Fire Performance of Cultural Heritage and Contemporary Timbers

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Abstract

Cultural heritage buildings are important reminders of our history, and timber is one of the materials commonly found within these structures. While cultural heritage buildings often hold significant aesthetic, historic, or cultural value, they are also frequently vulnerable to fire. In order to improve the fire performance of these buildings, the timber elements are often removed or covered by another material. When these alterations are done, the heritage value of the building is obscured. On the other hand, increasingly larger and taller timber buildings are being constructed out of contemporary / engineered timber, and fire safety engineering strategies have been found to justify the adequate fire performance of these contemporary structures. This manuscript herein addresses if historic timber performs significantly different to contemporary timber in fire. Controlled and repeatable fire tests have been performed on four different types of timber, two contemporary Glued Laminated Timbers (Glulam) and two historic timbers from buildings constructed in 1898 and 1839. The timber was tested using Lateral Ignition and Flame Spread Test and Cone Calorimeter apparatuses, following ASTM E1321 and ASTM E1354 standards, to compare the relative performance of the timber types in their char depth, time to ignition, and flame spread. Results showed that the historic timber did not perform as well as the Glulam in the aforementioned categories, with the historic timber charring at a rate up to 20% faster. This study is novel by providing an indication of the fire performance of timber that was used hundreds of years ago, by comparing it to timber used today. Successful heritage conservation efforts in leaving the timber exposed and in-place become possible once the performance of the timber is understood, and other fire safety engineering strategies (respectful of the heritage structure) are in place.

Keywords: Timber, fire, cultural heritage, Glulam, char

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1. Introduction and Motivation

Heritage timber buildings are exceptional and tangible reminders of our history. Often, they are recognized for their aesthetic, historic, cultural, scientific, social, or spiritual importance [1]. Timber is a building material that is commonly found in these heritage structures worldwide. While the presence of timber within historic buildings may represent the technology of the time period and may hold value architecturally, often, there are concerns regarding the performance of historic timber buildings in fire. Heritage timber buildings are vulnerable to fire for a number of reasons; to name a few, it is not uncommon for a heritage building to be neglected and as a result become vulnerable to accidental fire or arson. The fire safety systems within the buildings may also be reflective of the period in which they were constructed and may therefore not be as advanced as the systems we have in place today.

One strategy to improve the fire performance of a timber building, which is recommended by several sources (see [2, 3]), is to cover or encapsulate the historic timber with a material meant to improve the fire performance of the assembly, such as fire rated gypsum board. When the historic materials are covered by another material and cannot be seen the heritage value may be lost. Covering materials which hold heritage value or contribute to the character of the place is not encouraged by heritage guidance [4]. It is also possible that the historic materials are removed from a structure and replaced with contemporary materials. These strategies are not ideal from a heritage conservation standpoint and may stem from a need for additional information and guidance on how historic materials perform in fire, as well as how these historic materials may be respectfully conserved.

From a fire safety perspective, these heritage conservation restrictions can be challenging to overcome. Historic timber often does have some attributes which are beneficial towards the fire performance of the structures, for example, the members are often oversized [2]. In fact, historical guidance recommends ensuring that the member will have adequate strength even if a third of the original cross section has charred, so as to allow for business continuity in the event of a fire [5]. An example of a large historic timber assembly can be seen in Fig. 1. If a fire were to occur, the modern day ‘residual cross-section method’ would indicate that the undamaged portion of a timber member would still retain significant strength [6]. Oversized members would have a larger remaining cross section during and after a fire.

Fig. 1 A historic timber assembly found in Toronto, Canada

There is little guidance available for practitioners when assessing existing heritage structures, and often, the guidance that does exist suggests that historic timber performs extremely similarly (if not identically) to contemporary timber [2, 7], without significant evidence to suggest that contemporary and historic timber do indeed perform the same in fire.

Meanwhile, globally we are seeing a growing number of timber buildings being constructed in large and tall applications. These contemporary timber buildings are commonly requested to be left exposed (unencapsulated) [8]. One of these structures can be seen in Fig. 2. There has been significant research progress around the performance of contemporary timber in fire, and we continue to be able to create more complex buildings with contemporary timber [9].

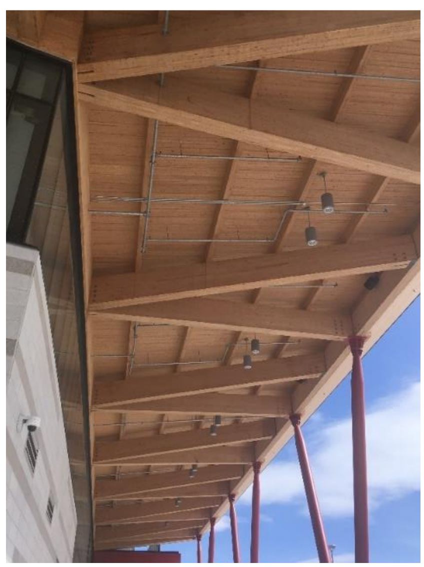


Fig. 2 A contemporary timber structure

As the level of knowledge regarding contemporary timber proceeds to grow, and more intricate contemporary timber buildings are constructed, historic timber continues to be removed or altered within heritage buildings. This may in part be due to the lack of knowledge and guidance regarding how to assess and improve the fire performance of a historic timber structure, however to the authors knowledge, there is limited evidence to show that historic timber performs significantly differently than contemporary timber or that the fire risk within a heritage timber building is notably different than within a contemporary timber building. The term 'historic' generally encompasses materials from structures that have, or that are eligible for, designation for their historic, architectural, or cultural value [2]. The experimental study within this paper focuses on timber removed from structures that fit within this definition, which were constructed in the 19th century and that is significantly different from contemporary engineered timber. The purpose of the research herein is to determine if historic timber performs substantially differently than contemporary timber in fire. This study's contributions to the state of the art include experiments which begin to quantify the fire performance of timber by looking as flame spread, char depth, and time to ignition, and using these characteristics to compare the fire performance of timber products that are used today with those used hundreds of years ago.

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

2. Background

Available guidance outlines methods for interpreting the performance of timber in fire. Of particular interest is the char depth, which can then be used to determine the dimensions of the cross-section of the unaffected timber. When wood is exposed to fire, it begins to char. The following layer after the char layer is known as the pyrolysis layer. The pyrolysis layer is comprised of timber that did not directly char but was still heated to the point where some material degradation has occurred. These layers can be seen in Fig. 3. In standard procedures, timber below the pyrolysis layer is considered as retaining full strength. Standards (such as CSA O86 and Eurocode 5) therefore allow for the determination of residual strength post-fire by calculation of the char depth (evaluated based on the time of heat exposure and using a constant charring rate), added to a constant 'zero-strength layer' (which allows for degradation below the char layer). The residual cross section is then taken as the original cross-sectional dimensions, less the char depth and the zero-strength layer [6, 7].

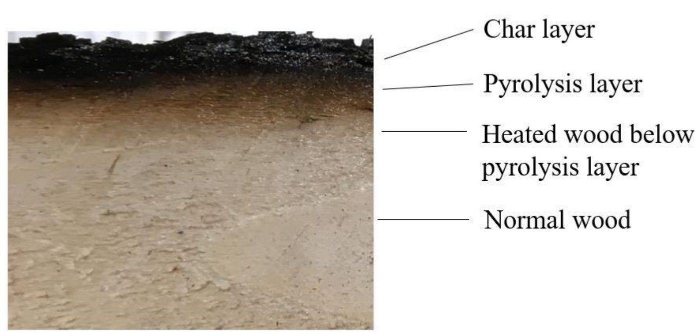


Fig. 3 Char formation on a piece of Glued Laminated Timber (Glulam)

The residual cross-section method is highly dependant on correctly determining the char depth and the zero-strength layer of the timber. Previous studies have shown, however, that the zero-strength layer currently used may not be conservative, even for contemporary timber [10–12]. Furthermore, the char rate may be taken as a constant value for a particular type of timber regardless of the severity or type heat exposure, as well as a number of other factors which have been shown to impact the charring rate of timber (such as moisture content, grain orientation, and density, to name just a few) [6, 13].

Historic timber differs from contemporary timber for several reasons. Historic timber was produced from trees that were grown hundreds of years ago. Ancient timber growing practices may be different than contemporary growing practices, which may affect properties inherent to the timber such as density and growth ring width [14, 15]. An example of this is seen in Fig. 4. In the particular samples shown in Fig. 4, it is apparent that the growth rings are significantly wider in the historic timber versus the contemporary Glulam. Furthermore, contemporary timber often frequently uses adhesives and other additives which may also impact the fire performance of the timber. Adhesive lines in the contemporary Glulam are seen as vertical lines holding together the wood laminates in Fig. 4a.

a.
b.

Fig. 4 Cross sections of showing the growth ring width of, a. contemporary Glulam and b. historic timber, from a building constructed in the 1840s

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

Radiant heaters are one method that can be used for fire testing. Fire testing apparatuses such as the Cone Calorimeter and the Lateral Ignition and Flame Spread Test (LIFT) both make use of radiant heat. In both cases (for the Cone Calorimeter and the LIFT), 50 kW/m^2 is on the upper end (safe operation) of heat fluxes that can feasibly be achieved for long testing durations, which is not as severe as a heat flux that may be expected from a real fire (>100 kW/m^2). Advantages of these apparatuses, however, are that they are useful for developing an easily controlled, consistent heat exposure, and are therefore useful for reproducible and comparative tests for research purposes.

The research herein will begin to look at the fire performance of historic timber from several sources, through examining properties such as char depth and flame spread. Assessing the fire metrics of historic timber will help to better understand how it performs in fire relative to contemporary timber, to evaluate if it is conservative to use contemporary procedures in the evaluation of historic timber, and if significantly more fire risk is presented by the historic timber versus the contemporary timber. This analysis will be useful in the assessment of heritage timber buildings, by understanding if the fire performance of the building is acceptable in its current state (mitigating unnecessary interventions), or if the building requires further fire safety strategies. In either case, avoiding unnecessary interventions and ensuring that the building is protected from fire are both steps towards successful conservation.

3. Methodology

3.1 Obtaining and Preparing Samples

Four different types of timber have been procured for testing; two historic timbers and two contemporary Glulams. The first type of Glulam tested used a polyurethane-based adhesive, and this timber will be denoted as ‘Glulam – PUR’ herein. The second type of Glulam used a phenol-resorcinol-formaldehyde based adhesive and will be denoted as ‘Glulam – PRF’. The historic timber was obtained from two different sources, both located in Ontario, Canada. The first location was an industrial ‘mill’ type building constructed in 1898. This building had a layout similar to the depiction seen in Fig. 5.

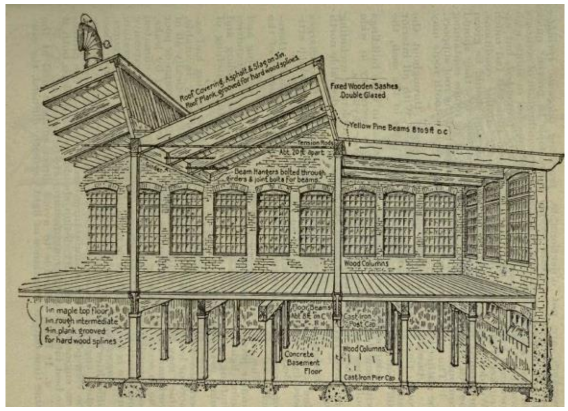


Fig. 5 A building of a similar layout to the industrial mill building from where the column was sourced [5]

The structure used large timber beams and columns connected by a cast iron cap, which is seen in Fig. 6. Several timber members were (carefully) removed from the structure by the building owner to accommodate an adaptive reuse project, and the timber samples used in this research were sourced from one of these columns (originally located in the basement). The dimensions of the column were 240 x 290 mm. All timber described as 'Column' indicates that it is timber from one of the columns within the industrial mill building. The materials were wrapped in plastic to allow slow acclimatization to new laboratory conditions.

Fig. 6 The timber column in the basement of the structure before removal

The second source of historic timber was from a commercial building, constructed in 1839. The interior of the structure was demolished to accommodate a new construction project, though the façade of the building was preserved and will be integrated into the new construction. The original structure was listed on the municipal heritage registry. Fig. 7 shows a photograph of the building dating to 1856. Wooden joists were obtained from this structure for fire testing. The original dimensions of the joists were 350 x 70 mm. As per the procedure used for the previous building, these materials were carefully wrapped and acclimatized to new laboratory conditions.

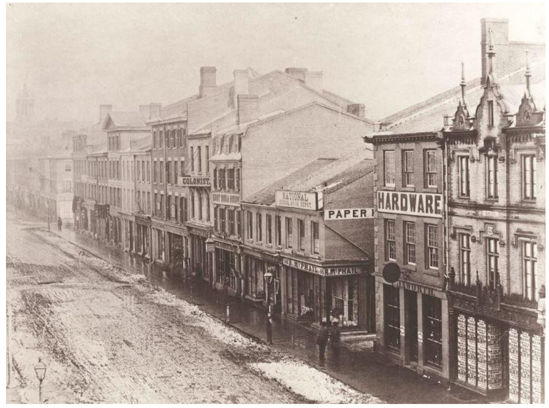


Fig. 7 An 1856 photograph of the commercial street from the building where the joist was obtained (5th building from the bottom of the photo) [16]

Once the historic timber was located, there were continued challenges in preparing the timber for testing. All of the timber was thoroughly inspected for pests, rot, and moisture damage, and none was detected. The moisture content of the timber was then kept relatively constant in order to avoid deformations or cracking. The moisture content of the timber was then slowly acclimatized to the lab where they were stored, eventually reaching a moisture content ranging from 7-8% which is within the acceptable moisture content for in service timber. The moisture content was determined following ASTM D4442 oven-dry procedure using a forced convection oven at 103˚C [17]. The timber did have some cracks, which made it challenging to obtain samples of the correct size from the timber. The dimensions of the original members also somewhat limited the shapes and configurations of samples which could be obtained. As a result, the side exposed to the radiant heater was freshly cut for all specimen (as opposed to having been allowed to oxidize over time). This side was chosen, as it allowed the required number of samples to be extracted from the Column and the Joist, in the dimensions required for the Cone Calorimeter.

All of the types of timber are seen in Fig. 8. The Glulam and the Joist timbers are Spruce, and the Column timber is Pine. The wood species affects the fire performance of timber (for example, Pine is typically considered to char at a faster rate than Spruce) [18], and this should be considered when interpreting the results herein, however variations in species may be representative of what has been used historically for construction versus what is used today (at least in the jurisdiction where the timber was procured).

The density of the timber was measured as 504 kg/m^3 for Glulam, 394.8 kg/m^3 for the Joist, and 417.6 kg/m^3 for the Column. As the Glulam and Joist are of the same species, the difference in densities may suggest differences in contemporary and historic growing practices, reinforcing the need to understand potential difference between the fire performance of historic and contemporary timber. The Glulam (both PUR and PRF adhesives), as well as the column and joist were tested with heat exposure perpendicular to the grain. The historic column was also tested with heat exposure parallel to the grain in the Cone Calorimeter phase of testing (Fig. 8d). The parallel grain orientation of the test was not possible in the historic joist, as due to the thin nature of the member, the required dimensions could not be obtained in that grain orientation.

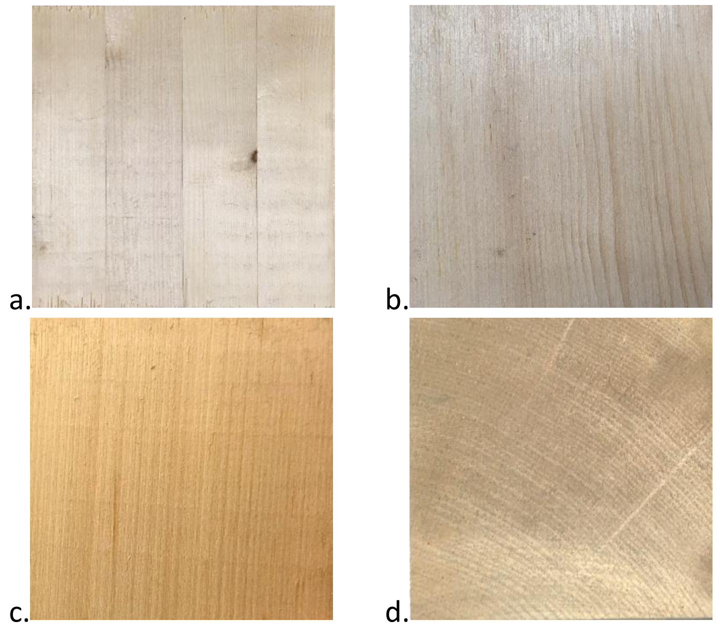


Fig. 8 Each of the timber samples and the surface exposed to heat, a. Glulam, b. Joist, c. Column – Perpendicular, and d. Column – Parallel

Timber samples were cut to the size required by the testing apparatus. Two test apparatuses were used, the first a Cone Calorimeter and the second a Lateral Ignition and Flame Spread Test (LIFT) apparatus. The samples tested in the Cone Calorimeter were 100 x 100 x 45 mm, while the samples tested in the LIFT were 800 x 155 mm x 35 mm.

3.2 Cone Calorimeter Tests

The Cone Calorimeter tests followed a modified ASTM E1354 procedure [19]. The Cone Calorimeter is an apparatus that uses radiant heating coils wound into a cone [20], and the irradiance of the apparatus can be controlled. Specimens can then be placed under the heater and exposed to the desired heat flux. The test setup is seen in Fig. 9. Modifications to the ASTM E1354 procedure were made in that each sample was removed from the Cone Calorimeter after a specific length of time and extinguished with water (which evaporated upon application to the timber). The use of water to extinguish a fire is representative of what would occur in a real fire scenario. Another modification to the procedure was that the spark igniter of the Cone Calorimeter was not used. The ASTM E1354 standard indicates that the exact irradiance levels or use of external ignition is not prescribed, and that these should be determined separately for each product [21]. The spark igniter was therefore not used in order to be most representative of a realistic fire, as if ignition were to occur, the timber would self-ignite.

For the Cone Calorimeter tests, samples were tested at two different heat fluxes, 30 kW/m^2 and 50 kW/m^2. These were selected as 50 kW/m^2 is towards the upper limit of heat fluxes that the Cone Calorimeter can sustain for long durations of time. 30 kW/m^2 was chosen as a less severe point of comparison. Heating durations of 3, 6, 10, and 15 minutes were considered, with two samples of each timber type being tested at each heating duration at each heat flux. Two additional samples of Glulam – PUR and Joist were also tested for 30 minutes at

50 kW/m^2. Time to ignition was recorded during testing. After the samples had cooled, each one was cut in half and char depth was measured (+/- 1 mm) along the centreline. Char depth was assessed visually, with the authors interpretation of the char layer seen in Fig. 3.

a. b.

Fig. 9 The Calorimeter test setup, a. the entire apparatus and data collection system, and b. the cone heater and a sample being tested

3.3 Lateral Ignition and Flame Spread Tests

Tests were also conducted using a LIFT apparatus, following a modified ASTM E1321 procedure (Fig. 10) [22]. The LIFT apparatus is useful for exploratory testing, which can then be used to direct larger scale tests [23]. This is adequate for the purposes of the research herein, which is to begin to compare the fire performance of different types of timber. Like the Cone Calorimeter, the LIFT also uses a radiant heater, though in this case the samples were tested vertically facing the heater and the spark igniter was used. The heat flux of the LIFT apparatus ranges from 50 kW/m^2 at one end of the radiant panel and decreases to approximately 2 kW/m^2 at the other end. The LIFT apparatus can be used for tracking flame spread across the sample. A series of pegs are located along the bottom of the sample holder, and the time at which the flame reaches each peg can manually be tracked. Samples were left in the LIFT for 18 minutes, chosen somewhat arbitrarily as a time which was deemed appropriate for allowing the flame to spread across the samples. Only subset of timber types were tested in the LIFT, with Glulam – PUR used to represent a contemporary timber, and timber from the Column representing a historic timber. Both timbers were tested with heat exposure perpendicular to the grain. After the samples were removed from the LIFT and had cooled, the char depth and the char front were measured. The char front was measured at the centreline of the beam.

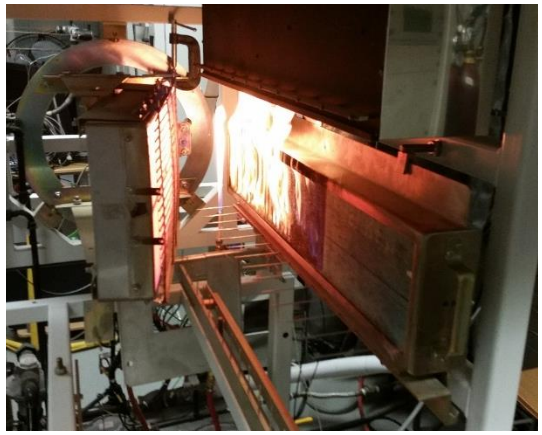


Fig. 10 The LIFT test setup, depicting the radiant heater and a test sample

4. Results and Discussion

4.1 Cone Calorimeter Tests

Time to ignition was one of several properties recorded in the Cone Calorimeter tests. These times are presented in Table 1. All of the samples ignited at 50 kW/m^2. At the lower heat flux of 30 kW/m^2, none of the samples ignited, with the exception of Column – Parallel. Six out of the eight Column – Parallel samples ignited at 30 kW/m^2, with an average ignition time of 134.8 seconds (standard deviation of 16.1 seconds). The Column - Parallel samples had the longest time to ignition at 50 kW/m^2. Both of the Glulam types had very similar average times to ignition, at around 31-32 seconds after heat exposure began. The historic timber which was exposed to timber perpendicular to the grain had the quickest times to ignition, at approximately 17 seconds for the Column and 19 seconds for the Joist.

Table 1. Average times to ignition of the Cone Calorimeter tests at 50 kW/m^2

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

The Column – Parallel sample had the longest time to ignition at 50 kW/m^2, however it was also the only type of timber to ignite at 30 kW/m^2 (with six out of eight samples igniting). Column – Parallel was the only timber type that was tested with the heat exposure parallel to the grain, which may be the cause of the differences in time to ignition. Grain direction is known to impact the fire performance of timber [13]. The notion that timber heated parallel to the grain would take longer to ignite at high heat fluxes aligns with previous studies [24]. The results of the timber tested perpendicular to the grain suggest that in this case, the contemporary Glulam performed somewhat superior to the historic timber.

The times to ignition observed in these tests are generally slower than as reported in previous literature, however, previous literature has largely used spark igniters in Cone Calorimeter testing [25, 26]. Harada (2001) generally reported times to ignition of 8-18 seconds for softwoods at 50 kW/m^2, and more recently Xu et al. (2015) observed times to ignition of 16-29 seconds [27]. Slight variations are expected due to differences in species, however as the historic timber tested with heat exposure perpendicular to the grain ignited at times similar to these previously reported values, even without the presence of a spark igniter, the notion that the historic timber may not be performing as well as the contemporary timber is reinforced.

The charring of the timber samples was also recorded. Fig. 11 presents the char depth results for the 3, 6, 10 and 15 minute tests for all timber types. At 30 kW/m^2, the char depth of all of the timbers are relatively close. At 50 kW/m^2, there is a bit more deviation. At the longer heat durations, and especially at 15 minutes (which is the most severe heat exposure considered), the historic timbers have charred more than the contemporary timber. On average for 15 minutes at 50 kW/m^2 the historic timber had 1.75 mm (13%) more char than the Glulam.

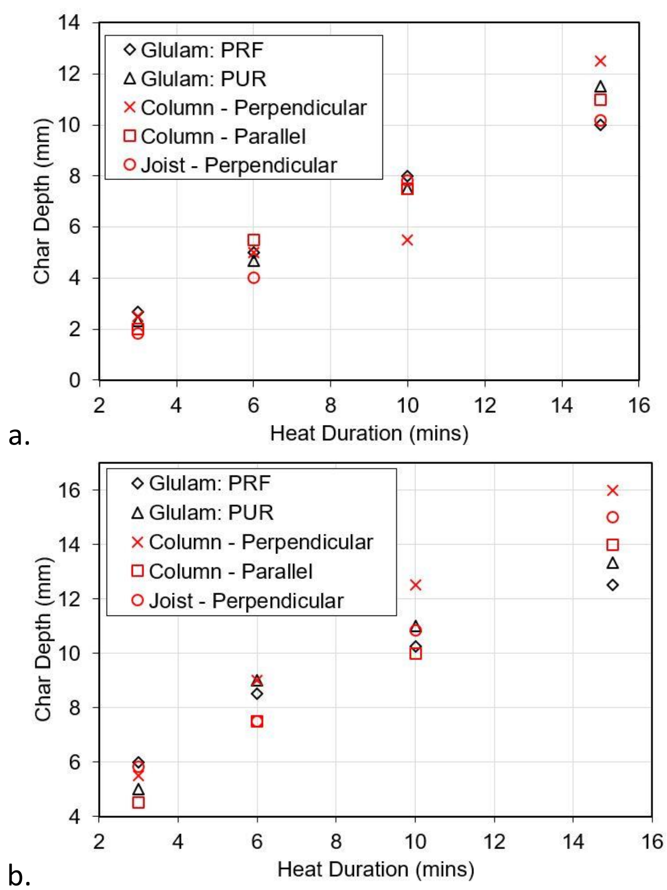
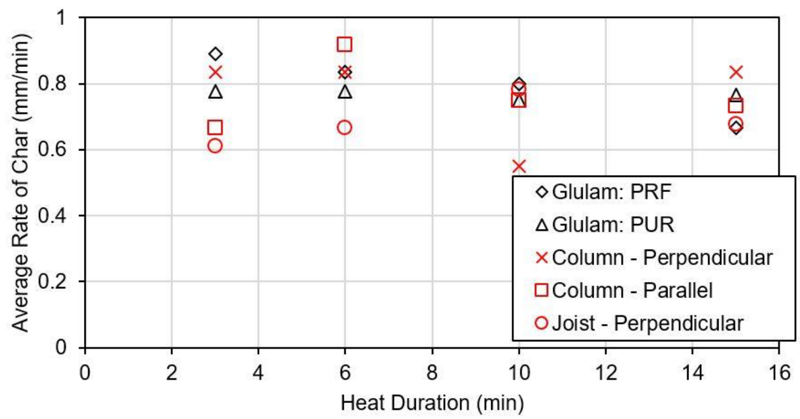
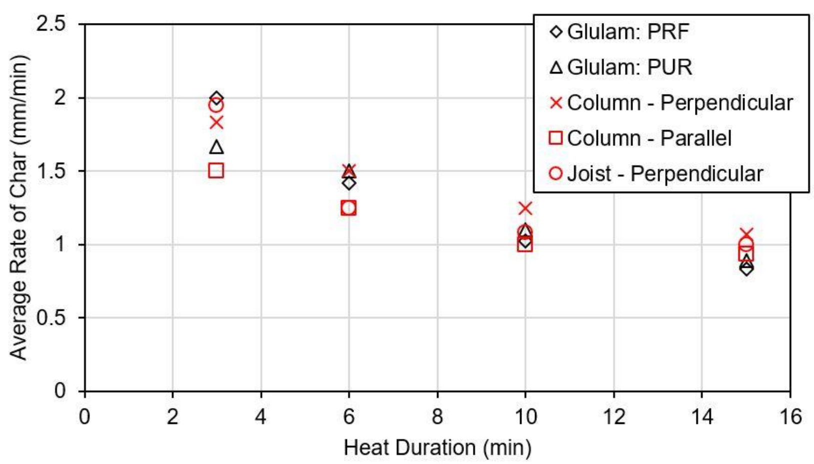


Fig. 11 Average char depths for each type of timber at a. 30 kW/m^2 and b. 50 kW/m^2. Each data point represents the average of two samples

The charring rate of the timber was calculated from the char depths and the heat duration. The charring rate was taken as the total char depth in millimetres, divided by the total heat duration in minutes. The charring rates for the 3, 6, 10, and 15 minute tests are seen in Fig. 12. Similar to the char depths observed, the charring rates at 30 kW/m^2 do not seem to indicate that any type of timber is charring particularly quickly or slowly. At 50 kW/m^2, it can be seen that the charring rates begin charring quicker and then level off. While all the timbers seem to be charring at similar rates, it is notable that at the most severe heat exposure of 50 kW/m^2 for 15 minutes, all of the historic timbers report a faster charring rate than the contemporary timber, however the charring rates at this heat exposure only range from 0.83 mm/min (Glulam – PRF) to 1.07 mm/min (Column – Perpendicular). These charring rates are slightly above the charring rates previously reported in experimental studies which consider standard fire testing, for example which range from 0.58-0.71 mm/min in wood-wood-wood connections [28].



a.



b.

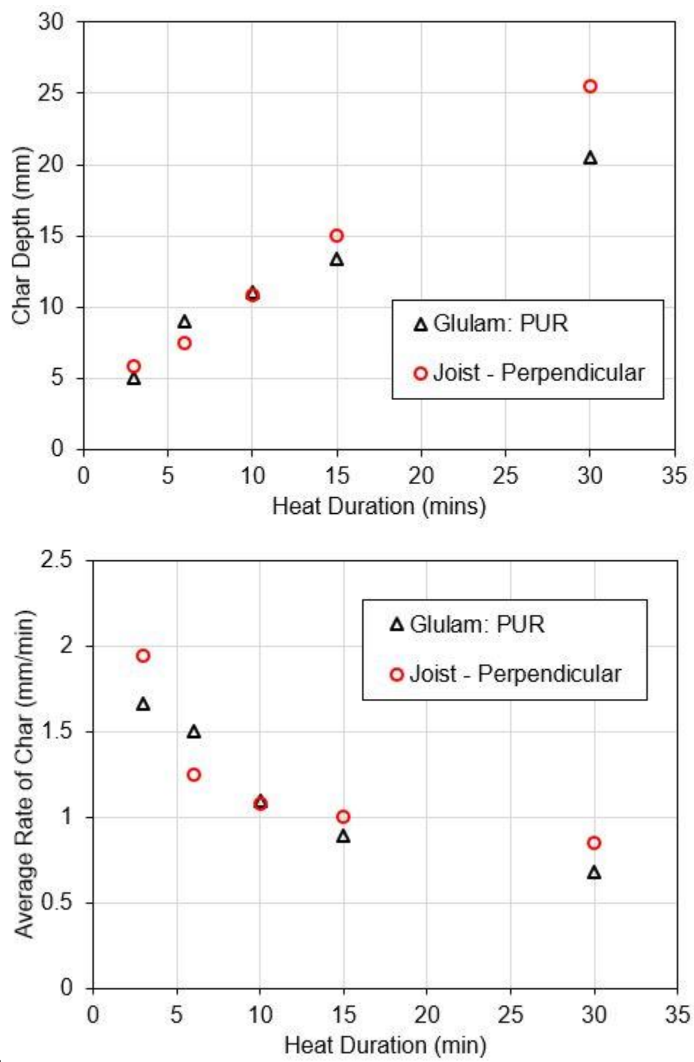
Fig. 12 The charring rates for the 3, 6, 10 and 15 minute test durations at a. 30 kW/m^2 and b. 50 kW/m^2

The results of the char depths and charring rates showed some discrepancy between the historic and contemporary timber. At 30 kW/m^2, all of the timber types charred similarly. At 50 kW/m^2, the historic timber had slightly more char depth, especially noticeable at the heat duration of 15 minutes. This may imply that at more severe heat durations the char depth of the historic timber will be slightly greater than the contemporary timber. One of the reasons that may help to explain the difference in char depths and charring rates is the density of the timber. The Glulam was denser than the historic timber, and increasing density has been shown to be tied to a decrease in charring [29, 30]. Many of the other variables known to impact fire performance were constant between each of the types of timber (for example, moisture content, species and sample size).

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

Two timber types (Glulam – PUR and Joist) were also tested for 30 minutes at 50 kW/m^2. The charring depths and charring rates for these timber types for every test duration are seen in Fig. 13. Some of the trends previously described are exemplified by the 30 minute test. For example, the char depth of the historic Joist is significantly more than the contemporary Glulam, with 5 mm (24%) more char at 30 minutes. The charring rate of the Joist is also clearly higher than the charring rate of the Glulam at 30 minutes.

As seen in Figs. 12 and 13, the charring rates of the timber at 50 kW/m^2 are beginning to plateau. Considering only Glulam PUR and the historic joist, the charring rate appears to be plateauing around 0.68 mm/min for the Glulam, and 0.85 mm/min for the joist. The joist was therefore charring at a rate 20% faster than the Glulam.



a.

b.

Fig. 13 Results for Glulam – PUR and Joist inclusive of the 30 minute tests, a. char depth and b. charring rate

4.2 Lateral Ignition and Flame Spread Tests

The flame spread results of the LIFT tests are seen in Fig. 14. Recall that in these tests, only Glulam PUR and Column – Perpendicular (heat exposure perpendicular to the grain) were tested. Data ends where the flames self-extinguished or the flame stopped spreading. The flame spread on the historic Column was faster and spread further than the flaming on the contemporary Glulam. The flames on the historic Column stopped spreading at 141 and 325 seconds (for Test 1 and Test 2, respectively), whereas the flames on the Glulam took longer to stop spreading, at 186 seconds and 388 seconds (for Tests 1 and 2).

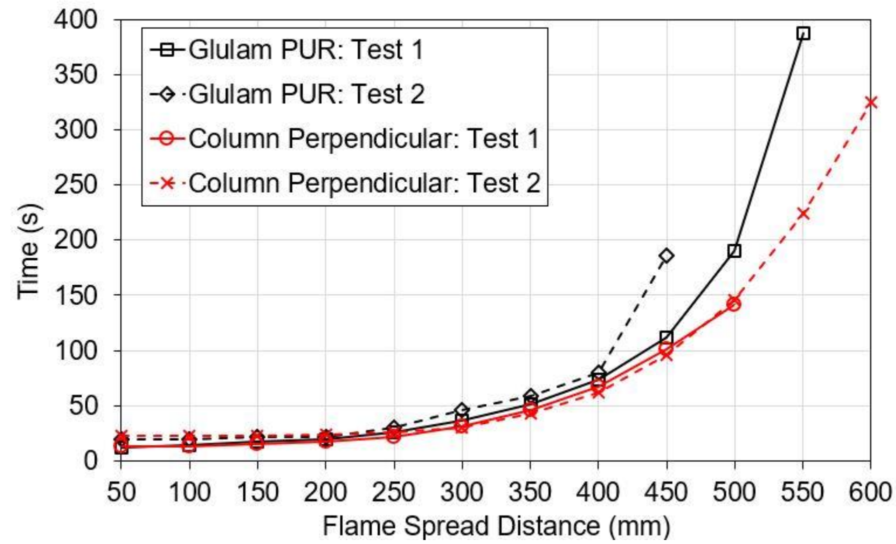


Fig. 14 Flame spread along Glulam – PUR and the historic Column

After testing was complete, the char depth and length of the char front were measured. These results are seen in Table 2. The timber from the historic column exhibited slightly less char depth than the Glulam, though it had a farther char front.

Table 2. Maximum char depth and length of char front of each test

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

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

5. Limitations and Research Needs

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

The scale of testing is relatively small, at only 100 x 100 mm for the Cone Calorimeter tests and 800 x 155 mm for the LIFT tests. Size is one factor that has been shown to have an effect charring rate [31]. Future research is needed on full-scale members. The results described above offer a preliminary indication of the anticipated fire performance of historic timber, but full-scale testing is needed for the results to be extended to full scale structures.

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

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

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

Finally, the heat exposure of a heat flux of up to 50 kW/m^2 through use of a radiant heater is sometimes considered to be a limitation, since 50 kW/m^2 is not generally considered to be representative of a realistic fire that would occur within a building. However, all of the samples that were tested at a heat flux of 50 kW/m^2 ignited, therefore the heat exposure may be more representative of a realistic fire since there was a fire on the surface of each of the samples. Furthermore, at 30 minutes of 50 kW/m^2, the charring rates of the Glulam and historic joist were observed to be 0.68 and 0.85 mm/min, respectively. The charring rate derived from standard fire exposure for these timbers is 0.65 mm/min, and experimental standard fire tests have reported similar values [6, 7, 28]. The charring rate appears to be greater or equal to the charring rate corresponding to the standard fire, however, this is not to say that the heat exposure of this test programme was equivalent or more severe than the standard fire. There are several differences such as the incident heat flux, ventilation and oxygen supply, and duration of exposure- and therefore the two experiments cannot be directly compared. In addition, a constant heat flux is used here while the standard fire follows a transient prescribed temperature time curve. Instead, the results simply suggest that the heat exposure the samples are experiencing is indeed greater than a heat flux of 50 kW/m^2 (due to the flaming on their surface), and is therefore an acceptable representation of a real fire. In this sense, the use of a radiant heater for a heat flux of up to 50 kW/m^2 allows for a repeatable measure of comparative performance between different timbers and does not present any limitations on this study.

Another consideration when evaluating the severity of the heat exposure is the notion that the timber also generates heat once it begins burning. The heat fluxes used of 30 kW/m^2 and 50 kW/m^2 in the Cone Calorimeter represent the heat fluxes generated by the apparatus, but do not necessarily represent the total heat exposure once the heat generated by the timber itself is considered. The heat release rate for the 30 minutes Cone Calorimeter tests are seen in Fig. 15. A higher heat flux will alter the performance of the timber, for example by accelerating chemical reactions which cause ignition at a faster rate [32, 33].

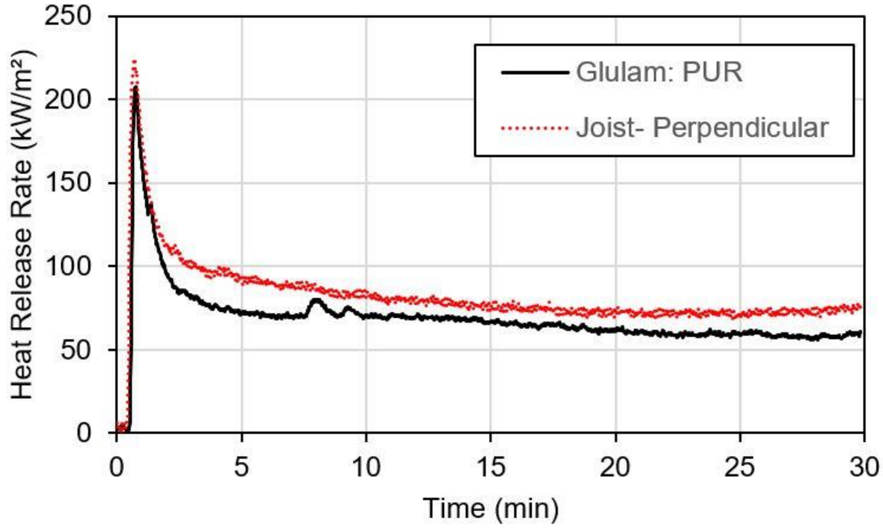


Fig. 15 Heat release rate of the 30-minute Cone Calorimeter tests

6. Conclusions

The purpose of this study was to compare the fire performances of historic timber and contemporary timber. Industry trends have shown increasingly larger and taller contemporary buildings being constructed, while at the same time, historic timber is often removed from heritage buildings. The results of this study compared the times to ignition, char depth, flame spread, and char front of several types of historic and contemporary timber through the use of the Cone Calorimeter and LIFT apparatuses. In comparing these properties, it cannot conclusively be said that the performance of the historic timber is identical to the performance of the contemporary timber, especially in the time to ignition and char depths of the Cone Calorimeter tests, and the flame spread and length of the char front in the LIFT tests.

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

This study was successful in comparing the fire performance of historic timber with contemporary timber, by evaluating characteristics such as char depth, flame spread, and time to ignition. An increased understanding of the fire performance of historic timber, coupled with other fire protection strategies which can be respectfully integrated within a heritage structure, will help to ensure the successful conservation of cultural heritage timber buildings.

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