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MASS HERITAGE TIMBER PERFORMANCE IN FIRE

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Abstract: Timber heritage structures are prevalent worldwide due to the inherent ease of their construction prior to the popularization of contemporary concrete and steel buildings in the late 19th century. As material reuse or conservation becomes a more popular and sustainable option, the performance of these timber structures is being (re) examined, and their performance in a fire is not an exception to this. This is particularly important as vulnerable structures are left to decay in some instances. For this reason, there is a value in researching the fire performance of existing mass timbers members found in infrastructure. This study aims to address this need and to provide a holistic study on the resilience of heritage timber with controlled fire exposure. The research presented involves testing sections of heritage timber (defined herein as timber which has seen over 100 years in service conditions) that were reclaimed from structural members in an existing adaptive reuse project in Canada. These samples were first characterized through mechanical tests, and then tested using a Lateral Ignition and Flame spread Test (LIFT) apparatus, with exposure to a severe heat flux to propagate flame spread down the length of the sample. This exposure would indeed be representative of a real fire exposure. The authors studied the char and pyrolysis depth of samples post heating. The results were compared to modern engineered timber samples (LVL and glulam) of equivalent moisture condition(s) that were also tested by the authors in this study. The results herein imply that heritage structures are indeed capable of illustrating similar if not superior fire resistance to modern day counterparts.

1. Introduction

We need to consider the motivation of the architect: to leave timber exposed and embrace a user's *biophilia* - positive reinforcement of an individual's desire to be working or living in an organic environment. From a designer's perspective, we refer to this as non-encapsulated timber. Non-encapsulation generates debate within the fire safety engineering community for the safety of timber and also for its required degree of engineering. Figure 1 describes the breakdown of timber in fire.

Figure 1. When wood is heated, a material degradation occurs with the creation of a carbon region called char, a weakened (strength) pyrolysis zone, and finally these zones protect an uncharred region.

Traditionally heritage structures, herein defined in this study as either a designated or an undesignated structure being over 100 years old, were constructed on the principle that they would include a sprinkler system (post 1880), and that the timber would be made larger than the design (expected) loads required. In the event of a small-contained fire, the damage could be easily repaired and the structural integrity of the system would remain so that the structure could still accommodate any usual business conducted inside. These solid mass sections, often of dimensions around 200 x 200 mm or larger were prevalent in commercial, residential and industrial design of the late 19th century (see Figure 2).

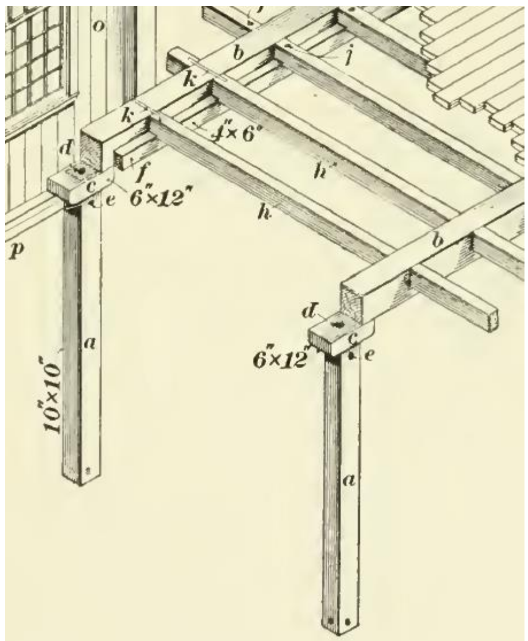

Figure 2. Solid timber was prevalent for a 19th century industry structure design called slow-burning construction (see Scanton 1899). The timber would be made sufficiently large so that business continuity was ensured if fire damage occurred. The timber would have a hollowed center, which would aid in connection and prevent moisture accumulation that would enable rot.

Today, design is relatively the same and we have quantified these numbers more scientifically, though exact quantification in fire is still in debate (see Hopkin et al., 2015). We up size the mass timber members accordingly to enact a sacrificial char layer in fire (see Quiquero et al., 2016) and we provide a robust automatic sprinkler system in case of fire. We perform a quantifiable analysis of flame spread of the timber species and demonstrate that, at least for mid-rise and smaller, we can leave the timber exposed or un-encapsulated with associative automatic sprinkler systems.

Our modern procedures (see Figure 3) for studying contemporary timber in fire are largely prescriptive in nature (see ASTM 2013, 2015) and very rarely are they extended to analyze heritage timber stock for the same quantifiers mainly due to the limited specimens that can be procured. For this reason, confusion can occur when asked to compare new to old heritage timber behavior in fire.

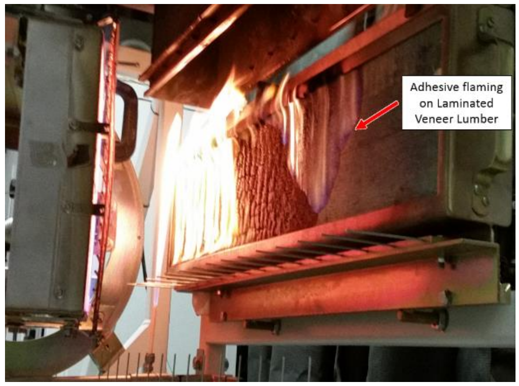

Figure 3. A contemporary flame spread test on laminated veneer lumber (LVL) conducted by the authors using a LIFT (Lateral Ignition and Flame spread Test) apparatus. In this test, adhesive flaming was observed demonstrating the complexity of modern engineered timber. The flame front of the adhesive would be quantified and a spread rating implied on the material (see Otto et al., 2017).

However, there are countless examples of heritage timber structures burning to complete destruction in the media. These fires are broadly portrayed in the media as warnings, for the most part, and lead to notions against the use of timber as a building material. Though in many circumstances these fires are often particular to heritage buildings undergoing renovation, or arson (Alma College, Watson Lake, Fleming Grain elevator etc.). In many of these cases, there was no working sprinkler system, which causes increased risk. One of the key aspects to consider when looking at modern timber in fire is that the mass destruction often incorporates structures where the timber is very thin or small meaning it propagates flame passage easily (consider lighting a match versus a log directly). Nevertheless, these aspects have people debating timber construction in society.

It is important, from a conservation perspective, that we must understand solid and non-encapsulated timber in our heritage (and even modern) stock. We choose to introduce an automatic sprinkler system which is contemporary in these structures and has more reliability than a Victorian era system. If this option is selected, in the event of failure (non-function of the system) we still want to limit the flame spread and damage to the structure to allow safe egress and business continuity after the fire. For this reason, we should investigate these properties just as we do with modern engineered lumbers rather than separating heritage timber under the pretense of challenging procurement.

The heritage stock of solid mass timber in Canada has not been well quantified, though it can be argued that over 120 brick and beam buildings remain in Toronto, and 50 or so in Vancouver. Khoo (2013) presents a detailed overview of Canada’s solid timber heritage stock.

There is always a debate which begins at any heritage or timber conference by practitioners asking “will heritage (solid) timber behave in fire in a similar fashion to contemporary counterparts like glulam?” or “will heritage timber, because it is less complex than engineered timber, be superior in fire performance?”. This study begins the work towards answering these questions.

2. Motivation

The study herein can apply to all mass, solid, or engineered timber providing there is limited to no fire retardant or preservation materials. It should be noted that engineered timber like glulam is proposed because solid timber is costly in larger sizes. When extending the results of heritage to contemporary solid stock, criticism may be in the aged condition of the material.

Figure 4 illustrates a heritage timber beam and column of a heritage building constructed in approximately the late 1910’s in Canada (the site is made anonymous for practical purposes of discussion). The structural system is similar if not identical to that shown in Figure 2. Juveniles subjected this structure to an act of arson. The fire was put out after approximately one hour and the damage was isolated to the area shown in the authors' photo. It is of note that the connection performed well as noted in literature (see FPInnovations, 2014). This case study served as the motivation to undertake an investigation of these materials using contemporary technologies for comparison – the exact materials from this very structure would be assessed.

Figure 4. An arson attack on heritage timber where the smaller timber beam components had significant damage, whereas the larger column had minimal damage as the core cross-section remained (authors' photo).

The authors caution that every building will have its own unique environmental and structural conditions, subsequently; every heritage building will behave differently in a fire. Therefore, a more detailed investigation into heritage timber is required prior to extending the results herein to a full fire risk or insurance discussion for any building. This paper merely serves to catalyze the discussion of this topic.

3. A Historical Basis of Timber Structures in Fire

This section serves to inform the reader a brief history of historical research, which had been undertaken to serve the basis of what architects and designers may encounter in heritage structures. Research into timber structures in fire began in the late 18th century with the investigation of encapsulation methods, which utilized steel or plaster. Figure 5 illustrates an 18th century mill where iron plating was used to encapsulate the timber behind it.

Figure 5. (left) The burning of the Pantheon in London (painted by Joseph Turner in 1792) provoked a group of architects to study timber in fire in the early 18th century, the results shown from a heritage Mill in the UK (authors' photo, right) were to propose encapsulation through the use of steel and the use of plasters (see Gales, 2013).

By the early 19th century, there was a need for a scientific approach to study timber in fire. Researchers decided to investigate the performance of timber through subjection to the standard fire test in 1918 (see Figure 6). They conducted six tests and noticed that it was nearly impossible to control the test because of the creation of flames, which drove temperatures too high in the tests (see Ingberg, 1921). Researchers classified timber as combustible, and subsequently attempted to develop new tests in order to classify its behavior (see Dunlap and Cartwright, 1927). However, the stock market crashed in 1929 (which prohibited new tests) and Ira Woolson, chair of the standard fire committee, passed away. There was little incentive to change the test to understand the underlying behaviors that timber undergoes in a fire to refine the advancement of the structures. Subsequently with the Second World War, various research programs began to exploit populations (through fire spread vulnerabilities) where the countries were reliant upon timber or combustible constructions (see Hottel 1984 for discussion on government research programs to investigate infrastructure vulnerabilities of other countries in construction during war time). As a result, it would seem apparent that global building codes mandated significant response restrictions on building height and timber construction (especially in the tall building case) (see NBC 1941). Recently there has been a surge of interest in timber construction, both heritage and contemporary, with the mid-rise timber code flexibilities. While we are testing still in standardized fire tests, various researchers (see Hopkin, 2015), are attempting to quantify the underlying behaviors, such as flame spread, pyrolysis behavior etc., appropriately so we can better understand and protect these buildings in the event of accidental or deliberate fire.

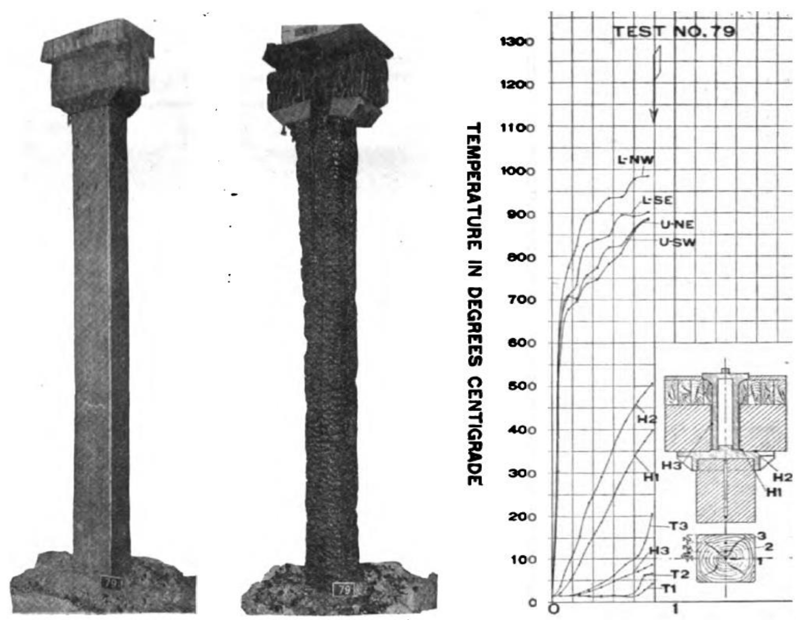

Figure 6. Early Standard fire tests were conducted on timber columns in the early 20th Century. It was difficult to control these tests due to the heat given off from the timber. Excerpted are the results of the first Standard fire test on un-encapsulated timber (Ingberg 1921).

4. Heritage Materials and their Characterization

Four heritage beams were extracted from a heritage building in Canada (not identified to protect anonymity of the owners). One beam (Beam 1) was collected without any applied covering for transportation to the Carleton University Minto lab, the other three beams (Beams 2 to 4) were enclosed and sealed in plastic wrap and transported to the lab. The beams remained sealed before and after testing in an attempt to preserve their in-situ moisture content, in order to more accurately relate testing to the case study. Visually the beams exhibited shakes, knots, and various signs of wear, but no visible evidence of rot. There were initial concerns about their remaining structural integrity, and therefore they were tested under a bending test with two applied loads, using standard deflection linear potentiometers and utilizing digital image correlation to characterize failure mechanisms (however that mechanical study is beyond the scope of this paper). These tests were performed to assess their remaining capacity and briefly characterize their bending strength (they were also tested as an experiential learning opportunity for students within the architectural conservation and sustainability program at Carleton University). All beams came from the same building site, and for the purposes of this paper they were classified as Northern Species (see Khoo, 2013 for information on classification of heritage timber in Canada). The moisture content of the timber would be representative of in-situ conditions approximately measured at less than 18% for Beams 2 to 4;

and 5% for Beam 1. The mechanical load-deflection results of these bending tests are illustrated in Figure 7 with associated beam size for those interested in classifying their representative capacities. All beams were tested with load applied along the greatest thickness of the beams. After testing when it was reasonable to approximate that the beams were beyond their peak load, load was taken off through slow application. Loading for all beams was applied at approximately 0.05 mm/min.

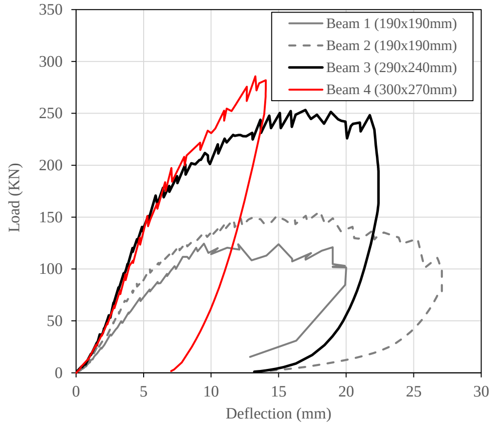

Figure 7. Load and Deflection Behavior of four Heritage Beams (loading and unloading shown).

As illustrated in Figure 7, Beam 3 was not taken beyond any distinguishable yield plateau, but Beam 2 and 3 were, though not to the degree that significant damage had incurred for Beam 3. Beam 1 and 2 had crushed completely at the supports and the test was halted. After hitting the peak in the testing, the beams were slowing unloaded. Naturally the load deflection responses are unique and highly dependent on their cross section. However, they all indicate a high reserve in flexural capacity indicating distinct quality despite their age, wear and observed defects. To characterize the heritage beams on strength alone (which should be considered with some level of caution as they were only cut to 1m clear spans) and assuming the beams are Northern species, they are classified in accordance to their bending strength with reference to CSA O86; Beams 1 and 2, can be classified as Select Structural, Beams 3 and 4 can be classified as No.1 grade though arguably Select Structural. Beam 4 did not reach its peak and therefore could be graded higher. In this sense, they are realistic grades to what would be specified today in industry (see Khoo 2013).

Figure 8. A heritage Beam (no. 3) after two strips were cut out to be tested under a controlled heat exposure. Note the hollowed core was traditionally added to prevent moisture accumulation.

After testing Beam 3, it was cut to fabricate two specimens of size sufficient for heat testing in a LIFT (Lateral Ignition and Flame spread Test) apparatus at the Carleton University Minto Fire lab. See Figure 8 for specimen and Figure 3 for LIFT apparatus. Beam 1 was harvested for square sections which could be used in future tests in the cone calorimeter to investigate the charring of heritage timber under various controlled moisture conditions (as underway by the authors to further complete this study).

5. Fire Performance (Flame Spread) of Timber

Figure 3 represents the use of a LIFT apparatus to test a laminated veneer lumber sample. This apparatus was utilized for six comparative tests as described in this section with their results.

A LIFT apparatus subjects a controlled angled heat source on a material from a radiant heater against a sample. This technology emits radiative heat in the form of a controlled and incident heat flux. In the tests herein it peaks at 50 kw/m^2 at the initial portion of the material sample and descends to less than 2 kw/m^2 across the sample. A sustained 50 kw/m^2 heat flux is a severe heat assault equivalent of a standard fire test (see Gales et al., 2014). A LIFT apparatus is used to propagate a flame spread across a combustible material. Flame spread measurements are made by utilizing a human eye interpolation of a mirror system at the base of the apparatus, which reflects the image of the material sample from behind the heater for the viewer. They are recorded as time to reach a specified distance along the member, depicted by pegs on the mirror. Practitioners have often used this technology to assess engineered timber flame spread potential particularly to justify un-encapsulated timber construction (see ASTM, 2016).

All tests were terminated after 18 minutes, chosen arbitrarily as a baseline for all tests, as this time was decided as appropriate to guarantee flame propagation for most timber-based materials across the length of a sample (approximately 0.8 m). After the 18-minute test time, the samples were removed from the apparatus and samples were extinguished using water. By keeping the heating time constant between tests with the same heat assault, char depth could also be compared (measured from the original surface to the bottom of the visible pyrolysis layer).

Two samples from Beam 3 were tested in the LIFT apparatus, along with two samples of laminated veneer lumber and two samples of glulam. All samples had a moisture content of less than 6 percent at the time of testing. The flame spread measurements are quantified in Figure 9 as well as the specimens after burning visually shown in Figure 10. The quantification of char depth and overall final char front, which will exceed the flame spread measure, are tabulated in Table 1 below. In following the ASTM standard, the definition of the char front was based on a drawn centerline as it was observed to progress more rapidly at the top of the member.

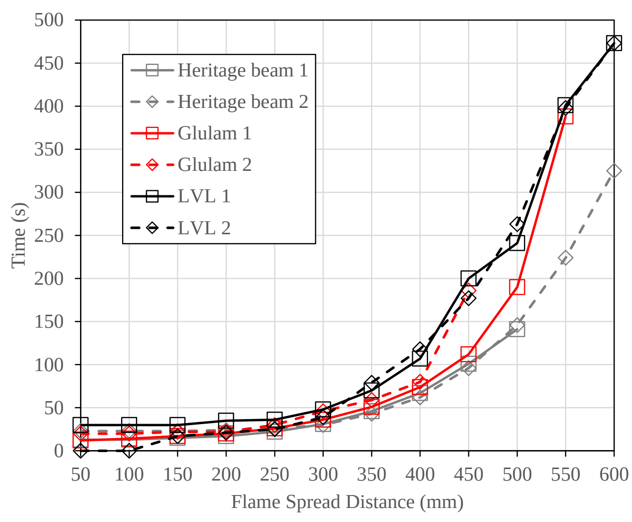

Figure 9. Flame Spread Observations.

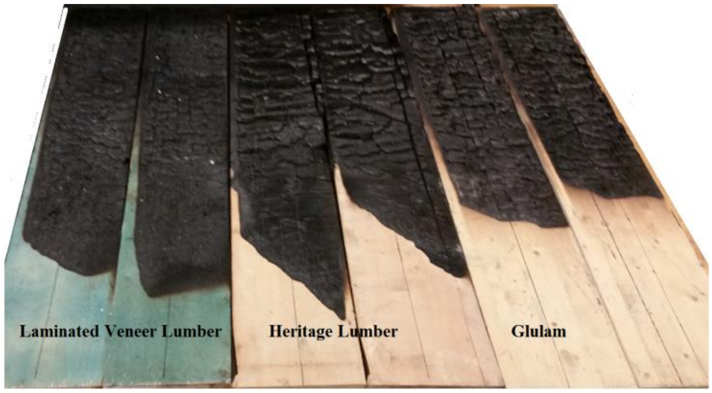

Figure 10. Timber Specimens after Heating.

Table 1. Maximum char depth and char front as taken from the centerline of the material.

Test	Maximum Char Depth (mm)	Char Front Distance from Start of Sample (mm)
Heritage 1	9	640
Heritage 2	10	560
Glulam 1	12	530
Glulam 2	14	500
LVL 1	13	650
LVL 2	14	610

6. Discussion of Results and Recommended Future Work

Considering all of the performed tests, there was an indication of good repeatability for relative comparison as all materials exhibited the same if not comparable moisture content. The function of these prescriptive tests is to allow materials to be compared under the same representative testing condition.

The laminated veneer lumber tended to have the worst flame spread characteristics, and consequently the more severe char depth. As shown in Figure 3, there is evidence to suggest that the adhesive may bleed during testing for laminated veneer lumber and propagate flame spread down the member. This behavior was not exhibited in the heritage timber, seeing as there was no adhesive, and the behavior was not observed with the glulam samples either. This behavior requires future study at a later time and is not an aspect of heritage stock. The glulam timber did have one of the highest char depths, but one of the lowest flame spreads. This was unique as the flame extinguished during testing, shown in Figure 6 when the data terminates. The heritage timber also had flame extinguishment, though much farther down the sample than the glulam, but also had the smallest charring depth. This is a very interesting result because the beam was severely tested in mechanical load before it was tested in the LIFT apparatus and it could have been expected to exhibit high degrees of cracking to propagate deeper charring. The cut samples did appear to be in good condition when they were heated with no observable mechanically induced damage.

It is recommended by the authors that a more exhaustive study in the future be undertaken to examine timber stock from various sources, as in this study, only one type of heritage timber from one project was procured. In heritage infrastructure specifically, there is a potential of contaminates being on the materials which can promote this spread. In this case, the timber procured for testing came from an industrial stock but there was no evidence of this treatment or resultant behavior. Additionally, the species will play a large role in the fire performance of the material.

7. Preliminary Conclusions and Recommendations

The authors posed two questions; "will heritage (solid) timber behave in fire in a similar fashion to contemporary counterparts like glulam?" or "will heritage timber, because it is less complex than engineered timber, be superior in fire performance?" The answer is provided, in this study, on the basis of char depth and flame spread. Considering these two properties, heritage timber seems to be equivalent if not slightly better in performance. However, there appears significant work to be undertaken to broaden our knowledge of timber (old and new) and of the effect of differing moisture contents. While the results were interesting in this study they are not to be construed as all positive. The initial rate of flame propagation, rather than total propagation, was very high for the heritage timber and slower for glulam in this case. The results herein imply that heritage structures are indeed capable of illustrating similar if not superior fire resistance to modern day counterparts.

Today we still do not have a comprehensive opinion on how best to describe heritage timber materials and characterize their performances in fire. This is notoriously the justification for the encapsulation argument for timber. Even in modern engineered counterparts there are debates to the degradation of adhesives, which Carleton researchers in collaboration with its collaborative partners are currently studying (see Quiquero and Gales, 2017 and Otto et al., 2017).

We can identify though that these heritage structural buildings are vulnerable either due to urbanization, abuse or even neglect. They are vulnerable in the sense that it is easy to exploit aspects of fire performance to put heritage structures at risk even though it may very well be that they would perform better in fire than modern counterparts. Quite often small aspects of timber testing are used against the promotion of timber construction or the conservation of such heritage buildings. This subject area of timber in fire requires serious attention by the fire safety engineering community and the regular inclusion of heritage timber in test plans. The risk of arson in heritage structures is large, they are vulnerable, and we must act to keep conserving them in our built heritage fabric. For this reason, as well as to inform design for the use of un-encapsulated timber, we must push forward in testing these materials and gaining greater understanding of their underlying behavior in fire.

8. Acknowledgements

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