1, upon the triggering of the alarm, automatic sliding fire doors closed the exhibits off from the main vestibule in an effort to direct occupants to the emergency exits that egress directly to the outdoors and to provide compartmentation that heritage buildings often lack (Bernardini, 2017). The occupants were not familiar with those emergency exits and worked together to pry the doors open that lead to the main entrance, where they entered originally, to egress through the atrium to the front doors instead. In Scenario 2, the fire doors did not close to separate the atrium from the exhibition spaces, and even more occupants egressed through the main entrance. Based on the events described, it is noted that 72.9% and 92.3% of occupants use the main entrance for their egress in the first evacuation scenarios, and later 34.2% with the measures improve egress for Scenario 3.

This highlights some considerations discussed in section 2.2.2 about heritage considerations in human behaviour, such as familiarity with the building layout, familiarity with egress routes, and behaviours or different cultural groups. The study discussed earlier on linguistic abilities effect on pre-movement times, Mazur *et al.* (2019), is based on this case study as well.

Movement profiles were derived from Scenario 2 using Kinovea, a software that tracks user-specified objects in videos and corrects for lens and angle distortions. These profiles were then used in a 3D model of the cultural center, and compared to the real data to validate the model. This preliminary modelling is presented in Harun *et al.* (2020) and used as a starting point for the modelling presented herein.

3.5 Methodology

3.5.1 Modelling

The pedestrian modelling software Pathfinder (version 2021.2.0525 x64) was used to create the evacuation simulations for the various interventions described in the previous section. Pathfinder is a social forces steering based pedestrian modelling software, that uses kinetics and inputted movement parameters to move occupants through a physical mesh determined by the layout of a building and available exits. A 3D model of the current building layout was used as a baseline and inputted into the software to conduct the pedestrian modelling. The presumed historic floorplans were simulated to serve as a baseline for the original egress. The interventions from the major renovation were then added to the model for simulation to represent the total egress improvement. With those two models as baselines, the individual contributions of each intervention were isolated to evaluate their effect on emergency egress.

The summarized (not separated by demographic) movement profile created during the previous study (Harun *et al.*, 2020) was utilized as the focus of the research is on the architectural details and comparison between the historic and current floor plans, not the validation of the model, which had already been completed. The maximum occupant loading was used to emphasise the differences between the historic and current layouts, as with lower occupancy the number of exits is less critical to the total egress time.

Table 3.1. Summarized occupant loading table, based on the cultural center and OBC/NBCC requirements (National Research Council of Canada, 2015).

Floor	Occupant Load
Basement	253
Ground	1777
2^{nd}	682
3^{rd}	872
4^{th}	600
Building Total	**4184**

Table 3.1 is a summary of the occupancies based on information provided by the museum and the designers of the major rehabilitation. Where occupant loading data was missing, occupant load determination was used from the OBC 1997 (in use during the current fire protection design of the building). The occupant loading is based on the modern loading, and the same occupant distribution is used for each of the models, including the historic versions, to facilitate comparison. The summary of occupant distribution is presented in Table 3.1 by floor, but the calculations were conducted based on the use of each space, whether exhibition space, cafeteria, theatre, board room, to name a few examples. The occupant density is relatively uniform across the building on each floor except for the ground floor, where the west wing of the building serves as exhibition space (with a lower occupancy), while the east wing serves as an additional entrance space that has a significantly higher density. This is important to note when considering the egress of the building, as some sections will evacuate faster than others. The distribution of occupants was conducted randomly in Pathfinder within the specified areas corresponding to specific occupant loads. Therefore, the total number of occupants on each floor remained consistent through each simulation, but the original occupant location varied between the simulation runs.

Movement profiles and pre-movement times were developed from videos from the real evacuation Scenario 2 and were counted from the 2^{nd} stage alarm (the alarm indicating to occupants to evacuate the building).

Table 3.2. Summarized movement profile (not separated by demographic).

Movement Profiles	Min Speed	Max Speed	Mean	Std
Summarized Museum Profile[1]	0.58 m/s	1.98 m/s	1.15 m/s	0.28 m/s
Pathfinder Default Profile[2]	1.19 m/s	1.19 m/s	1.19 m/s	0 m/s

[1] (Harun *et al.*, 2020)
[2] (Thunderhead Engineering, 2021)

Table 3.3. Pre-movement times from scenario 2 (n=204) (Champagne et al., 2019).

Pre-Evacuation Time (Seconds)	No. of Occupants	Percentage of Occupants (%)
0-5	35	17
6 - 10	36	18
11 - 20	30	15
21 - 30	38	19
31 - 60	40	20
61 - 120	18	9
121 - 210	7	3

The summarized movement profile presented in Table 3.2 was created using computer-aided tracking (Kinovea) on various populations walking through an open area of the museum (the atrium), so this is considered an unimpeded walking speed. Different walking speeds for different age demographics were collected, but since an adequate sample size for each demographic could not be tracked, the summarized movement profile (not subdivided by demographic) was used for this study. This way the overall characteristics of the occupants that are seen in cultural centers are used. These movement speeds have been validated in the previous study (Harun *et al.*, 2020), in which the models are tested to check that the simulated models capture the egress behaviour in real experiments (Thunderhead Engineering, 2021). Table 3.2 also presents the default movement profile used by pathfinder if no alternate movement profile is used. While the mean walking speed of 1.19m/s only has a 3.4% difference from the museum profile mean of 1.15m/s, the specified movement profile with minimum, maximum, and standard deviation values for this unique cultural center captures the different movement speeds of the great variety of occupants from toddlers walking hand in hand with their parents or elderly occupants walking with the help of mobility aids, to able bodied teenagers and adults walking swiftly through the building. Table 3.3 presents the pre-movement times unique to the cultural center, considered in human factors in the pre-movement phase of egress where occupants are gathering information to make evacuation decisions and gathering belongings before egress. The pre-movement times in this case consists of the time from the alarm notifying the occupants to evacuate, to when they began their egress. Pre-movement times are not included in the default Pathfinder parameters, and these times are specific to this building which is unique in occupant demographic and layout.

3.5.2 Building Layouts for Evaluation

To evaluate the interventions of interest introduced in the previous section, the new exits, new stairs, and new columns in the foyer, a number of modelling layouts will be conducted to isolate the effects of each of the changes, detailed in Table 3.4. The models with all the columns, with only the back columns, and without columns in the foyer are shown in Figure 3.2.

Table 3.4. Building layouts evaluated and their details.

Layout ID	Name	Details
L1	Historic	Historic
L2	Historic + Stairs	Historic + Stairs
L3	Historic + Stairs + Columns	Historic + Stairs + Columns
L4	Historic + New Exits	Historic + New Exits
L5	Current – Door Columns	Historic + Stairs + Exits + Back Columns
L6	Current – All Columns	Historic + Stairs + Exits
L7	Current	Historic + Stairs + Columns + Exits

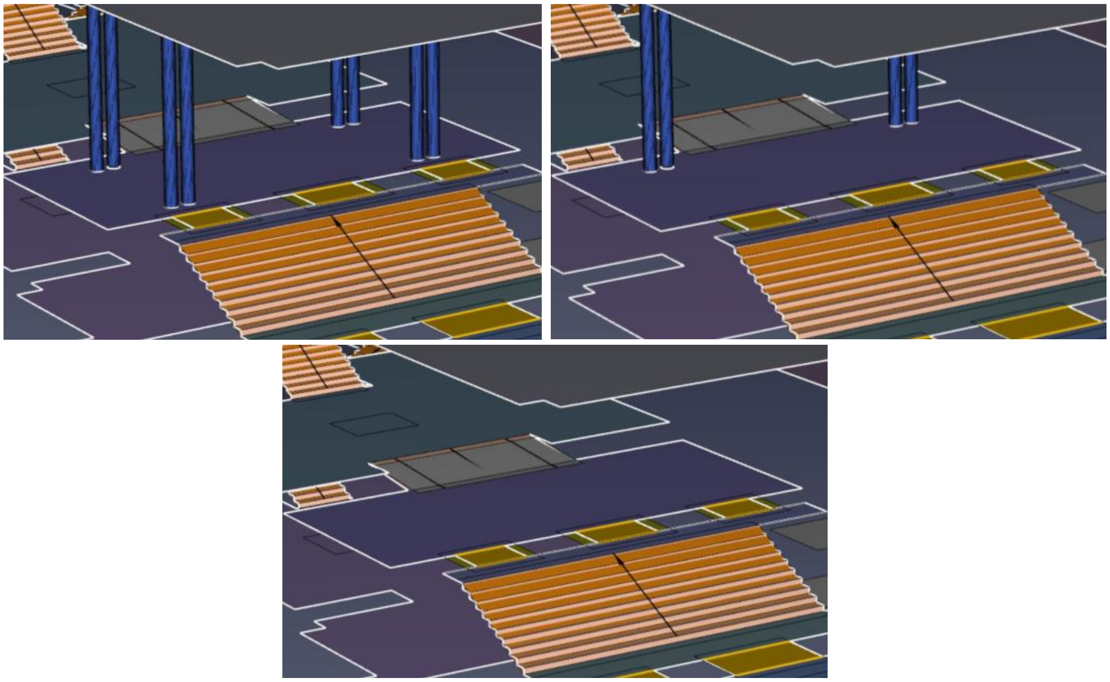


Figure 3.2. Model with and without the columns obstructing two of the three main entrance doors.

Layouts L1 and L7 will serve as a baseline to isolate and evaluate the effectiveness of each of the interventions individually, as they represent the historic and current layouts of the building.

Each of the models representing the different layouts of the building were run 10 times to converge on the average results between the simulations. Random sampling of the occupant location (within the room with the occupancy) is used to create variation within the models. With only one changing variable, the convergence of results can be achieved in a small number runs. The methodology of Smedberg, Kinsey and Ronchi (2021) calls for more simulations for the design of buildings, but with only one changing variable and for the services of comparison, a limited number of runs is sufficient. The other variables used during simulation are based on real evacuation data that has been validated in this model, such as pre-movement times (wait times) and movement speeds. The egress times presented herein, and other values analysed, represent the average of the 10 model simulations.

3.6 Modelling Results

3.6.1 Historic vs Current Layout

According to the simulation, the historic layout's egress time with the same occupancy of today would be 12:31 minutes, while the current layout's total egress time is 10:29 minutes. This is a difference of 122 seconds, a little over 2 minutes (17.7% difference). The decrease in occupants in the building over time is seen in Figure 3.3. While the total egress time is only 2 minutes apart, the differences in egress can also be seen in the differing slopes and they key points in the graph. The historic layout has a slower egress initially, which slows even further between 400-500s. The slowing rate after 400s is due to the lower occupant density in the west wing of the building, so all the agents have all completed their egress, so the egress rate is from the use of only two exits, and not the original three.

The current layout has a faster start (and end, ultimately), but with changes in slope points at 250-300s and 500s. The first change in slope is due to the end of a queue of agents in a back east exit. All the agents using that exit evacuated. The other change in slope is due to a similar effect, but with the main exit, and other side exits soon after.

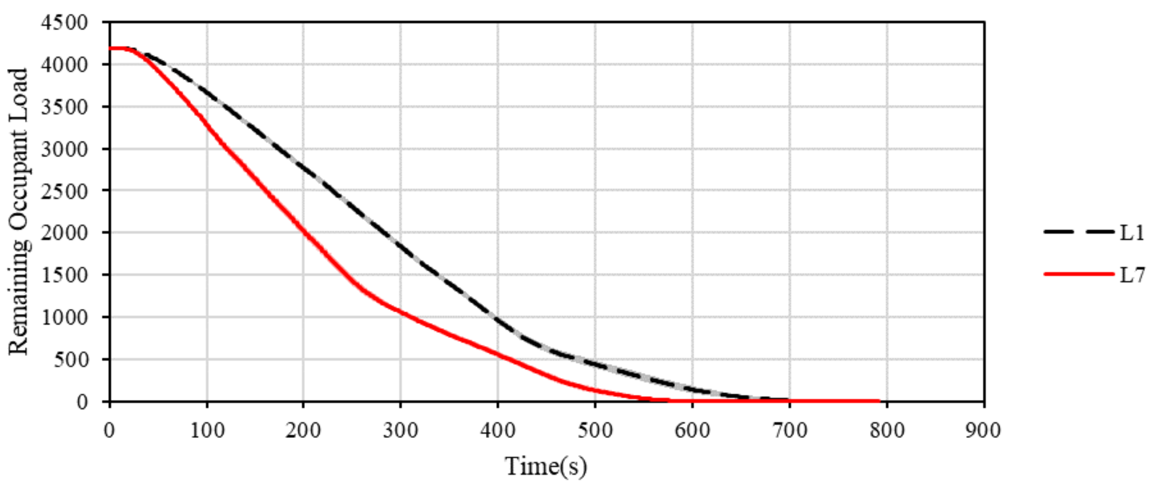


Figure 3.3. Total average egress times of historic (L1) and current (L7) layouts.

3.6.2 Intervention Isolation Models

To understand the individual effects of each of the intervention, all the hypothetical building layouts must be considered. The total egress times of each layout is presented in Table 3.5. The longest egress time is 13:12 minutes from L3, the historic layout with additional stairs and columns, while the shortest is 10:14 from L6, the current layout without any columns. This represents a 25.3% difference.

Table 3.5. Average total egress time of each layout.

Layout	Name	Total Egress Time (min:s)
L1	Historic	12:31 (751s)
L2	Historic + Stairs	12:48 (768s)
L3	Historic + Stairs + Columns	13:12 (792s)
L4	Historic + New Exits	12:10 (730s)
L5	Current – Door Columns	10:15 (615s)
L6	Current – ALL Columns	10:14 (614s)
L7	Current	10:29 (629s)

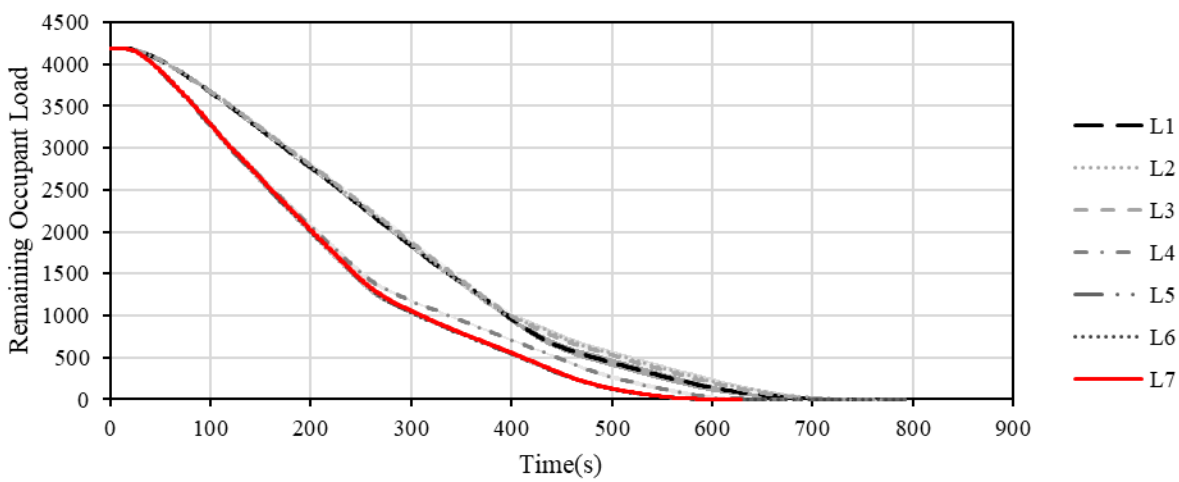


Figure 3.4. Total average egress times and standard deviation of all the layouts (L1-7).

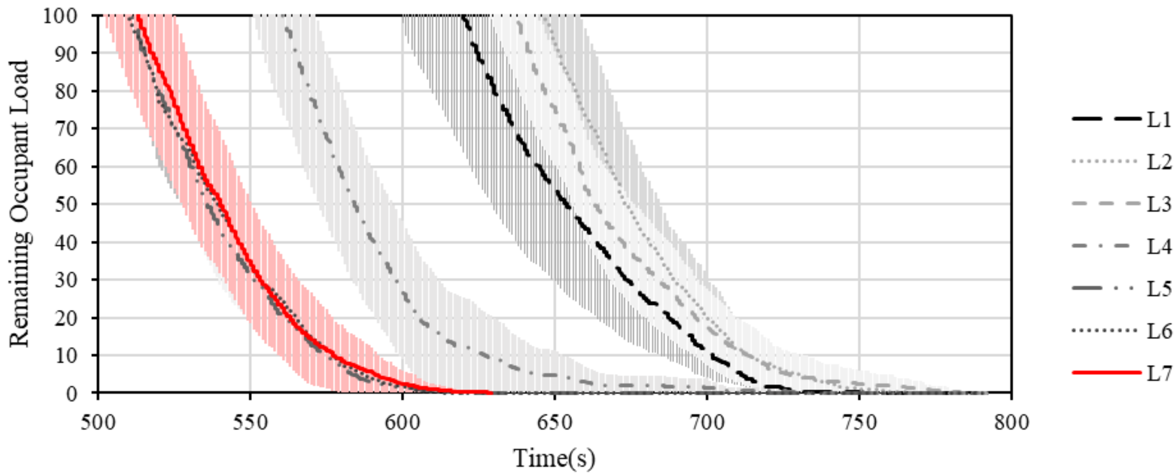


Figure 3.5. Close up of total average egress times and standard deviations of all the layouts (L1-7).

Figure 3.4. shows two distinct trends between the layouts, with L1-3 having a slower start, and L4-L7 with a steeper initial slope. Upon closer inspection in Figure 3.5. L4 (historic layout with new exits only) deviates from the other layouts after the 200s mark.

The general trends of the changes in slopes at critical points in the egress discussed for L1 and L7 hold true for the intervention isolation models as well (L2-6), and represent the end of use of one of the exits.

Table 3.6. Peak density and time in the main entrance (atrium).

Layout	Peak Occupant Load (n)	Time (s)
L1	325	164
L2	346	60
L3	345	81
L4	275	6
L5	281	6
L6	286	6
L7	277	6

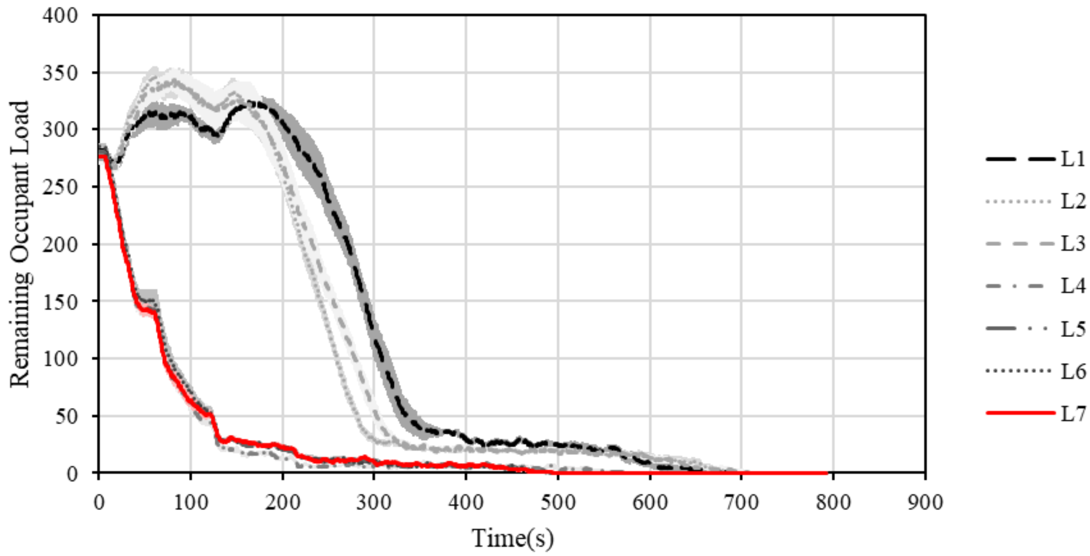


Figure 3.6. Average occupant load in main entrance (atrium) and standard deviation for the different modelling scenarios.

Similar to Figure 3.4, Figure 3.6 shows trends between layouts L1-3 and L4-7. L1-3 layouts are characterized by their original exit layout (3 exits), and layouts L4-7 by the new exit design (12 exits). The first three layouts using the original exits have an increase in occupant density in the atrium (in front of the main exit) for the first 200s of the egress, while those with with new exits do not experience this bottleneck at the main exit. For those with the new exits (L4-7), the peak occupant density in the main atrium is at the beginning of the simulation, and agents do not accumulate in that area, as they have access to many other exits.

3.7 Discussion of Study Areas

3.7.1 Main Foyer Columns

The columns in front of the doors in the main foyer were isolated in the model using various layouts, through adding and removing from both the historic and current layouts. Overall, they were found to have a negative effect on the overall egress time of the cultural center. This is best illustrated by L3, which is the historic layout with the stairs and column additions, which had the longest total egress time of 13:12

minutes. The direct effect of the columns can be found through the difference of total egress times between L2 and L3 of 24 seconds, where the only change to the model was the addition of the foyer columns in L3.

When comparing the current layout (L7), to the hypothetical current model without the columns (L6), removing the columns decreased the average egress time by 15 seconds. This is in line with the effect observed between L2 and L3, though the time difference is less significant because the later models had a greater total number of exits, therefore less occupants were using the main entrance where the columns were located.

In evacuation models, it has been observed that obstacles, especially circular ones like the columns in the cultural center, placed in front of doors limit bottlenecks occurring in those doorways and facilitate egress (and ultimately improve egress times) (Frank and Dorso, 2011; Yano, 2018). This is due to agents in the modelling software using obstacles, such as columns, to queue while waiting to exit. In a recent study titled "Redefining the role of obstacles in pedestrian evacuation" (Garcimartín *et al.*, 2018), it was found that unlike an effect observed in evacuation software, the presence of an obstacle in front of the door does not reduce egress times in real evacuation drills. To address the possible positive effects of the columns in the foyer on the model, the models L5 and L6 were both analysed, which represent the current layout without any of the foyer columns (L6) and the current layout with only the back columns (L5). These layouts only had a difference of 1 second in total egress time, illustrating that the back columns had little effect (positive or negative) on the egress of the cultural center, and the columns in front of the doors are responsible for the delayed egress in L3 and their removal of the faster egress in L5 and L6.

The effect of agents queuing along the columns was observed in the simulations, however the columns were close enough to the entrance doors that a bottleneck was still created, and the columns ultimately slowed egress in the models. This effect is important to note, since it could imply that the effect of the columns in front of the doors has a greater negative effect on egress then evacuation modelling is able to capture.

When considering the effect on door usage, the percentage of occupants using the central door versus the side doors obstructed by the columns, the simulation data shows that there was an increase of 1.5% of the occupants exiting the center door in the model with the columns (L7) compared to one without (L5). Therefore the presence of the columns in front of the doors has a small effect on which door the occupants use. More importantly, the small difference indicates that the egress is slowed from the columns in front of the doors, and not due to larger travel distances to other exits or a bottleneck created in the center door from agents avoiding the obstacle. There was less than a 1% difference in the quantity of occupants using the main exit between the two scenarios considered (L5 and L7), so again the columns slowed the egress but did not change the exit usage. In the video footage of the real evacuations, this path along the columns was not observed and most of occupants used the central door to egress from the foyer, though the occupancy was much lower which allowed for minimal queuing in that area and less of a need to use the side doors.

Another aspect to consider that might indicate the columns have a more significant effect on the egress than the modelling can capture is the exit usage. In the current layout model (L7), the average exit usage was 14.9%, whereas in the real evacuation data shows that 34.2% of occupants used the main entrance to evacuate for scenario 3 (where improvements were made to improve occupant decision making). This is due to the familiarity of the route to the main entrance, the point of entry for most occupants to the cultural center. This is in line with the findings from Kinateder, Comunale and Warren (2018), which found that exit familiarity had an effect on exit use in virtual reality experiments. The more occupants using the main exit to egress, the more significant effect the columns will have on the total egress time.

3.7.2 New Stairs

The new stairs that connected the 3rd and 4th floors in the atrium to publicly connect the higher and lower floors, and bridge the gap between intended public and private space in the original building design, were observed to have a negative effect on the total egress time. They were not egress stairs, but provided occupants an alternative staircase to access the lower floors, and get to an egress staircase on the 2nd floor. They are not designed as an egress route as part of the emergency plan, but occupants did use them to descend floors of the building to access the main atrium stairs on the second floor. This is in line with what was observed during the real evacuation scenarios, were occupants used the main atrium space for the egress, despite signage to use the egress routes that were less familiar to occupants.

The addition of these stairs to the historic layout, captured in L2, increased the total egress average by 17 seconds compared to the historic layout. From observation of the simulations, this is due to the central placement of the staircase, in which the agents used to get to the second floor and were funneled into the main staircase. Whereas without that staircase, those occupants directed themselves to the less used side exits, and didn’t contribute to the bottleneck at the main entrance. This theory is supported by the occupant density graph of the main atrium (figure 3.6 and table 3.6), where the highest occupant loads of 346 and 345 are from L2 and L3 respectively, the historic layouts that include the new staircase.

3.7.3 New Exits

When looking at the trends of all the layouts modelled in Figure 3.4, the element that has the most effect is the addition of the new exits. Beyond the trend analysis between L1-3 and L4-7 (where the visible difference in egress times is due to the presence or lack thereof of the new exit layout), the impact of the new exits is captured in the comparison between L1 (historic layout) and L4 (historic layout + new exits), with a difference of 21s. The addition of the 10 new exits has a clear positive impact on the total egress time, even though one of the original exits was closed during renovations, bringing the total available exits from 3 to 12 between the historic and current layouts.

3.7.4 Overall

Despite the breakdown of significance of each intervention (columns, stairs, or exits), it’s important to note that the overall egress improvement from the extensive renovations only represents a 17.7% decrease in total egress time.

The interactions between the interventions cannot be overlooked, especially those with the new exits. Notably the additional stairs increased the egress time in the historic layout by 17 seconds because it funnelled occupants to the center of the building where there was only one exit, and the new exits alone only reduced the egress time by 21 seconds. Though the layout including the new exits and the new stairs (L6), had a reduced egress time of 137 seconds compared to the historic layout (L1), and notably had the shortest average egress time of all the layouts. As discussed, the new stairs direct more occupants to the center of the cultural center where there was only one exit, but with the new exit layout there are 7 exits in the center of the cultural center. The combination of these two interventions is what ultimately reduces the total egress time from the historic to the current layout. The overall 17.7% reduction of total egress time from all the interventions are from the positive combined effect of the new stairs and exits, and the negative effect from the columns in front of the doors.

3.7.5 Limitations

One aspect of the major renovations on the cultural center that was not considered in the evacuation modelling was accessibility. There were several changes to the heritage building to facilitate accessibility, notably an elevator in the entrance foyer that reduces the total width of stairs in between the atrium and foyer. The research is based on validated movement speeds and behaviours observed in the cultural center, which included occupants walking with aids (canes, for example) and families with strollers. Though beyond their movement speeds being included in the summarized speeds used in the model, architectural changes to the building for the purpose of increasing accessibility were not included in this study in an effort to isolate the fire related code compliance updates. Any accessibility features (such as the entrance elevator), that are in the current layout of the cultural center were included in all the models.

This introduces another limitation, the historic layout of the building is speculative, due to restricted access to the original floor plans. The details of the major rehabilitation project are well documented, therefore all the elements considered were added in the renovation, but there could have been other undocumented changes to the building layout in the building's early history that are not captured in this study. The purpose of the study was to isolate the effects of particular code compliant interventions, not to evaluate the historic egress of the building.

Considering the modelling, increasing the modelling runs for each layout would allow the simulations to converge on a more accurate result.

3.8 Conclusions and Recommendations

Comparing the historic layout of the cultural center to the current layout, the models show a decrease in total egress time of 17.7%, from 12:31 minutes to 10:29 minutes. At first glance, it can be noted that the major renovations improved the egress of the building, but when isolating the interventions (the new stairs, new columns, and new exits) each of them can be evaluated for their effect. Of all three interventions, it was found that adding more exits (new emergency exits) has the most significant improvement on egress time (considering the reduction of total egress time). From the increased egress time with the addition of the stairs and columns to the historic layout, it was found that obstructing egress routes with architectural features increases egress time. Complicating egress routes with additional paths that do not connect to the outdoors also increases egress time, unless used to redistribute occupants away from bottlenecks.

The interactions between prescriptive changes must be studied in the specific context of the building being rehabilitated. Blanket prescriptive methods are not appropriate for heritage buildings, and performance-based approaches are preferred. More research into modelling of heritage buildings is needed to ensure the validation of these models, considering appropriate input data (movement speeds of modern populations, considering factors such as cultural background and building familiarity) and accurate modelling parameters. This study highlights the need for heritage conscious performance-based fire safety design for emergency egress in heritage cultural centers.

Chapter 4: Timber Material Factors

4.1 Introduction

Timber is a common building material found in historical buildings in Canada and across the world. 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 (*La Charpente*, 2021)) and the spire (which dated to the 19th century) collapsed and were destroyed in the fire (Manuello Bertetto, D'Angella and Fronterre', 2021). 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 (Araujo, 2019). 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 (Tannous, 2019) (US$330-670 million (Noack, 2019)) and US$125 million (Daley, 2019) 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 (Kincaid, 2020).

There is limited guidance available in standards and codes on heritage timber in fire as there is in general, discussed in chapter 1. To determine the fire properties of timber, it suggests referring to *Eurocode 5: Design of Timber Structures* which targets contemporary timber products (European Committee for

Standardization, 2004). 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 affects the fire performance of all timbers is the presence of radial cracks or gaps within the timber (Stanke, Klement and Rudolphi, 1973; *Technical Report No. 10: Calculating the Fire Resistance of Wood Members and Assemblies*, 2018). 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 4.1. 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 4.1. Partial attempted sealant repair on a radial crack present on a column.

A limited number of studies have previously investigated heritage timber. Chorlton and Gales (2019) obtained timber from one mid-1800s structure and another early-1900's structure, both in Ontario. The timber was tested relative to contemporary Glued Laminated Timber (Glulam), and all timber sources were tested in a Cone Calorimeter apparatus, with a subset of timbers further tested in a Lateral Ignition and Flame Spread Test (LIFT) apparatus. Metrics recorded from the Cone Calorimeter tests included char depth, time to ignition, and heat release rate, whereas flame spread rates and self-extinguishment were noted from the LIFT tests. Conclusions by Chorlton and Gales (2019) included that heritage timber charred at a rate up to 20% faster than contemporary Glulam, and it is therefore not always conservative to assume heritage timber will perform as well as contemporary timber (Chorlton and Gales, 2019). Chorlton and Gales (2020) recreated five types of heritage encapsulation materials, used during the 18th and 19th centuries in attempt to protect timber from fire. The history of each encapsulation material was presented, and recreated plasters, metal plates, and paints were applied to timber and tested in a Cone Calorimeter apparatus. It was found that each of the heritage encapsulations had some drawback (i.e. the encapsulation would fall off, allow charring around fasteners, or not significantly contribute to improving the fire performance of the material), and that the encapsulations cannot be relied upon if found in heritage structures in practice (Chorlton and Gales, 2020).

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.

4.2 Background

4.2.1 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/m2 to heat the beams which had embedded thermocouples (Ervine *et al.*, 2012). 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 (Ervine *et al.*, 2012).

Studies regarding the effect of cracks on 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 (Liu *et al.*, 2021). 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 (Liu *et al.*, 2021).

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).

4.2.2 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 (Richter *et al.*, 2020). 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 (Roberts, 1971).

The 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 (Bartlett, Hadden and Bisby, 2019). A review by Friquin (2011) concluded that most studies correlated increased moisture content with decreased charring rates (Friquin, 2011). Moisture acts as a heat sink and slows the temperature rise of timber as well as cools the pyrolysis zone through convective transport of water vapour (Di Blasi, Gonzalez Hernandez and Santoro, 2000). Further, moisture content can affect the mechanical performance of timber. In general, the flexural properties including the strength and stiffness of timber increase with reduced moisture content below the fibre saturation point (Nocetti, Brunetti and Bacher, 2015).

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.

4.3 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 analyses of the full-scale members and the small-scale test programme were not included at that the conference stage in the study (Harun, Chorlton, *et al.*, 2020) and are discussed herein.

4.3.1 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 4.2. 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 (Koo, 2013). 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 4.2. Material acquisition from an industrial building in Toronto, Canada.

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 4.3 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 4.3. Improper storage of heritage timber materials.

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 at 50% after procurement to maintain their equilibrium moisture content between 5-10% (Wang, 2016). 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 the 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 4.1, 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/m3 (standard deviation of 13.7 kg/m^3) and a moisture content of 6.6% (standard error of 0.1%) as measured from oven-controlled heating. This equilibrium moisture content corresponds to the low end of accepted relative humidities (Schaffer, 1967). 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 (Michel Njankouo, Dotreppe and Franssen, 2004; Babrauskas, 2005; Friquin, 2011)), though other parameters such as density and species are thought to have a much greater influence on the charring behaviour of the timber (Bartlett, Hadden and Bisby, 2019).

Table 4.1. 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

4.3.2 Full-Scale Tests

Heritage 1 and 2 were tested in a 30-minute methanol pool fire with an average steady state temperature at the soffit of 845°C and allowed to cool for another 30 minutes. The test setup is seen in Figure 4.4. Further details of the methanol pool fire can be found in (Nicoletta, Kotsovinos and Gales, 2019; Nicoletta *et al.*, 2021). Narrow spectrum illumination (as described in (Smith and Hoehler, 2018; Gatien *et al.*, 2019)) 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 spectrum 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 member was centred over the fuel, and the distance from the initial surface of the fuel to the soffit of the member was 0.2 m. The process for determining the most suitable fuel type and volume is detailed in (Chorlton *et al.*, 2020). At the end of the 30-minute cooling period, the members had self-extinguished with no external flaming. Light amounts of water were used at the end of the 30-minute cooling period to extinguish any residual smouldering, though no smoke or signs of residual combustion were observed..

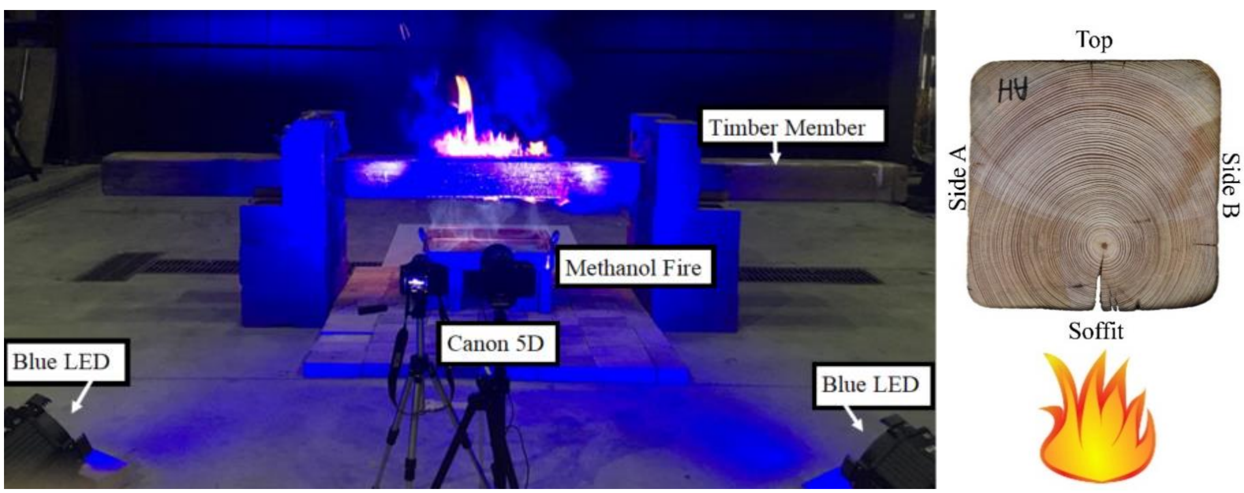


Figure 4.4. Experimental test setup for pool fire, view of beam Side B.

A pool fire was selected instead of a radiant heater for this phase of testing. This was done 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 (Gales, Chorlton and Jeanneret, 2020) was also not practical for this type of study as one of the aims of 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 fire (Nicoletta *et al.*, 2020). Chorlton et al. (2020) 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 (Chorlton *et al.*, 2020). 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.

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 (ASTM International, 2014). The loading rate is also inline with ASTM D198 (ASTM International, 2015). The test setup is seen in Figure 5. 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 understanding the recovery of a heritage timber structure that had previously experienced a fire.

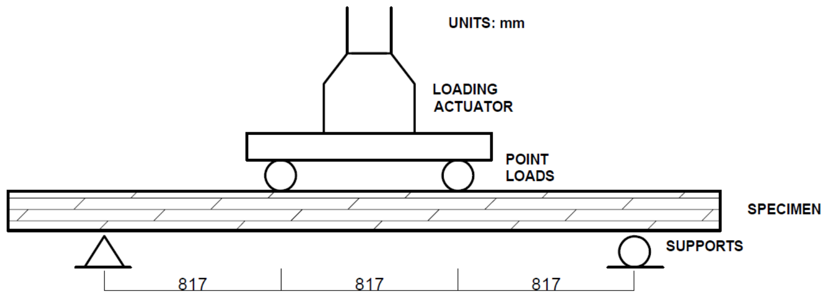


Figure 4.5. Four-point bending test setup.

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 4.6. 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 4.6, 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 4.6 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) (Stanier *et al.*, 2015), a technique shown to be accurate for monitoring displacement in wood specimens (Quiquero and Gales, 2016).

Figure 4.6. Loading test setup (left) and member cross section slices (right, top- towards the end of the member, bottom- towards the center of the member).

After the timber members were loaded until failure, they were cut into 25 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 4.6. The cross sections are vital to evaluating the char penetration into the crack present in the timber as a result of the fire test.

4.3.3 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 4.2. 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. All Cone Calorimeter samples were tested with the heat exposure perpendicular to the grain direction.

Table 4.2. Summary of Cone Calorimeter tests, where "Solid" samples are characterized as having a maximum crack width of 2 mm.

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

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 (ASTM International, 2017) shown in Figure 4.6. 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/m2, 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/m2 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 (Xu *et al.*, 2015). 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 (Xu *et al.*, 2015)). 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 a previous research program using the same methodology (Chorlton and Gales, 2019), 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.

Figure 4.7. Cone calorimeter test setup.

4.3.4 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. Finally, future research could consider the effect of combined heating and loading of cracked timber. Previous research has shown that creep can occur in timber that is simultaneous heated and loaded (Wiesner, Deeny and Bisby, 2020), and the expected crack width could be impacted by this effect.

4.4 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.

4.4.1 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 4.3. 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 4.3 include the existing cracks on the soffit for member Heritage 1 and side A for Heritage 2. Figure 4.8 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 thermal image serves as a confirmation that the narrow spectrum illumination technology indeed shows the development of the crack, as the heat in the cavity is captured in the thermal imaging.

The char depth measured at each 25 mm slice for the soffit of Heritage 1 and 2 were recorded and presented in Figure 4.9, 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 4.10. 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 4.9 represents the char measured on the soffit of the member, while Figure 4.10 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. Char depth can provide an idea of the temperature distribution reached within the sample, with a temperature of 300 °C being generally accepted as the onset of charring (Bartlett, Hadden and Bisby, 2019). Figures 9 and 10 therefore give an idea of the location of the 300 °C isotherm along the length of the member.

Table 4.3. 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)	10.4 mm (Side A)	16.9 mm (Sides)	39.0 mm (Sides)
	0.9 mm (Side B)	11.5 mm (Side B)		
Heritage 3	2.0 mm (Soffit and sides)	NA	NA	NA

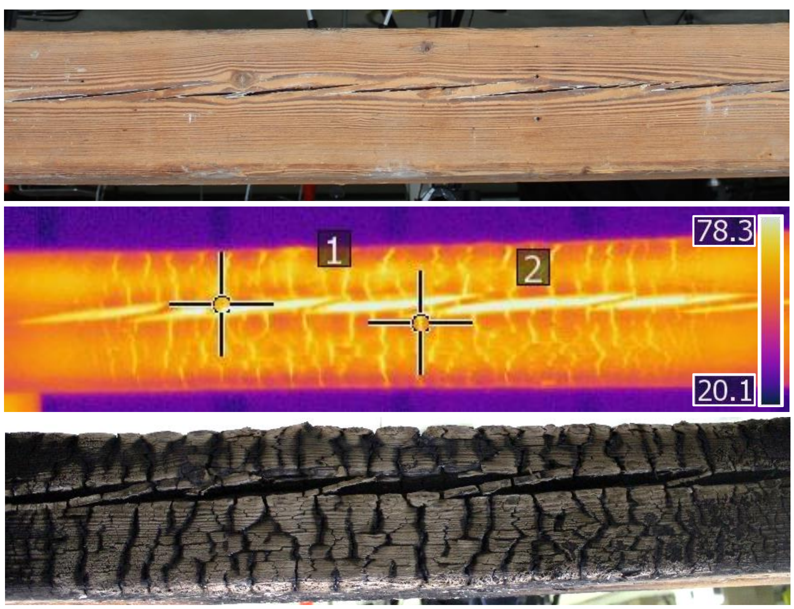


Figure 4.8. Side A crack progression before (top) and after fire (middle and bottom) on Heritage 2 (identifiable markings were recorded temperature markers and scale is in °C).

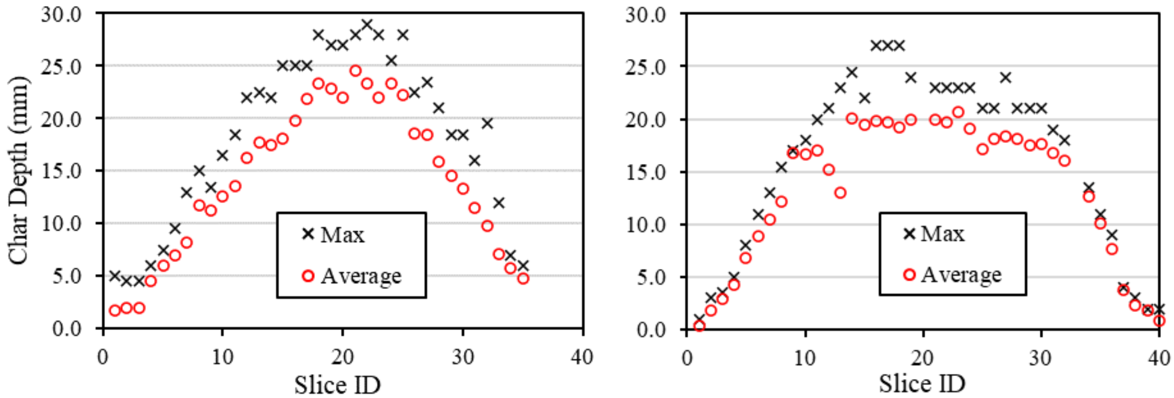


Figure 4.9. Char depths after loading on soffit of Heritage 1 (left) and Heritage 2 (right), where Max is the maximum char depth around the crack, and Average is average char depth away from the crack.

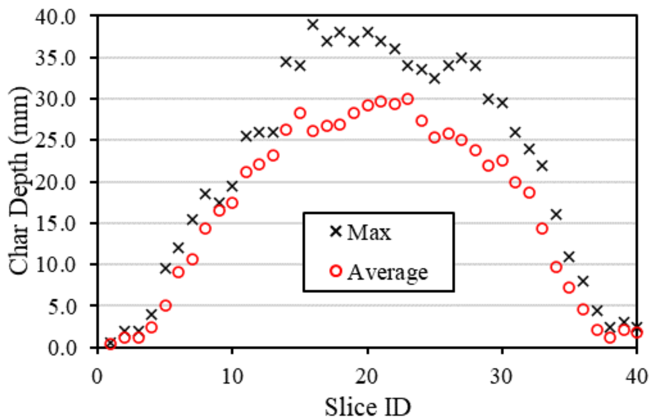


Figure 4.10. Char depths after loading on the sides of Heritage 2, where Max is the maximum char depth around the crack, and Average is average char depth away from the crack.

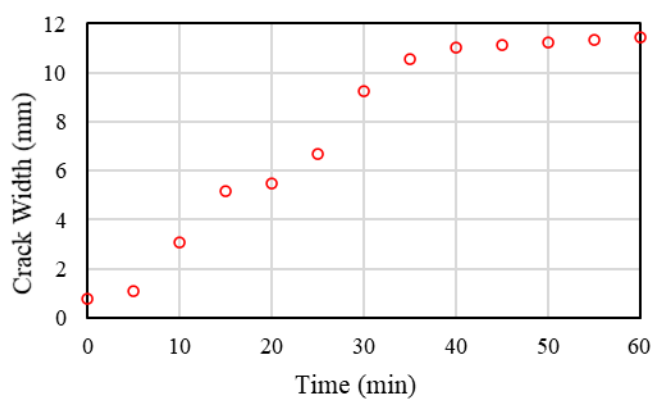


Figure 4.11. Crack expansion over time during the 30 minute pool fire and 30 minute cooling phase on Side B of Heritage 2.

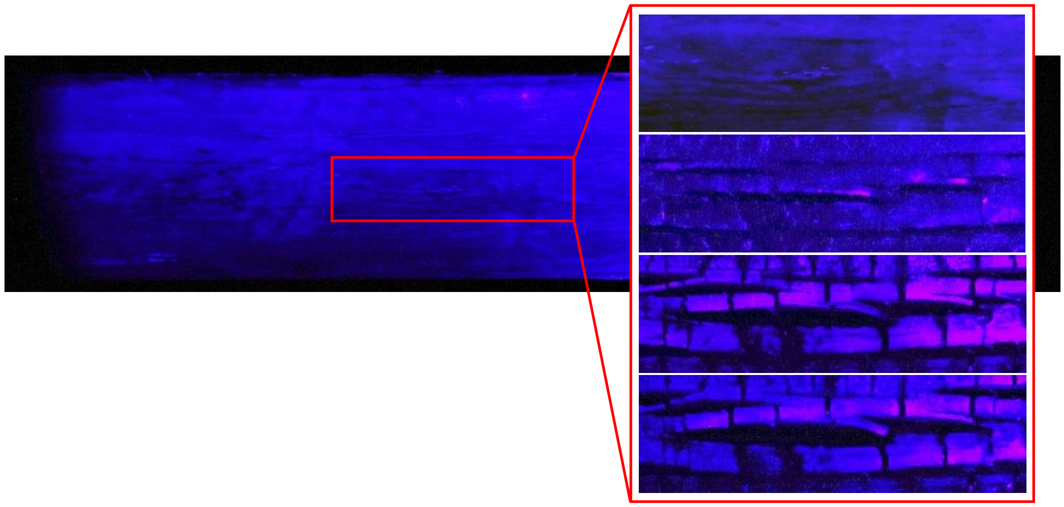


Figure 4.12. Crack expansion during heating at 0, 15, 30, and 60 minutes on Side B of Heritage 2.

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 is representative of timber with no significant initial cracking (as even new structures see cracks of 1mm or more). This expansion over time is plotted in Figure 4.11 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 4.12 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 Figure 4.11 and 4.12 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 4.11 and 4.12 show that the crack did continue to increase in width after the heating phase was complete. Figure 4.11 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.

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 13. The deflections measured in millimeters are plotted in relation to the force applied in kilonewtons until failure.

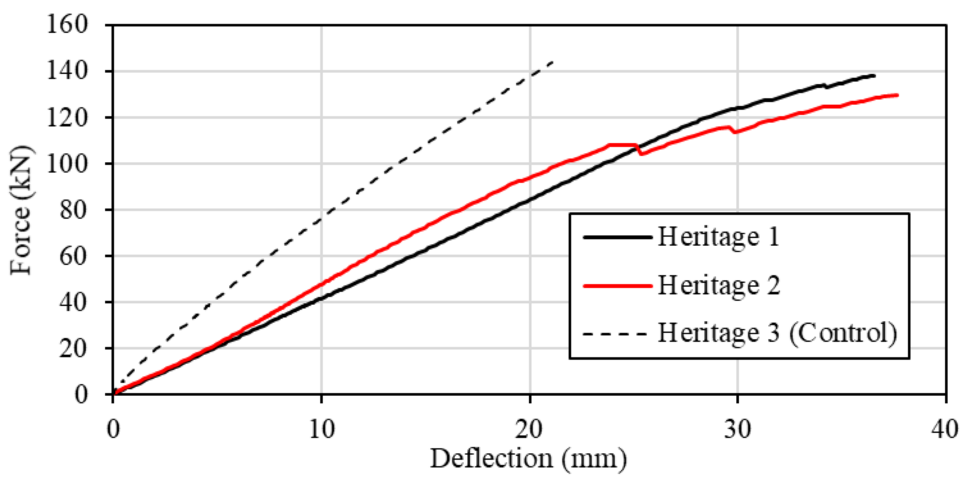


Figure 4.13. Force vs deflection for the charred heritage and control members.

4.4.2 Cone Calorimeter Tests

Figure 4.14 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 characterised 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 4.15 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 4.4 presents the maximum width of cracks present in all samples before and after exposure, as well as the time to ignition in seconds.

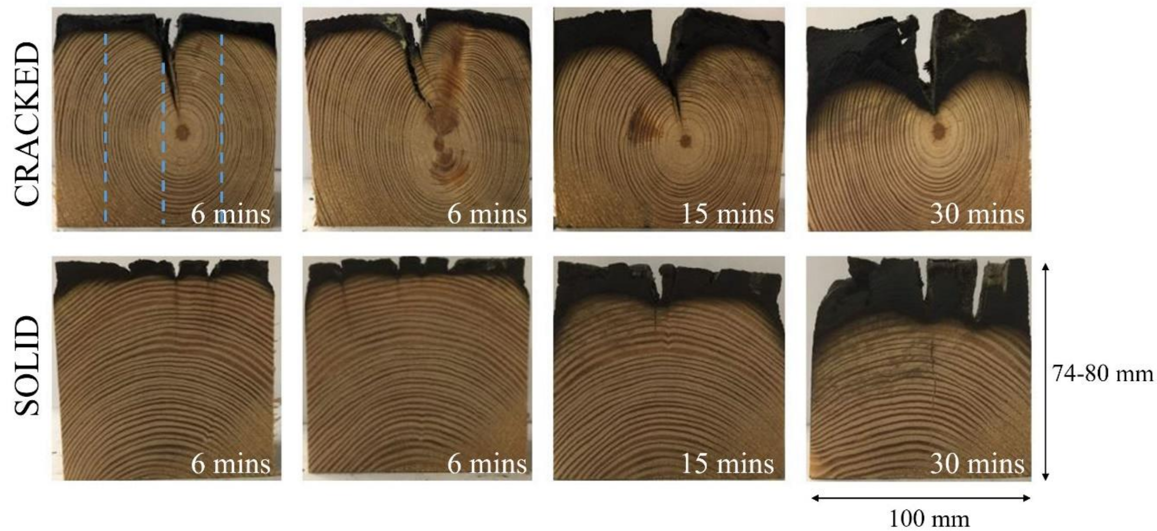


Figure 4.14. Char depth of cracked (top) and solid (bottom) timber samples at various exposure durations. Blue dotted lines indicate where char measurements were taken, and original dimensions of all samples are illustrated in the bottom right corner.

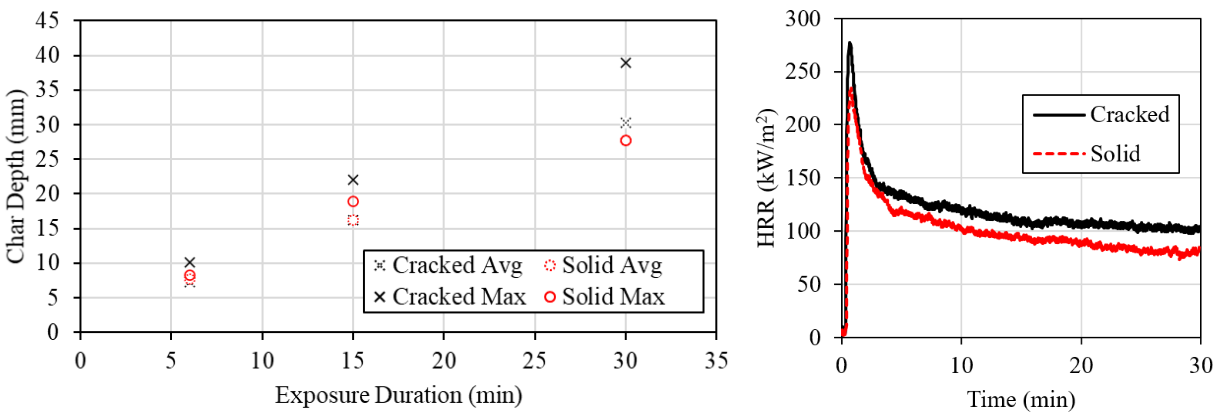


Figure 4.15. Average and maximum char depth of cracked and solid specimens, and heat release rates of cracked and solid samples tested to 30 minutes.

Table 4.4. 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. 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/m2 (6.7%) higher than the average peak heat release rate of the solid samples. The average heat release rate over 30 minutes was also higher (118 kW/m^2) than the solid samples (100 kW/m^2). While the sample number in this case may not allow for tests of statistical significance, these preliminary findings show the potential for differences to be found in the heat release rate between the cracked and 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. Considering the crack expansion only observed in the cracked samples, and not the solid samples presented in Table 4.4, the presence of existing cracks could facilitate the dehydration of timber deeper in the sample, resulting in more significant crack expansion compared to the solid samples that have not experienced previous dehydration (where only the superficial layer of timber is dehydrating). Overall, the effect of moisture content on crack expansion and charring around the crack should be considered as a future research need.

4.5 Discussion

4.5.1 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 (Liu *et al.*, 2021). 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. It is acknowledged herein that concrete has distinct differences in its material response from timber, such as smouldering which would have unique effects when occurring in a crack. However, there is extremely little available information on the thermal effects created by cracks in any material, and some mechanical effects observed may be comparable between materials. Thus, discussion of previous research examining the effect of cracks in concrete serves as a point of comparison and reference in contextualizing the results of this test series.

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 opposing 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 4.3.2). 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. Considering the reduced cross section taken by subtracting the maximum observed char depth on each side of the member from its initial dimensions, calculated strengths were determined from the CSA O86-14 procedure (CSA Group, 2014). The failure loads of Heritage 1, 2 and 3 were calculated as 26.3 kN, 25.4 kN, and 44.1 kN, respectively. These are far below the observed failure loads shown in Figure 4.13 (which were 138.1 kN, 129.5 kN, and 143.8 kN for Heritage 1, 2 and 3). Though Heritage 3 (the control member) was not charred, the relatively similar performance across all members indicates that in this case, the presence of the radial crack and corresponding char depths did not greatly affect the structural capacity of these members in bending, though the CSA O86-14 code procedure predicted the structural capacity would have been reduced by up to 58%. The smaller reduction in strength due to heating (of 7.2% on average) also indicates that the existing cracks are not expanding beyond the char layer to reduce the effective cross section of the beam further. If the structural capacity of the cracked and charred members were worse than that predicted, the presence of cracking would need to be considered well beyond the char layer. The similar mechanical performance of Heritage 1, 2 and 3 show that with short duration, mild heat exposures, the impact of charring and charring in radial cracks impacts the stiffness of the member more severely than the strength of the member.

4.5.2 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 (Bartlett, Hadden and Bisby, 2019). 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 (Ervine *et al.*, 2012). Again, there are notable difference between the material performance of concrete and timber, however the lack of available literature regarding the effect of cracks on fire performance of any material still makes the Ervine et al. (2012) study a useful point of comparison. 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 (Richter *et al.*, 2020), 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.

4.6 Conclusions

To put these results into context in a grand scale, fire safety of heritage buildings as a whole must be considered. Addressing existing radial cracks in heritage timber is just one consideration in a holistic approach that is needed with heritage buildings. Two concepts to consider in the fire safety of buildings with exposed timber is structural stability and compartmentation, both which increase the tenability of egress routes during fire and limit the damage afterwards. Structural stability during and after heat exposure is vital to the stability of the structure as a whole, which is addressed in the loading tests conducted herein and evaluating the influence of the radial cracks versus the charred region. Fire in timber heritage buildings can be mitigated through compartmentation to limit smoke and fire spread to egress routes, and is an important passive fire protection system to consider in heritage timber buildings (Torero, 2019).

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 full-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 full-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.

Chapter 5: Masonry Material Factors

5.1 Introduction

Masonry is included in a considerable amount of built heritage across the world (Lourenço *et al.*, 2014). In Canada, our masonry heritage dates back only to our settler history (Drysdale and Hamid, 2005). In early Quebec stone houses were popular, and clay brick became popular in Ontario for both residential and commercial construction in the 19th century (Humphreys and Sykes, 1980). These vernacular brick buildings are often recognized collectively in heritage districts, such as Cabbagetown in Toronto (Heritage Preservation Services, 2003). While a large percentage of recognized heritage masonry buildings are made of stone, clay brick is the most widely used masonry material in the world due to availability and affordability of materials (Drysdale and Hamid, 2005).

Fire is a risk to built heritage and results in the loss of many original heritage materials, but that is not always the case with masonry. Due to the limited combustibility of most heritage masonry units, they are largely left intact after a fire. The entire masonry assembly is often left standing, even without the lateral support of the interior structure, but are demolished due to their potential instability (Buchanan and Abu, 2017). The lack of understanding of the after-fire strength of masonry assemblies and their components results in the loss of original heritage material that may be salvaged or even restored in its original context.

Masonry assemblies are made up of two parts: masonry units, such as bricks or stones, and mortar to bond and create uniform bearing between the units (Drysdale and Hamid, 2005). Brick masonry is studied in this section, and all the samples tested are made of clay. Historically, clay has been used as a fire performance improving material, commonly used in chimneys and ovens (Hartmann and Burkert, 2018).

Clay bricks are exposed to heat during the manufacturing process. The process involves a drying period of 24-48 hours at 40-205°C to ensure all the moisture has been removed before exposure to higher temperatures. Then they are fired in a kiln for 60-80 hours reaching peak temperatures between 930-1320°C to achieve vitrification, a process of ceramic fusion that provides the strength and durability of the bricks (Drysdale and Hamid, 2005).

Experimental testing on the mechanical properties of heritage masonry, both stone and brick masonry is needed to determine their residual performance after fire. Damage from spalling and thermal cracking can be observed visually, whereas the disintegration of the stone (from anisotropic thermal dilation of calcite crystals) cannot be seen (Praticò *et al.*, 2020).

There is also a need for research on the after-fire strength of masonry considering the cooling phase. Praticò *et al.* (2020) hypothesised that the more severe thermal gradients in the stones of the Notre Dame Cathedral were created from the abrupt cooling more than the slower heating from the fire itself.

This chapter presents a preliminary study on the residual strength of heated heritage clay brick samples and discusses methods for testing heritage masonry after fire.

5.2 Background

The majority of fire research on heritage masonry structures are on stone masonry from Europe, there is a dearth of focus on heritage clay brick, that make up most of the vernacular masonry buildings in Canada to date. The existing studies on heritage masonry in fire, or modern tests that can be applied to heritage masonry, are reviewed below. The review process involved google scholar (and York University library) searches of the following phrases: “heritage masonry in fire”, “heritage mortar in fire”, “masonry in fire”, and “brick masonry in fire”, and combinations of the following keywords: heritage; historic; masonry; bricks; and fire.

5.2.1 Stone Masonry Fire Research

Most of the heritage stone masonry testing is done in-situ on heritage buildings (with non-destructive testing). There is some laboratory testing conducted on new stone samples that are relevant to the fire performance of historic stone masonry, though the samples tested are modern representatives of the masonry present in heritage buildings and structures.

5.2.1.1 Case Study In-Situ Testing

Delegou *et al.* (2019) presents a case study of a 19th century monastery in Greece that suffered from a fire consuming most of the monastery in 2017. The fire impact on the limestone and sandstone masonry was evaluated based on analytical techniques conducted on the limited sampling allowed from the historic site and in-situ non-destructive techniques and on both historic and newer masonry found on the site and their mortars. Physical and chemical compositions of the masonry were found to have changed as a result of fire, for example a reduction in surface hardness for the stones was found in both the limestone and sandstone samples, more so in the historical masonry (Delegou *et al.*, 2019).

No tests on mechanical strength were conducted do to the limited samples that could be removed for testing, but the differing results on the same stones based on their age (in the building) indicate that the aged stones have a different response to fire, and highlights the need for mechanical strength testing of historic samples (addressed by this research), not just modern samples representative of historic materials (Delegou et al., 2019).

Similarly, Dionísio *et al.* (2021) presents the assessment of the chemical and physical properties of granite from a historic property that was destroyed, all but the masonry walls, by a wildfire. The temperatures achieved in the granite were between 280°C - 490°C, and did not change the porous network of the stone significantly compared to samples from unaffected areas (Dionísio *et al.*, 2021). Mechanical properties such as compressive strength were not evaluated.

The case study presented in Miano *et al.*, (2020) focusses on the seismic upgrading of a historical building, but also conducts a thermomechanical analysis of the building. Though only on the 3rd floor made of reinforced concrete, and not the lower levels in masonry, highlighting the need for fire analyses of historical masonry buildings.

Horta, Carvalho and Rato (2008) presents a mortar study from a 19th century masonry cottage after a fire destroyed the wooden elements in 1999. The limestone masonry survived the fire, but without analysis the residual properties of the masonry are unknown. The study found no significant damage to the mortar samples due to the fire, but evidence showed the fire consisted of a slow combustion up to 400°C, which is not a severe fire.

In a similar case study, the fire at the Notre Dame Cathedral in 2019 also involved a fire in the timber roof, leaving standing masonry structure with unknown residual properties. An estimation of the residual strength ratio and compressive strength based on theoretical analysis is proposed by (Manuello Bertetto, D'Angella and Fronterre', 2021) to be a 50% reduction in load bearing capacity, based on fire temperatures of 800°C at the masonry and the effect of water extinguishment. No in-situ experimental testing was conducted, so these values are only theoretical. Other studies conducted based on the charcoal formation in the timber during the fire (based on samples collected on site) estimated the fire temperatures at Notre Dame to exceed 900°C up to a maximum of 1300°C (Deldicque and Rouzaud, 2020) so the theoretical reduction could be even higher, though those high temperatures were found in the timber and the temperatures the masonry were subjected to were likely in line with the study (Praticò *et al.*, 2020). These studies highlight the need for experimental results to validate these theoretical models.

5.2.1.2 Laboratory Testing

McCabe, Smith and Warke (2007) presents a comparison between furnace heating and fire on sandstone samples that reveals differing responses based on the heating method. The sandstone samples were not historic, but lime renders were applied on some of the samples to simulate historic properties. The main goal of the research is to evaluate the sandstone's response to salt weathering (and not residual strength), resulting in more unpredictable responses to salt weathering from the fired samples compared to those heated in the furnace. This is due in part to the soot cover from fire that slows salt penetration initially but after delamination of the soot layer accelerates deterioration. The study also highlights the differences in temperature gradients between fire and furnace heating, with non-uniform heating from fire and uniform heating from the furnace (McCabe, Smith and Warke, 2007). While this test programme doesn't address residual strength, it stresses the differences between fire and furnace tests (and the need for experimental results from both), and other considerations like salt and freeze-thaw weathering on historic masonry after fire. This topic was studied further in McCabe, Smith and Warke (2010) which revealed similar results that both fracture networks and soot cover from the fire have a significant effect on salt weathering performance. The fractures lead to spalling, and the soot cover can lead to the detachment of the layer below the soot, exposing fire-damaged stone.

Considering weathering and deterioration mechanisms that historic stones are subjected to over time, Gomez-Heras et al. (2009) wrote that little in known about the influence of existing decaying mechanisms on historic masonry's fire performance. After a review of literature since then, this is still true, emphasising the need for experimental results using historic stones (not just modern stones of the same types).

In the absence of experimental results on the fire performance of historic stone masonry, the following are studies using modern samples meant to represent the masonry stock in heritage stone buildings. (Ozguven and Ozcelik, 2013) presents a study of limestone and marble under a variety of temperature exposures (200-1000°C) in a furnace. The results showed that colour changes proportionally with temperature increase, and natural stone structure deteriorates above 800°C. It's also important to note that natural stones undergo calcination when heated between 800-1000°C, which reacts with water causing exothermic reactions and pH changes that deteriorate the stone (Ozguven and Ozcelik, 2013). Under further analysis on the stones' mechanical properties presented in Ozguven and Ozcelik (2014), it was found that compressive strength values of stones heated above 600°C are relatively low, and tensile strength decreases proportionally with temperature increase. Water absorption and capillary water absorption also increases at 600°C which contributes to exothermic reactions described above, therefore additional caution is needed when exposing heated stones to water which is common during the suppression of a fire. Samples heated above 600°C are also more susceptible to freeze-thaw damage (Ozguven and Ozcelik, 2014).

Those results are in agreement with Borg, Hajpál and Török (2013) that tested limestone from Malta and Hungary, and found discoloration of the stones was observed starting at 400°C, and a significant reduction of residual strength at 800°C (30%) to 1000°C (12%).

5.2.2 Brick Masonry Fire Research

The current fire research on brick masonry only includes laboratory testing, as far as the author has examined, there are no in-situ analyses of brick masonry in fire.

Russo and Sciarretta (2012) conducted experimental tests on brick samples and wallets, which were the basis of numerical modelling approaches to extrapolate values beyond the experimental data developed in later studies (Russo and Sciarretta, 2015a, 2015b). The original laboratory experiments tested clay brick units, mortar samples, and masonry prisms before and after a maximum heat exposure of 300°C and 600°C on one side in a furnace with a 19°C/min heating rate, and then tested in uniaxial and diagonal compression. The results showed superficial cracks in the exposed sides of the masonry prisms, a decrease in compressive strength in the 600°C samples (of 13%), and a substantial decrease in shear stiffness in both 300°C and 600°C samples (of 68% and 82% respectively) compared to unheated samples. The material selection and arrangement (wall thickness, brick pattern) were meant to represent historic buildings, but are contemporary in nature. The testing of historic clay brick masonry samples in fire is novel to the author's knowledge.

In a review of existing literature conducted in 2013, it was found that the mechanical properties of clay masonry units and assemblies before and after fire were scarce, and the influences of exposure duration, cooling, testing time intervals, unit types, wall thickness, and wall texture on those properties were missing entirely (Russo and Sciarretta, 2013). From a review of published materials after 2013 it is clear that those aspects are still missing from experimental data sets, a dearth that this study attempts to address. With the preference for performance-based approaches for heritage buildings in fire, experimental data must be provided.

Andreini *et al.* (2015) included clay cylinders in their experimental study on the mechanical behaviour of masonry, which showed no change in average compressive strengths at all the temperatures investigated up to 700°C (4 hour ramp time including 2 hour break at 100°C, and 2.5 hours at target temperature) and a slight linear reduction of elastic modulus. This is to be expected as the clay was selected to match those in common Italian building stock, that has maximum firing temperatures of 950°C during production (Andreini *et al.*, 2015).

Nguyen and Meftah (2012) also presents experimental results of clay brick walls subjected to fire using the standard fire resistance test but using modern materials. The study found that for load bearing walls, spalling on the heated side is observed, creating eccentricity of vertical applied loads which contributes to out of plane deformations and eventual failure. Bošnjak *et al.* (2020) also presents an experimental study on the mechanical properties of modern clay and calcium silicate bricks after furnace heating from 20-1100°C under both hot and cold conditions, including masonry units, mortar prisms, and masonry prisms. The results show that temperature increases have more of an influence on stiffness of masonry prisms then on strength and is governed by the mortar stiffness more than that of the brick units. The heating increased the differences in stiffness between the mortar and brick units, leading to axial and lateral deformations in the mortar during compression, creating eccentricities in the prism and tensile stresses in the bricks. The study also found that the residual compressive strength of clay units differs from the "hot" compressive strength (while the brick units are heated). The "hot" compressive strength reduces linearly with temperature to 70% capacity at 750°C, but the residual strength (at ambient temperature) is relatively unaffected (Bošnjak *et al.*, 2020). The results of this study highlight the importance of testing residual strength at ambient temperatures for accurate results pertaining to the reuse of building materials, and supports the theory that repointing mortar could restore residual strength of assemblies after heat exposure.

All of the studies presented in this section also presented numerical studies using finite element models based on their experimental results characterizing modern masonry units in fire, which were excluded to focus on the experimental results and implications on heritage materials.

5.2.3 Summary

From this overview of research in the mechanical properties of masonry in fire relevant to heritage masonry, it is clear that there is a dearth in experimental results using historic materials, especially considering brick masonry. From the small sampling that has been taken from historic masonry subjected to fire, its performance differed from contemporary samples. This is due to the influence of deterioration mechanisms present in historic samples, which have not been considered in research so far.

5.3 Research Objectives and Motivation

The motivation of this research is in filling the dearth of information on heritage masonry in fire, specifically clay brick masonry which is more common worldwide than stone (Drysdale and Hamid, 2005). Another motivation is in the interest of reusing building materials, and addressing the repairability of heritage masonry after fire.

The subject of this research doesn't deal with the concepts of fire resistance, so much as fire resilience. The fire resistance of masonry is well established in it's ability to maintain sufficient load carrying capacity during fire, to avoid collapse, and to prevent temperature rise and flame spread when the minimum thicknesses for materials are followed (69, 97, 124, 152mm for solid clay brick masonry for 1, 2, 3, 4hr resistance ratings) (Drysdale and Hamid, 2005). The purpose of this section is to characterise the residual strength of clay brick masonry for potential reuse after fire. This reuse is important especially for heritage structures where there is a great interest to rebuild after fire, as highlighted with examples in Chapter 1.

There are two main research objectives to be addressed in this section. Firstly, to determine the fire properties of heritage masonry from different periods in Canadian building history. The goal of this research is to determine the fire resilience of heritage masonry assemblies, and their repairability after fire by determining their residual properties after heating. Secondly to develop a framework for testing heritage masonry units and assemblies fire resilience and repairability after fire for future research.

5.4 Experimental Methodology

The provisional tests that were conducted involve material collection, material heating, and compression testing until failure, outlined in the following sections.

5.4.1 Material Collection

Masonry materials were acquired from four different building time periods in Ontario: the 1840s, 1900s, 1920s, and today. The heritage materials (from the first three eras) were collected from building demolition sites, where the masonry's structural integrity was not the reason for the demolition. The samples from the 1900s were collected from the same former industrial building the timber materials were sourced from, and can be seen in Figure 5.1. The 1840s bricks were sourced from the brick and beam building on King Street East presented in Chapter 2 that was demolished due to a heritage easement agreement (as with the 1900s bricks as well). As can be seen in Figure 5.2, the 1920s bricks have the name PHIPPEN embossed in the frog of all the masonry units reclaimed from the 1920s era house. The company, Phippen, H.W., & Son were included in a list reported by the Government of Canada of firms that shipped bricks made from domestic clays in 1933 (Department of Trade and Commerce Dominion Bureau of Statistics, 1934). The same challenges regarding collecting and storing heritage materials discussed in the previous chapters also apply to the materials collection herein. The available stock of heritage clay brick materials is summarized in Table 5.1. and 8 bricks from each were tested in the provisional study presented.

All the masonry tested are moulded clay bricks with a frog, as can be seen in Figure 5.2. The densities of the bricks tested range from 1505-1905 kg/m^3 with an average of 1656 kg/m^3, and the manufacturer specified density of the new bricks is 1650 kg/m^3. These are all within the expected density range of 1300-2250 kg/m3 for solid clay brick (Drysdale and Hamid, 2005). The modern clay units are handmade using historic techniques and are predominantly used as replacement heritage bricks when needed.

Figure 5.1. Material collection of 1900s bricks from deconstruction site.

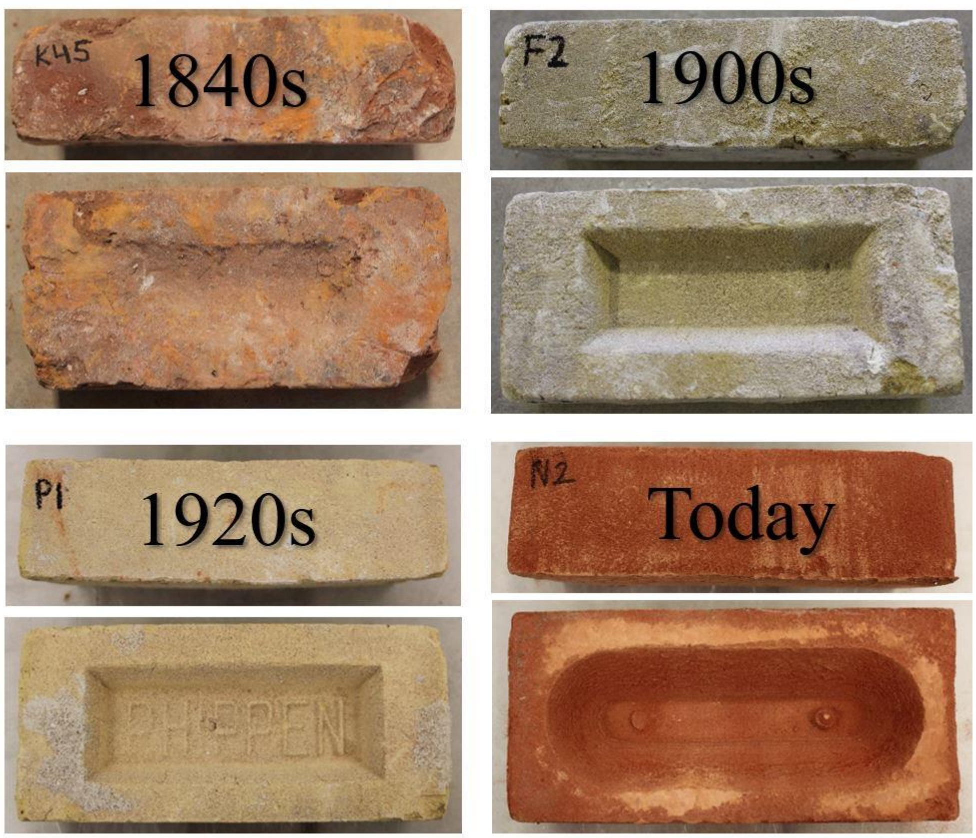


Figure 5.2. Brick samples from the 4 eras of Canadian brick masonry construction.

Table 5.1. Heritage clay brick stock available for testing.

Sample Type	Estimated Amount
1840s	50
1900s	500
1920s	150
New	500

The clay masonry units are commonly found in Ontario's heritage stock, but their fire resistance is unknown, and they are usually discarded after fire due to their unknown structural capacity. These tests on the moulded clay bricks in isolation is the first step of the overall research goal to study entire masonry assemblies.

5.4.2 Heating

The bricks were heated in a Thermo Scientific furnace to 800°C as a starting point for testing clay bricks in heat exposure. This temperature was chosen for a multitude of reasons. Firstly, it is the maximum temperature recorded in the methanol pool fires used for other materials testing (see Chapter 4). It is also the beginning of degradation of stone masonry from literature outlined above (with significant degradation between 800-1000°C in most test programs). It is also representative of a temperature exhibited by masonry in fire, for example in an estimate of the temperatures reached by the masonry at the Notre Dame Cathedral fire were estimated to be up to 800°C (Manuello Bertetto, D'Angella and Fronterre', 2021).

Trials to determine the true temperature inside the furnace, using thermocouples and comparing to the display in the furnace. It was determined that the furnace is on average 16°C hotter than the displayed temperature, so the target temperature was adjusted to get the desired internal temperature in the furnace. This value of 16°C is the average temperature difference between the furnace display and our thermal couple, of 19 values taken over a 5°C/min ramp to 500°C. A thermocouple was also placed in between the bricks to ensure a uniform heating with the brick configuration inside the furnace (configuration seen in Figure 5.3).

Figure 5.3. Brick configuration in the furnace (1840s and new (2010s) bricks).

The value of 16°C was also confirmed when testing the inter-brick temperature, of 5 values taken over two hours at a stable temperature, after nearly a 2 hour ramping period based on the specified ramp rate. Because of this recorded and actual temperature difference, the furnace temperature was lowered by 16°C to get the desired heating rate. Therefore, to heat the bricks at 800°C, the furnace was programmed to 784°C.

From each of the eras, 1840s, 1900s, 1920s, and today, 8 bricks were tested (4 heated and 4 unheated). The 16 bricks were heated (4 from each of the 4 eras) to 800°C for 2 hours, after a 5°C/min ramp rate. This ramp rate was chosen as not to create severe thermal gradients in the brick units while heating, but represent a more realistic heating rate than the 2°C/min used in most of the test programs above, which are based on the RILEM methods for concrete, a material more susceptible to spalling due to heat exposure then clay masonry (RILEM Technical Committee, 2007). This slower heating ramp rate largely resulted in no reduction of residual strength in clay bricks, so the faster rate of 5°C/min was chosen, in line with the test procedure of Ozguven and Ozcelik (2013) that conducted a similar study on limestone masonry. This heating rate is still conservative compared to the Russo and Sciarretta (2012) study that used a 19°C/minute heating rate and found only a 13% decrease in compressive strength at 600°C. The ramp time was approximately 2.5 hours for each test to reach the desired 800°C temperature. The cooling phase occurred for approximately 12-24 hours in the furnace after it was turned off, and the bricks were removed when they were cooled (so they could be handled with bare hands).

5.4.3 Compression Testing

Both the unheated and heated bricks were tested in compression at ambient temperatures after cooling from the furnace heating. Before being tested in uniaxial compression in the Pilot Compression Tester, the samples must be prepped to achieve an even loading surface. This involves filling the frogs (the indentations at the top from hand-production in accordance with CSA A82-14, details described below (Standards Council of Canada, 2015).

The sample frogs were then filled with a high early strength cement mortar (Portland Type HE) with a water, cement, and sand mix ratio of 0.5:1:2 , as per CSA A82-14 (Standards Council of Canada, 2015), and allowed to cure for at least 48 hours before shellac and capping. The compression faces were then coated with shellac and dried for 24 hours, to seal any pores in the masonry from absorbing any moisture during the plaster application. The compression surfaces were then capped with Plaster of Paris (No. 1 Moulding Plaster) with a water and plaster ratio of 29-32:45 grams, as per CSA A82-14. The capped surfaces were aged at least 24 hours before compression testing.

Figure 5.4. Process of filling frogs with mortar, covering with wet burlap and wrapping in plastic to moist cure for 48 hours.

Figure 5.5. Mortar filling and plaster capping of clay brick samples.

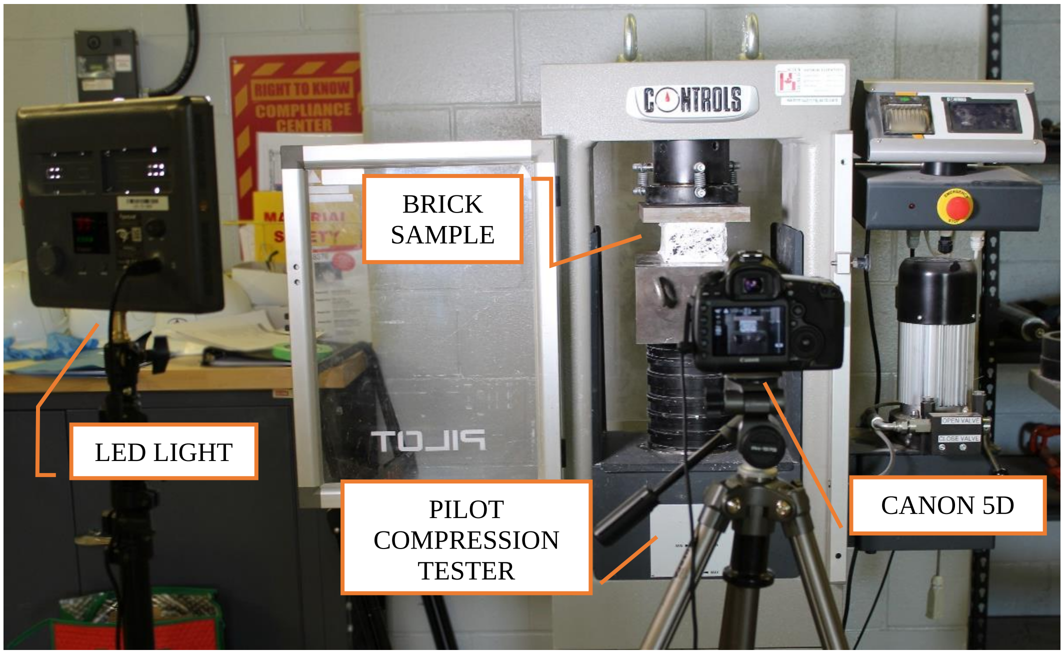


Figure 5.6. Compression test setup.

One end of all the samples were painted white with black speckles for digital image correlation (DIC) analysis. The camera lens was set up 90mm from the end of the brick in the compression tester.

All samples unheated and heated, from all time periods were tested in compression until failure, using a peak load of 2 kN. An inch thick steel plate was used on the top of the bricks to evenly distribute the load to the entire surface of the brick, because the compression tester had a circular shape with a diameter smaller than the length of the bricks (as seen in Figure 5.6). The testing speed used was 0.083 MPa/s, which complies with cl. 13.5 of CSA A82-14, based on the expected maximum compressive stress of 20MPa (based on the new brick product sheet stress of 15 MPa).

Digital image correlation (DIC) was then conducted on the bricks to determine the ultimate strain at failure, or until the face of the bricks being evaluated delaminated from the surface.

5.5 Experimental Results

The experimental results of the heating and subsequent compression testing is presented here. No observable damage was noted on any of the samples after heating. The average ultimate compression strength (MPa) of the 32 bricks tested and their standard deviations are presented in Figure 5.7 below. The samples are organized by time period, from oldest to newest, and separated into unheated and heated categories.

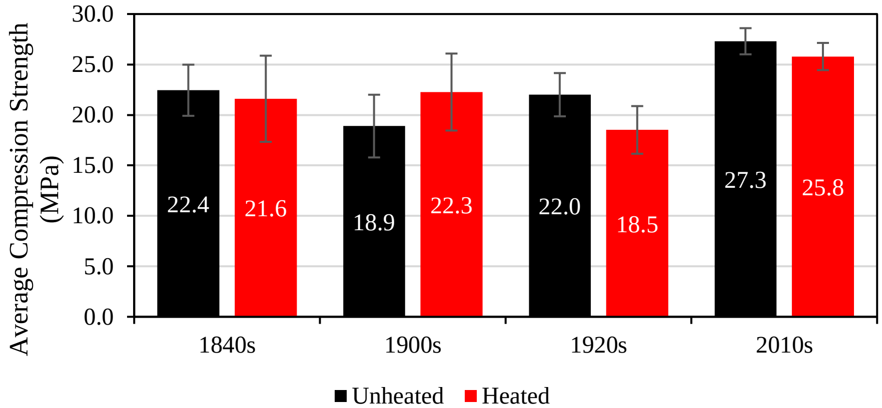


Figure 5.7. Average compression strength of heated and unheated heritage and modern bricks.

The determination of specified compressive strengths for masonry units using experimental data is calculated using Annex C.2.1 in S304.1-04 (Canadian Standards Association, 2010). The coefficient of variation (*v*) is calculated by dividing the standard deviation by the average compressive strength of the units tested. Since less than 10 units are used (only 4 for each time period and heating condition), *v* is equal to the higher of calculated value or 10%. If the variation is greater than 15% more units should be tested. Only the new bricks had a coefficient of variation low enough at 9.5% and 10.4% for the unheated and heated samples not to require a minimum of 10 units to be tested. The heritage samples had coefficients between 19.5-39.5% (greater than 15%) which would require an increased sample size of at least 10 units total for each era and heating condition (unheated or heated).

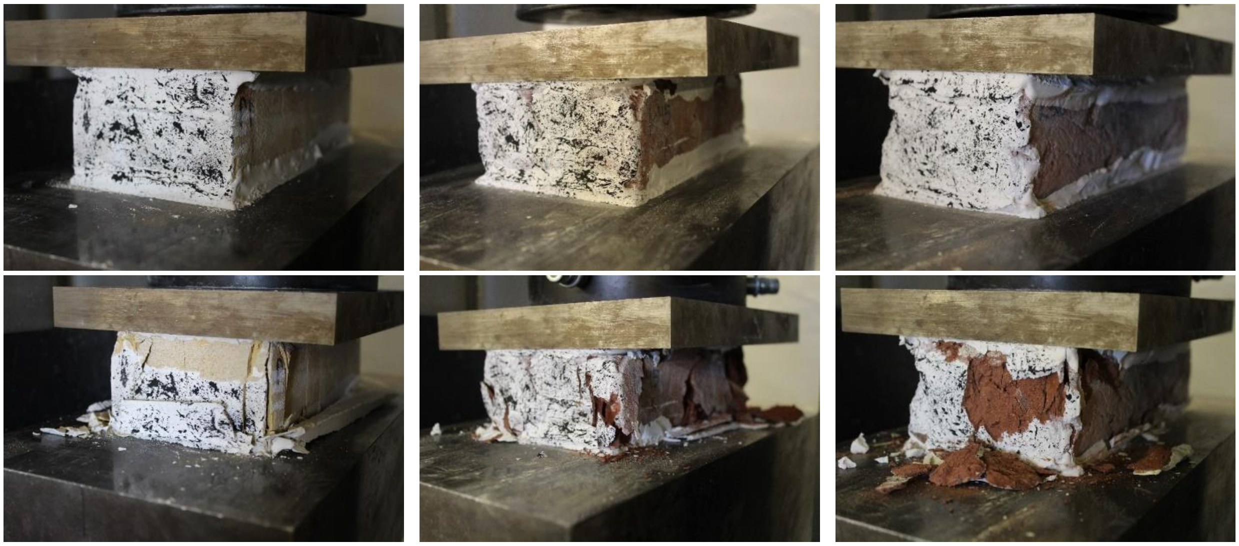
This preliminary testing program had a limited sample size, so more testing should be conducted to produce more confident results. But from these preliminary tests some of the following trends can be observed.

For all the time periods except for the 1900s samples, the unheated samples had a higher ultimate compressive stress then the heated samples. Though the percent difference from those from the 1840s and now are only 3.6% and 5.6% respectively. The 1900s and 1920s samples had higher percent differences of 16.5% and 17.3% between the unheated and heated samples, but they were not consistent with which sample grouping had the highest compressive strength. Due to the small differences between sample groups, and the inconsistency in which sample group had a better performance, it cannot be concluded at this time that the 800°C furnace test had an effect on the compressive strength of the clay brick units from any era.

Unlike the differences between the unheated and heated samples, there is a distinction between the heritage brick samples and the new samples (2010s). The average compressive strength of the new samples (both heated and unheated) is 23.6% higher than the average of all the historic eras. The standard deviations of the new samples are also quite low at 2.6 and 2.7 MPa for both sample groups, whereas the heritage samples range from 4.3-8.5MPa (2-4x bigger). This variability in the heritage samples is the main reason why larger sample sizes are needed.

It is important to note that in relation to the minimum compressive strength stated in CSA-A82 (Standards Council of Canada, 2015), all of the bricks tested meet the minimum interior grade strength of 17.2 MPa (average) and 15.2 MPa (individually). And most meet the exterior grade requirements of 20.7MPa average (75%) and 17.2 MPa individual (78%). Only the unheated 1900s bricks and heated 1920s brick averages are below 20.7 MPa, and only 7 of the individual compressive strengths are below 17.2 MPa. The averages are based on 4 bricks, and not 5 as required in the testing standard (Standards Council of Canada, 2015). Therefore, if the same trends are seen with the increased sample size, these bricks would pass the compressive strength test that new bricks are subjected to for interior grades bricks, and most for exterior grade.

In accordance with cl 4.11.2 in S301.1-04 Design of Masonry Structures, for reclaimed masonry units, any reclaimed or previously used units have to comply with the requirements for new masonry (Canadian Standards Association, 2010).



(a) (b) (c)

Figure 5.8. Bricks before (top) and after (bottom) compression failure from the 1920s (a) and 1840s stock (b + c). The samples chosen do not represent the only delamination failures, only those that can clearly be seen on the face pointed towards the camera. New bricks samples failed in similar ways.

As seen in Figure 5.8 the face of the brick being tracked for digital image correlation (DIC) sometimes experiences spalling. When that occurred before the failure of the brick, the ultimate strain could not be measured, only the strain before the delamination of the brick face. The DIC found strain measurements ranging from 0.0012 mm/mm to 0.030 mm/mm. The high end of that range is more comparable to mortar samples than brick samples, but more than 78% of the samples were within a more expected range of 0-0.016 mm/mm for bricks. These represent the maximum strain recorded by DIC, but not necessarily the ultimate strain for all the samples due to spalling of the recorded area before the ultimate load.

While the 1840s bricks had comparable compressive stresses to its other historic counterparts, those samples experienced the most spalling at failure. This could be due to a higher porosity in older bricks (Lourenço *et al.*, 2014) or due to increased deterioration due to the age of the samples.

An increased sample size is needed to draw accurate conclusions, but from these preliminary results it can be seen that the modern bricks had the least amount of variability in both the heated and unheated samples. Overall, there is no significant deterioration of the bricks at 800°C, and any other trends will have to be evaluated with an increased sample size due to the variability of the heritage samples, both heated and unheated.

5.6 Testing Masonry in Fire (Hypothetical)

The following section outlines plans for testing heritage brick masonry materials, from individual components to full masonry assemblies.

Another important step for evaluating the individual brick masonry units would be to characterize the raw clay that makes up the masonry unit, using mineralogical and chemical studies based on small samples of materials (Lourenço *et al.*, 2014). This way any differentiation between the fire performance of different bricks based on their clay makeup can be identified, and more tailored fire performance data can be applied to existing buildings.

5.6.1 Brick Unit Testing

Due to the variability of the results from the heritage bricks, no real trends appeared from the data collected so far. To address this, the sample size of the experiment will be increased by completing the same testing program on another 48 bricks to bring the total of each brick category to 10 to comply with the unit strength calculations found in Annex C2.1 in S304, with the same distribution between the 4 eras tested. Like the experiment described in this chapter that will be reproduced, all testing procedures are in accordance with CSA A82-14. The completion of this experiment will provide the data to confidently identify trends in compressive strength before and after heating for moulded clay bricks from 4 different eras of masonry construction in Canada.

Similar test programs should also be conducted to test the clay bricks to 1000°C and 1200°C to see if higher temperatures affect the compressive strength of the units, though all those temperatures are within the expected peak heat of the firing process used to create clay brick masonry. To reproduce the effect of a realistic fire, the bricks should also be tested at a higher temperature ramp rate than 5°C/min, which is more likely to create thermal gradients that contribute to the brick damage. A ramp rate of 19°C/min is suggested for easy comparison to the extensive study on modern clay brick masonry conducted by Russo and Sciarretta (2012), meant to reproduce a short-hot fire.

They will be tested in the furnace for easy comparison to other studies (Nguyen and Meftah, 2012; Russo and Sciarretta, 2012; Andreini *et al.*, 2015) discussed earlier. They should also be heated using a high level of energy from a realistic exposure, so the performance of the bricks can be compared using the different heating methods (McCabe, Smith and Warke, 2007), and so the results can be more easily compared to the prism tests discussed in the next section. The prisms will only be heated using a pool fire, as they are too large to fit into available furnaces.

Though when considering case studies like Notre Dame, and most brick and timber historic buildings, the masonry is not the fuel to the fire, so even if the fire temperatures of the combustible materials are high, that heat radiates more slowly towards the masonry.

Other than compressive strength, factors such as deterioration and weathering after fire should be considered, much like the McCabe, Smith and Warke (2007, 2010) study on frost and salt weathering after heat exposure based on stones commonly found in the UK. In Canada's climate, freeze-thaw cycles should also be considered with the cold/boiling water absorption tests and the freeze-thaw performance tests prescribed by clauses 14 and 15 respectively in CSA A82, or with frost dilatometry (Straube, Schumacher and Mensinga, 2010; Standards Council of Canada, 2015). Freeze-thaw can also be considered with frost dilatometry, to find the critical moisture saturation for freeze-thaw damage where permanent damage occurs from expansion during freeze-thaw cycle, used to test the durability of bricks (Williams and Richman, 2017).

5.6.2 Mortar Study

This phase would focus only on heritage mortars in comparison with contemporary mortars, and their material properties before and after heating. At least six 50mm cubes of mortar mixed with materials and proportions imitating heritage mortars will be created, as well as modern mortar mix cubes. Hydraulic lime mortars with historic mix proportions compared to modern mix proportions in accordance with CSA-A179-14 (Standards Council of Canada, 2014). They will also be prepared in accordance with CSA-A179-14 for compressive strength testing, in cubes. After being allowed to cure for 28 days, half of the samples will be heated to 800°C for 2 hours, similar to the brick tests. All the samples will then be tested in compression. These tests should also be completed at 200°C, 400°C, and 600°C as mortars are more susceptible to heating than the brick units.

Historic mortars vary by binder-sand volume ratios of 2:1 – 1:4 (Lourenço *et al.*, 2014). In Canada, the National Research Council presents the hydraulic lime mortar ratio of 1:2-3 (hydrated lime powder or lime putty to sand) as appropriate for repointing of older masonry buildings (Maruenbrecher *et al.*, 2008). Lanas and Alvarez (2003) presents a study on lime-based repair mortars that recommend a lime and sand ratio of 1:2 (of the 1:1-1:5 mixes they tested), and a water/binder ratio of 0.5-1.2 for workability. A historic architecture and building construction book from 1899 suggests a ratio of 1:3 (1:4 if using good quality materials but no more) (The Colliery Engineer Co., 1899).

Modern mortar mixes including Portland cement should also be tested. Type S and N are structural grade mortars for modern masonry units, and O and K are meant only for restoring old masonry structures (Drysdale and Hamid, 2005). It is important to note that Portland Cement is no longer used to restore heritage masonry due to strength incompatibilities that lead to damaged historic fabric (Pavia and Brennan, 2019). That is why it is excluded from most repointing mortar mixes, and is in low quantity in mortars O and K.

Table 5.2. Mix ratios for historic and modern mortars.

Type	**Mix Design**			**Notes**
	Portland Cement	**Lime**	**Sand**	
Historic	0	1	2-3	For repointing
S	1	½	3 ½ - 4 ½	Structural grade
N	1	1	4 ½ - 6	Structural grade
O	1	2	9	Repointing only
K	1	3	12	Repointing only

These mortar samples should be tested, with 3 historic mixes with a ratio of lime to sand of 1:2, 1:2.5, and 1:3. Along with one sample each of modern mortars S, N, O, and K. One of the most promising historic mortars will be selected from this test programme to be used in the masonry prisms discussed in the next section.

5.6.3 Masonry Assemblies

The testing conducted on masonry assemblies builds on the research done in the earlier sections, combining the brick masonry units and historic mortar (selected from the previous study) to create masonry prisms to be tested in compression in accordance with Annex D of S304.1, which is based on ASTM C1314 except for the capping requirements (Canadian Standards Association, 2010; ASTM International, 2018). The prisms will be at least 4 courses with a height/thickness ratio larger than 2. It will have 2-3 wythes to represent common historic masonry walls. Fifteen prisms will be built and allowed to set for 28 days and ten will be exposed to a 30-minute pool fire on one side. Of the 10 heated prisms, half of them will be repointed with the same mortar mix used initially, then all fifteen of the prisms will be tested in uniaxial compression in accordance with S304.1 (and ASTM C1314). The number of prisms tested is determined by the minimum requirement of five prisms to be tested at once.

The entire experimental procedure can be repeated to test the prisms (heated, repointed, and unheated), under combined axial and flexural loading, by loading the prisms eccentrically. This will represent the behaviour of the masonry prisms under lateral wind and seismic loads.

The program can also be tested with different cooling methods, either letting the masonry cool slowly to ambient temperatures or using water, similar to what would be done during a fire. Historic clay brick materials have higher porosity and absorption then modern materials (Lourenço *et al.*, 2014), which would change the effect of water on the residual strength of the masonry.

This hypothetical test program would characterize the mechanical properties of heritage masonry assemblies at ambient temperatures, and after fire with and without repointing. The same test procedures can be conducted on modern masonry components as well to provide comparison, or other clay bricks from different eras.

5.7 Conclusions and Recommendations

The study presented herein takes the first steps to address the dearth of experimental data on heritage or historic brick samples after fire. The summary of research on historic masonry in fire highlights the unique challenges with regards to testing heritage materials, access to samples for destructive testing. The samples of heritage materials are limited, and those present in heritage buildings are protected which limits the size of samples (and therefore tests that can be conducted). Most tests done on heritage samples are non-destructive tests in-situ on an existing stone masonry wall that has experienced a fire, and other test programmes that are heritage focussed but use representative modern materials. To the authors knowledge there is no testing on heritage brick samples in fire.

The preliminary study on the effects of 800°C furnace heating on clay brick units from various eras of Canadian building history found no significant reduction in the ultimate compressive stress of the bricks after heating. An expanded sample size is needed to draw accurate conclusions from the data, but initial trends showed that the modern bricks performed better (by 23.6% and with a smaller standard deviation) then the historic bricks.

The testing outlines considers the physical characterization of the heritage masonry materials individually (brick units and mortar separately), and as an assembly, before and after heat exposure to determine their residual strength after fire. Several testing programs are suggested, including expanding the sample size, heating at higher furnace temperatures with faster ramp rates, heating with pool fires, and various physical tests to determine the mechanical properties. Mortar repointing is suggested as a method to increase residual strength after fire, and can be evaluated by repointing some of the heated prisms before testing in uniaxial compression, or in combined axial and flexure.

Different recommendations for repairing and reusing masonry after fire will be determined based on the length and duration of heat exposure. Those recommendations will be informed by the experimental results of the test program outlined in the last section.

Clay brick masonry has had a longstanding reputation of surviving fires, and the provisional results and subsequent testing program will provide the missing data to confidently evaluate the potential for reuse after fire.

Chapter 6: Conclusions and Recommendations

6.1 Summary of Findings

The following section summarizes the topics covered in chapters 2-5 of this thesis. The conclusions from each research topic are included in the next section, followed by academic and practitioner recommendations

The review chapter provided a theoretical background to several of the various topics discussed herein. Basic concepts regarding fire and fire protection engineering were introduced, including fire resistance testing based on standard fire curves versus fire resilience, which includes residual strength of materials after fire. Fire protection systems were discussed, passive systems like encapsulation or active systems like sprinklers. Human factors were considered, with an introduction to emergency egress and wayfinding. Unique considerations for heritage and human behaviour such as narrow passages and complex layouts were discussed, along with existing research on the topic. Heritage conservation was then introduced, including how heritage buildings are considered in building codes with regards to fire safety of occupants and materials.

Moving to the first research topic on human factors affecting the fire safety of heritage buildings, this section presented a case study of a heritage cultural center that underwent a major rehabilitation that included a number of code compliant changes to improve emergency egress. A study was conducted using Pathfinder, a pedestrian modelling software, to determine the effectiveness of these code compliant changes to reduce the total egress time of the building. The renovations considered were the addition of new emergency exits, the addition of an internal staircase linking the top floors to each other but not connecting directly to an egress path, and new structural columns in front of two of the three main entrance doors.

The second topic of study is introduced in the next section, timber material factors, with a study on the effect of radial cracks on heritage timber's fire performance was conducted using heritage pine timber collected from an early 20th century building being partially demolished to accommodate a new high rise on site. The members were exposed to a 30-minute pool fire and after cooling, loaded until failure in a 4-point bending test. Narrow spectrum illumination was used to visualise the crack expansion during the fire exposure, allowing the surface of the member to be seen through the flames. Cone calorimeter samples were then taken from cracked and solid portions of the beam to be tested under 50 kW/m^2 heat exposure at 6-, 15-, and 30-minute time intervals to investigate char depth with the presence of radial cracks and without.

The other material factor discussed are masonry materials performance after fire, which is considered from a theoretical and experimental perspective. An overview of the limited experimental studies on heritage masonry performance after fire is presented. Most of the research is on stone masonry and not clay brick masonry. There are limited in-situ tests on heritage samples, and the laboratory experiments use modern masonry materials that are meant to be representative of historic materials, but results from historic sites disagree with that assumption. Provisional experimental results are then presented on clay brick masonry units from 4 eras of Canadian history, the 1840s, 1900s, 1920s, and today. A hypothetical test program for expanding the knowledge on clay brick masonry's residual properties after fire is presented.

6.2 Conclusions

The following conclusions were found from each of the studies from Chapter 3-5, respectively:

- **Human factors –** Considering the pedestrian modelling of the emergency egress of the heritage cultural center, increasing the number of emergency exits decreases the total egress time of the building, and had the greatest impact (reduction by 21 seconds alone, and more in combination with other measures) of all the interventions considered. Adding elements that complicate exit routes slows the total egress time, in the case of the additional staircase that does not connect directly to an egress path. The layout with the longest egress time was that of the one with new stairs and columns but no new exits, with a 41 second increase from the historic layout with no changes. Obstructions in front of exit doors slows the total egress of the building by 24 seconds.

Overall, the renovations collectively resulted in a 17.7% reduction in total egress time (approximately 2 minutes).

- **Timber material factors –** Existing radial cracks increases the char depth in regions around the crack by 64% in the large-scale testing program. The effect of fire reduced the stiffness of the member, with an increase in deflection of 43% compared to the unexposed sample. The small-scale testing showed a 29% greater char depth on the cracked samples versus the solid. Overall, the existing radial cracks did have an effect on the fire performance of heritage timber.
- **Masonry materials factors –** There is no experimental data for heritage masonry units in fire, only results with comparable modern materials. From the provisional study on the clay brick masonry, 800°C heating with a slow ramp rate does not have a significant effect on the ultimate compressive strengths of the bricks.

The conclusions presented above relate specifically to the topics discussed in each of the individual sections, but the overarching conclusion from the investigations into different topics relating to heritage considerations in fire safety engineering is that heritage buildings are in need of unique design solutions to adequately protect them from fire. There are unique considerations in heritage buildings, whether architectural layouts or differing material properties, that are not present in contemporary buildings and cannot be addressed solely using contemporary design practices. A knowledge of heritage buildings and their characteristics, coupled with contemporary understanding of building design and fire safety are needed to bring these historic buildings up to modern safety standards without compromising their value or applying prescriptive strategies that are not effective.

6.3 Recommendations and Future Research

6.3.1 Academic Recommendations

For the human factors for heritage conservation, more case studies on the evacuation of heritage buildings are needed to continue to fill the dearth of information regarding egress and heritage, and their accurate representation in pedestrian modelling.

For the timber material factors, additional research should be conducted on the repair strategies for existing radial cracks, for example the epoxy filling frequently used to fill existing cracks. The effects of moisture content on char depth and crack expansion should also be considered.

For the masonry material factors, the academic recommendations for future research are provided in great detail, with an outline of an extensive testing program to expand on the provisional results found in the initial material study. The main components on the future research regarding masonry materials in fire are as follows:

- Expanding the sample size to be more confident in the results obtained, and to determine if any trends among the heritage samples appear.
- Conducting a study on historic and contemporary mortars exposed to heat in a furnace in compression. Several historic mortar mixes should be tested to narrow down the ideal properties to be compatible with the heritage masonry units.
- Testing heritage masonry prisms exposed to a pool fire to find their residual uniaxial compressive strength. Unheated prisms should be compared to heated prisms with and without repointing to determine the effectiveness of repointing masonry after fire on restoring strength.

For both materials studied, and any future research on additional heritage materials, the stages of decay should be investigated on their effect on fire performance. The proper care and conditioning of materials was vital for the testing materials, but also to building materials in existing heritage buildings themselves. The encompassing academic recommendation regarding all the topics discussed herein is to fill the dearth in experimental data considering fire safety of humans in heritage buildings and heritage materials in buildings. This would involve more case studies to be evaluated, more samples to be collected and tested, and critical thinking to be applied to existing fire safety practice applications to heritage buildings.

6.3.2 Practitioner Recommendations

Performance based approaches are most appropriate for heritage buildings because of the complexity and unique features in each building. Studies like those presented herein can inform design approaches, but each design solution should be tailored to the specific building. Unique approaches are needed for unique buildings such as heritage. Risk-based approaches are needed for heritage fire protection design based on the building condition as well as the materials and layout. The fire risk associated with abandoned buildings is vastly different (much higher) then occupied and well-maintained structures, or buildings that have been retrofitted in recent years. The presence of moisture, often associated with abandoned buildings, also has an impact both on deterioration and fire performance of a building and its materials. All these factors must be considered in the fire risk and protection of heritage buildings. The framework for fire protection of heritage buildings requires an understanding of a risk-based approach considering the building materials, moisture conditions, use, deterioration level, and layout.

For human behaviour modelling, the unique challenges regarding emergency egress in historic buildings should be considered. For timber, practitioners should not assume heritage timber has the same fire performance as contemporary timbers and should be aware of the effect of radial cracks on charring to make informed design decisions. For masonry, heritage samples also should not be assumed to have the same fire properties as contemporary masonry materials. For recovery after fire, the temperatures reached by the masonry should be investigated, and the reuse decisions be based on the level of fire exposure. From the provisional results obtained herein, temperatures of 800°C with a slow heating rate do not have a significant effect on the residual compressive strength of clay masonry bricks from any time period in Canadian history.

6.4 Closing Remarks

Among the various topics covered in this thesis, the overarching goal of this research is to improve the fire safety of heritage buildings while protecting character defining elements and heritage value wherever possible. The unique nature of heritage buildings is explored, and the need for exclusive design solutions for their safety and rehabilitation is highlighted. The research presented herein serves as the beginning stages of the development of an analytical framework to highlight work that has been completed and to bring attention to current research needs that would further enhance the fire performance of heritage structures. Heritage buildings are important representations of our past, but in protecting and preserving them can serve us well into the future.

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Appendix A: Heritage Implications in Egress and Modelling

Attached Paper:

Harun, G., Huang, L., *et al.* (2020) 'Heritage implications in egress and modelling', in *Fire and Evacuation Modeling Technical Conference*. FEMTC, pp. 1–9.

A1. Abstract

Movement parameters which reflect diverse populations in egress such as those for cultural centers are in need. Furthermore, cultural centers which are often of heritage value see architectural changes through time which can complicate existing evacuation strategies. Herein we recorded and analyzed two real emergency evacuations of a heritage cultural center. Using recorded CCTV footage from these real events, we employ developed tracking software and post-processing algorithms to derive a novel movement profile for representing a diverse demographic expected within buildings similar to that considered herein. We then validated these movement parameters within two typical software against the actual egress observed in the two evacuations. By verifying modelling tools and validating input movement speeds for use in this infrastructure, our study then considers a range of actual and potential architectural changes a building may experience and the new architecture's implication on emergency evacuations. Practitioners may find the discussion herein useful towards planned or recently executed architectural changes in historic buildings such as cultural centers. The results lay the foundation for further work which will help enhance knowledge on decision making in evacuations.

A2. Introduction and Background

Currently there exists a need to develop accurate movement speeds of diverse sets of infrastructures and buildings that can be utilized within evacuation modelling tools. This has been outlined through the SFPE research needs roadmap, and recently explored in the author's SFPE foundational report which considered a diverse range of structures (SFPE 2018) (Gales et al. 2020). Herein we describe the process of obtaining raw data which was later translated into movement speeds through the use of existing but modified open-access tracking software. We then utilize these movement speeds in existing software to validate the proposed movement speed profile, while also validating the use of these software tools for describing evacuation in complex cultural centers. The motivation of this current research project is to utilize evacuation modelling tools to understand the implications of architectural changes as are seen on heritage cultural centers.

The egress analysis of heritage buildings for new use is often performed by practitioners. Heritage buildings often present challenges with regards to emergency egress. New flow patterns, population density variations, changing and evolving demographics all reflect the challenges in egress design. These designs can affect the heritage value of these buildings and subsequently can conflict with conservation standards and guidelines. Herein we consider a 110 year old cultural center that has undergone several changes in use as well as structural and architectural modifications. It exemplifies the challenges in performing an egress analysis of a heritage building, which are discussed herein. The hundred-year-old cultural center serves the same purpose for which it was built, but it has not been exempted from the common changes of use that most heritage buildings experience. Most older buildings have changes in use and occupancy later in their lives to meet modern societal needs and changing industries (for example old industrial buildings becoming commercial offices). Even if the use has not changed, many interventions for structural stability are often required, changing the layout or certain building elements. When considering emergency egress in heritage buildings, there are often adjustments needed to the original egress routes to comply to modern building codes, while simultaneously respecting the heritage value of the structure and not changing those heritage defining elements. After many occupancy changes and hosting many different museums, extensive renovations altered the building's structure, organization, and egress routes to how they are today. These interventions have a variety of effects on the emergency egress, whether positive or negative, to be determined through modelling. The most significant addition to the building is the glass tower containing scissor stairs at the entrance to the building. These stairs provide additional connection between the second and fourth floors, where there was once supposed to be a separation between the public and private access to the building. The entire building is now open to the public, contrary to the original architect's intent, which causes unique egress challenges. In addition to the new staircase, six emergency exits were added to the various corners of the building, in an attempt to facilitate emergency egress. Another aspect of the renovations under consideration is the support columns for the new glass tower, which are placed very close to two of the three entrance doors. During regular ingress and egress the center door (not blocked by columns) is the only one utilized, but during emergency egress the two side doors are useful for evacuating the main entrance, where 70-90% of occupants exit according to the observed scenarios.

The museum study was conducted as a continuation of research program on a cultural center (Gales et al. 2020) (Champagne et al. 2019) (Mazur et al. 2019). Two scenarios are analyzed herein, originating from the CCTV records taken from real evacuations of this cultural center in 2016, on two separate occasions. From these recorded evacuations, the actual floor loadings and exit use rates were documented to create the two scenarios. A third scenario has not had its analysis completed, and therefore will only be included in future research. The following information was extracted and used for analysis: floor loading, exit use rates, and movement speeds organized by age demographic. A model of the building has been created and was utilized within different (though similar) movement based modelling software tools. The authors choose to consider two anon movement software technologies herein; Anon in the sense to not directly compare short comings, but to exemplify that the movement data inputs can be used with confidence (movement speeds unique to modified public heritage buildings). One of these softwares used a social forces based model where the other is based on the inverse steering movement model. The movement data was validated and the models verified to represent the real scenarios observed. An added point of interest with this particular case study was the heritage status of the building, and the major renovations and occupant changes throughout its year lifespan. The changes in use have an effect on the emergency egress, and many of the renovations had the purpose of improving the emergency egress of the building for the new occupancies. Therefore, in addition to the model validation, various simulations were run to be able to isolate the impact of specific elements of the renovation on the emergency egress of the building. The specific elements of interest were notably the columns in front of the entrance doors, the new tower stairs, and the new corner exits.

A3. Movement profile generation

CCTV footage was analyzed to determine the time between the activation of the evacuation alarm and the movement of the occupants. This was applied as a pre-evacuation time in the models to best reflect the behaviours observed these are presented in Table A1. A custom movement profile for the museum occupants was derived from walking speeds observed during one of the real evacuations. The input movement speeds for the evacuation software used is intended to be taken from an uncongested environment. Through reviewing security camera footage, the atrium was selected as the people walking through this area met this criterion. Additional post-processing code was developed to be used in conjunction with Kinovea, freeware, open-source sports kinematics software. With this new post-processing code, it was possible to easily generate movement speeds from the CCTV footage provided by the cultural center. An example of Kinovea in use is shown below in Figure A1.

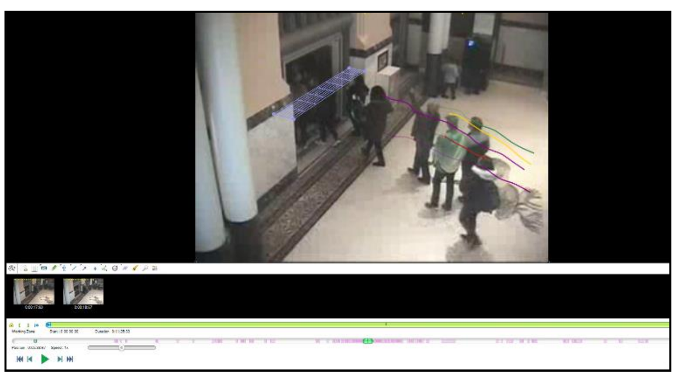

Figure A1: Example of Kinovea with tracking and perspective grid.

In regular use, Kinovea can track user-specified objects in video feeds, correcting for lens and angle distortion. However, Kinovea could not directly provide average speeds for an entire population, nor could it adapt to the occasional duplicate frames observed in low-framerate CCTV Video. Custom post-processing code was developed by the authors using excel VBA scripts to determine average speeds for entire populations over the course of tracking, while also detecting and accommodating frame duplicates from the camera footage. The developed script takes the coordinate data and times for each tracked object (i.e. person being tracked) and calculates the per-frame instantaneous speed. An overall average speed for each tracked object is generated based on the speeds observed over the object's entire track. Frame duplicates are detected when the change in coordinates between frames is zero. When this occurs, the duplicated frame's data is deleted, avoiding a velocity data point of 0 which would otherwise significantly impact average data. The developed script also sorts and categorizes the final average speeds based on the names manually given to the tracked objects within Kinovea. In this case, age demographics were tagged. 90 occupants passing through the atrium were analyzed. The population analyzed was composed of parents with children, adults, and youth. There were not enough seniors in the museum's footage to represent a statistically significant profile and this is in need for future use. The final profile is averaged and summarized in Table A2 below. The full profile broken between demographics was utilized in modelling efforts.

Table A1: Summarized pre-movement time.

Pre-Evacuation Time (Seconds)	**Percentage of Occupants (%)**
0-5	17
6 - 10	18
11 - 20	15
21 - 30	19
31 - 60	20
61 - 120	9
121 - 210	3

Table A2: Summarized movement profile (not separated by demographic).

New Profile	**Min Speed (m/s)**	**Max Speed**	**Mean**	**Std**
	0.58	1.98	1.15	0.28

A4. Modelling

In industry, Anon Software A and Anon Software B are both common pedestrian movement software used for evacuation analysis and prediction. They are both driven through similar movement frameworks, and were therefore chosen to analyze the cultural center crowd egress. The overarching goal of this paper is to validate movement profiles but not yet explore the software's decision making benefits or pitfalls. The names of the software used have not been included, as this is not a critique of any particular software. The intent is simply to show in both tools that the movement profile can represent the realistic speed of evacuation seen in reality. The authors restrain from making direct comparisons between the software's underlying mechanics as that is appropriate in future research – hence no imagery of the models are shown herein beyond the construction of the model space. In future research these implications may be beneficial to research.

Software A and Software B have similar construction and input procedures. For both, the model spaces were generated by using the cultural centre floor plans as supplied by the directors themselves and refined by the authors with surveying procedures in order to update certain aspects and incorporate blockages as would be present via exhibits. These floor plans were then transferred into a SketchUp file where elements were then defined in order to appropriately import into the software user space. The model space was then verified to ensure doorways, stairways, obstacles were assigned according to the floor plan to ensure the correct scale. Figure A2 shows the floor plan of the museum in SketchUp prior to import.

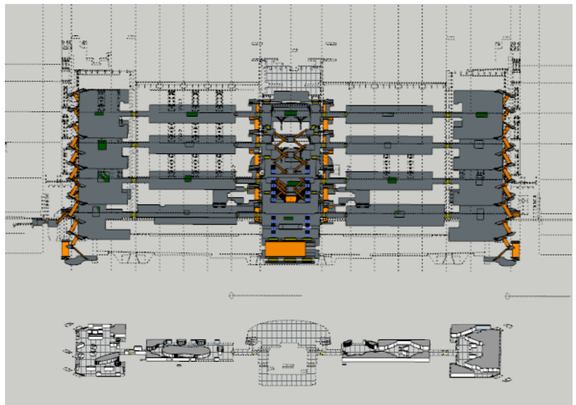

Figure A2: Cultural center museum floor plan rendered in SketchUp.

A5. Modelling Validation of Movement Speeds

These models used the novel movement profile as defined in previous section by the authors. The validation of the profile was across two evacuation scenarios which reflect the first two evacuations. Note the profile was derived from data from Scenario 2 alone, but would be validated against Scenario 1 and 2. At the time of writing, the third scenario (the 2017 evacuation) has not been used for validation purposes as the footage is still being analyzed by the authors. The intent of these validation exercises is to verify the authors movement (pre and evacuation) profiles for use in a range of computational egress modelling tools. It is not to validate the decision making or underlying movement framework in the models.

Scenario 1 shows the modelling of a relatively large evacuation with a population of 1742 patrons that was rationally distributed in the museum. This represents a credible occupation on a given autumn day whereas the maximum allowed population of the building is 4000. In Scenario 1, all of the programmed agents were assigned the recorded pre-movement time developed by the authors and assigned tendency of choosing specific exits as were seen in the real evacuation. By assigning the exit use we do not attempt to interrogate modelling decision making on wayfinding. In Software B, the pre-evacuation time in the movement profile section was assigned to all of the agent population by giving a waiting task to all agents. The length of waiting time was assigned in percentage accordingly to Table A1. An exit seeking task was then assigned after agents finished their waiting tasks. The seeking task simulates the exit choosing tendencies of the reality, and the exit seeking task was assigned in percentage following the summarized exit usage rate according to the real events. The model of Scenario 1 in Software A is similarly constructed. Since Software A supports assigning a percentage pre-movement time directly in a table form, with the pre-movement time set up according to the recorded data, only one exit choosing task needed to be assigned to the agents to develop the scenario. The plot of the main entrance exit count comparison between two software was shown by Figure A3 in comparison to the observed evacuation. The main entrance is shown as it represented a population of over 70% who exited in reality.

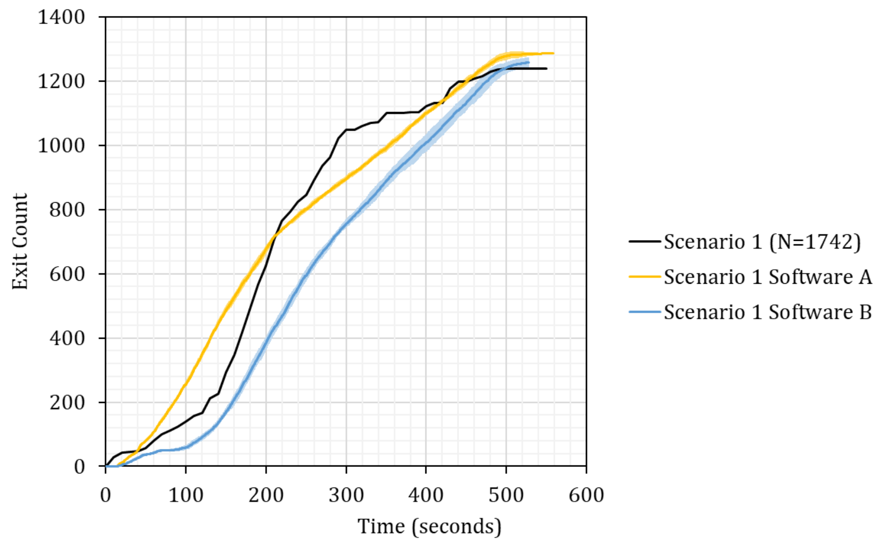

Figure A3: Comparison between the model results and real data for Scenario 1 (main entrance only).

Scenario 2 required additional consideration as in reality the majority of those leaving exited in the main entrance (>90%) and in addition the occupants were retrieving possessions such as coats during the evacuation (due to a snow storm). The population of the model is much lower with 459 agents. The authors analyzed footage of the event and concluded the process of coat retrieval was on average 60 seconds. In Software B, the agents were firstly assigned the waiting task same as Scenario 1 to simulate the pre-movement time reflective of their position in the cultural center. To simulate the exit choice the cost of route was manually set. The exit cost distribution was tuned close to the distribution recorded in the event. A waiting task initiator was also applied to the atrium floor so that once an agent enters the atrium, the agent will perform a 60 second wait time task to simulate the picking up coat process. After the waiting time, agents will continue their egress. In Software A, an alternative approach is applied. First, all agents had applied a general pre-evacuation time as before in Scenario 1. After the pre-evacuation time, approximately 92% of the population was assigned a task of picking up coat in the atrium. The 92% of population was assigned to seek for the atrium, waiting for 60 seconds in the atrium and extract from the main entrance. The other 10% of population will perform a normal evacuation that the agent will choose any exit with no restriction. The plot of the main entrance exit count comparison between two software is shown by Figure A4.

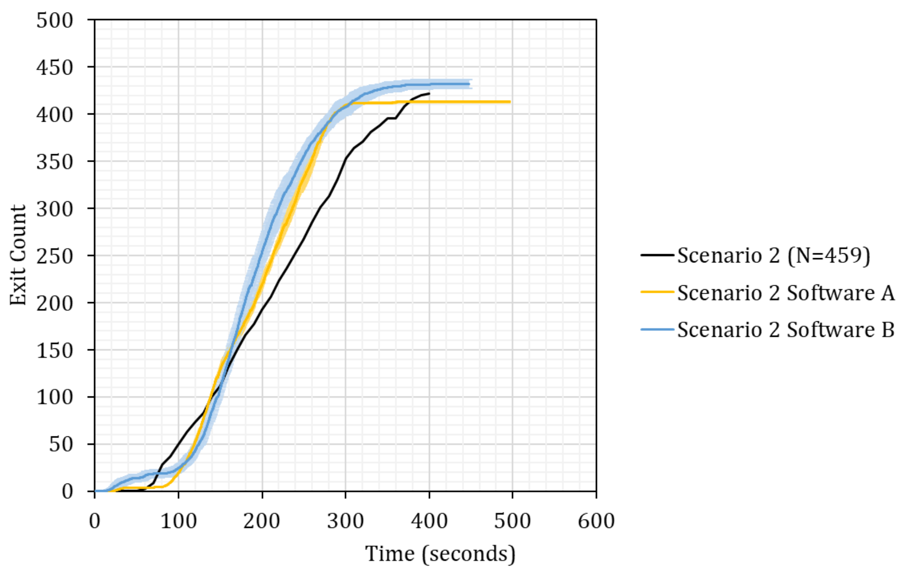

Figure A4: Comparison between the model results and real data for Scenario 2 main entrance usage.

In Scenario 1, both the simulation result curves have a trend that generally conforms to the real data curve. Before 100 seconds, Software B generates a mild increasing trend similar to the real situation, while the curve of Software A is steeper. At 200 seconds, Software A shows the same trend as the real situation that the exit count increasing rate is slightly decreased, while Software B simulates the decreasing trend after 250 seconds. Both software results in a similar total main entrance evacuation rate around 70%. The result generated from Software B is wider spread than Software A, illustrated by a wider shaded standard deviation area.

In Scenario 2, Both the software-generated result follows the trend of the real situation with a small difference between software. A notable difference between the simulated result and the real situation is the exit count increasing slope. It would relate to a small discrepancy between the ideal movement profile and real population movement speed. All modelled trends in Figure A4 suggest a plateau. This is actually not so as there are still a number of slow moving agents with large travel distances which result in these times appearing extended.

A6. Heritage Considerations

A range of analyses of the original 1911 building configuration and the building as it is today after significant renovations were conducted. The purpose is to identify the effects of the renovations on the modern egress of the building and determine their efficacy. To isolate the effects of specific additions, (for example new emergency exits or stairwells,) simulations were run with all the additions as the building is now, with each addition tested individually to see their effect on the overall egress time. These models were built based on archival data about the museum, which are not entirely complete at this stage. More accurate models will be created as additional information is researched by the authors.

The elements that were analyzed specifically were new staircases added in the new tower, six new exits at the bottoms of existing staircases in the corners, and columns supporting the new towers located at the foyer (seen in Figure A5). As the first iteration of these analyses, it did not yet consider the behavioural aspects that were included in the validations. These aspects will be interesting to consider in future research, as the population will have significantly changed socially and demographically from the museums use 100 years ago till today.

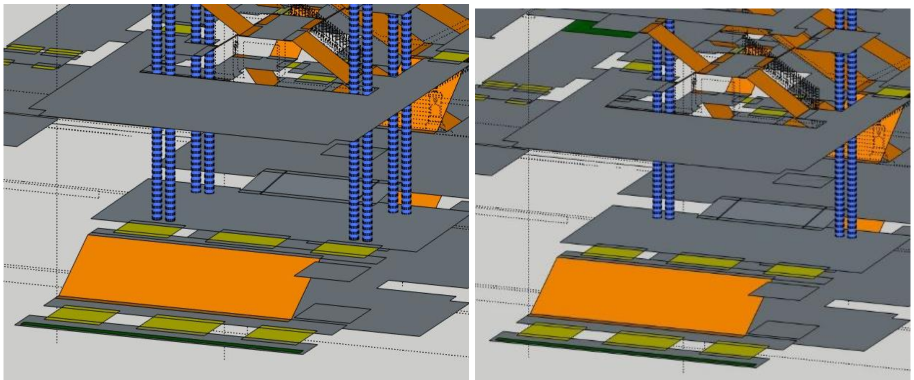

Figure A5: Model with and without the columns obstructing two of the three main entrance doors.

The occupant loading used was the maximum of 4000 for the museum to highlight the differences in egress times between the various scenarios in the worst situation, with or without certain additions. From the preliminary analyses, the new columns in the entrance, as well as the new staircase, had little effect on the egress time. The most significant additions in terms of egress were the six corner exits connecting directly to stairwells linking all four floors and the basement. The governing elements in the emergency egress of the building are still being explored, and the models will be further developed with some of the considerations discussed herein and more. These analyses are part of an important next step in this research, and give an idea of what interventions were effective in improving the egress of the structure and which weren't, which is valuable information when working with heritage buildings where minimizing interventions is recommended.

A7. Conclusion

The comparison between Software A and Software B was completed with a model validation regarding movement speeds, as well as a preliminary analysis and heritage considerations. The model validation found similar results between the software when evaluating the main exit use, and only a slight difference of slope between the simulations and the real exit use data. That difference can be attributed to the idealization of the population's movement speeds. The preliminary parametric analysis using default parameters found minimal differences between total egress times with various populations. Overall, Software A and B were verified to produce similar analyses possibly influenced due to their similarity in movement algorithms. The comparison by parametric analysis will continue in future work. Future research will also expand upon the findings in this paper with the inclusion of the third recorded evacuation scenario for validation and more analysis on the renovation of the building and the heritage aspects that influenced the layout decisions.

A8. Acknowledgements

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