The Effects of Radial Cracks on the Fire Performance of Heritage Timber

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Abstract

Heritage timber buildings are found worldwide, and their irreplaceable nature makes them of high value. A common occurrence on heritage timber members is radial shrinkage cracks resulting from changing moisture contents over time. There is little information available that can be used to assess the fire performance of heritage timber members (which has unique differences from contemporary timber), and, to the author's awareness, no information regarding how the presence of radial cracks affects the fire performance and char depth of a timber member. The purpose of this study is to provide an evaluation of the effects of radial cracking on the fire performance of timber members, including its effect on char depth, time to ignition, and residual strength. Full-scale heritage Pine timber members were procured from a 115-year-old building undergoing demolition and then subjected to a pool fire. Cracked samples were also extracted from the members and tested in a Cone Calorimeter apparatus relative to solid samples. It was found that the presence of cracks did allow for deeper charring, with the full-scale tests showing 64% greater char depth in the cracked region and the Cone Calorimeter tests showing 29% greater char depth on the cracked samples. Four-point bending tests of the full-scale members subjected to a pool fire showed that the effect of the fire exposure and the cracks did not significantly impact the capacity of the members (7.2% difference) but reduced the stiffness as the ultimate deflection increased by 43%. These results can help to inform practitioners who encounter heritage timber members to more accurately assessing the fire performance of the member, such that they can make informed decisions on the level of fire protection required. The study also provides methodologies for the collection of heritage timber test materials.

Keywords: Heritage structures, timber, radial cracks, char depth

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1. Introduction

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

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

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

This lack of guidance coupled with conservation guidelines that value minimal interventions leads to practices that are unproven. For example, a key factor that affects the fire performance of all timbers is the presence of radial cracks or gaps within the timber [13], [14].

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 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 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 [15]. Chorlton and Gales (2020) recreated five types of heritage encapsulation materials, used during the 18th and 19th centuries in an attempt to protect the 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 [16].

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.

2. Background

2.1 Cracks in other Structural Materials

Ervine et al. (2012) considered thermal propagation through tensile cracks in reinforced concrete by loading concrete beams in four-point bending to induce tensile cracks of varying severity and then using a radiant panel at 35 kW/m^2 to heat the beams which had embedded thermocouples [17]. 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 [17].

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 [18]. 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 [18].

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).

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 [19]. 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 [20].

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 [21]. A review by Friquin (2011) concluded that most studies correlated increased moisture content with decreased charring rates [22]. 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 [23]. 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 [24].

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.

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 [25] and are discussed herein.

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 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 [26]. 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 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 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 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% [27]. 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 1, and were used as columns in the original building. The timber was of Pine species, commonly found in heritage stock in Ontario, with a density of 657 kg/m^3 (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 humidity [28]. 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 [22], [29], [30]), though other parameters such as density and species are thought to have a much greater influence on the charring behaviour of the timber [21].

Table 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

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. Further details of the methanol pool fire can be found in [31], [32]. Narrow spectrum illumination (as described in [33], [34]) 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. As described in [32], 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 [35]. 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.

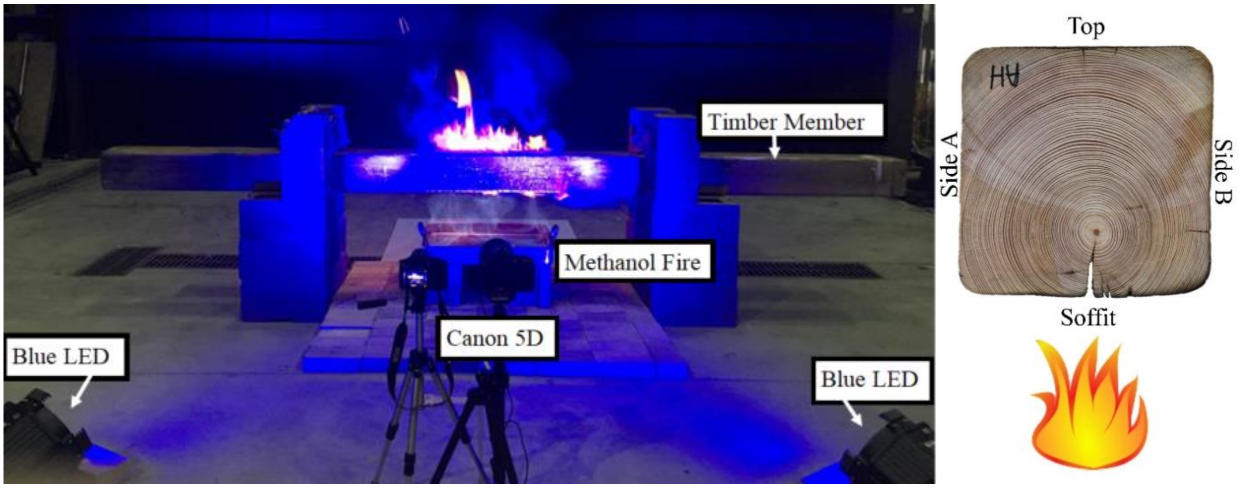

Figure 4. Experimental test setup for pool fire, view of beam Side B.

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 standard fire resistance furnace test [36] 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. (2021), where narrow spectrum illumination was used to monitor strain in steel stay-cables during a 30-minute methanol pool [31]. 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 [35]. 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 [37]. A four point bending test is a traditional structural test which creates a constant flexural condition (applied moment) between the applied load locations. This allows flexural resistance to be compared from one test to the other. The test also permits the central fire damage zone to be assessed more directly for flexural capacity under constant moment. The loading rate is also inline with ASTM D198 [38]. 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.

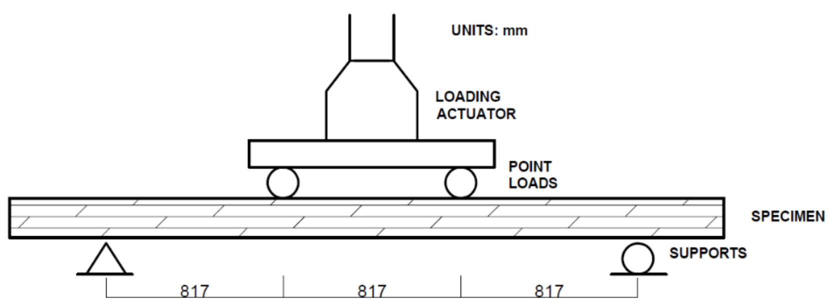

Figure 5. Four-point bending test setup.

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 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 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 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) [39], a technique shown to be accurate for monitoring displacement in wood specimens [40].

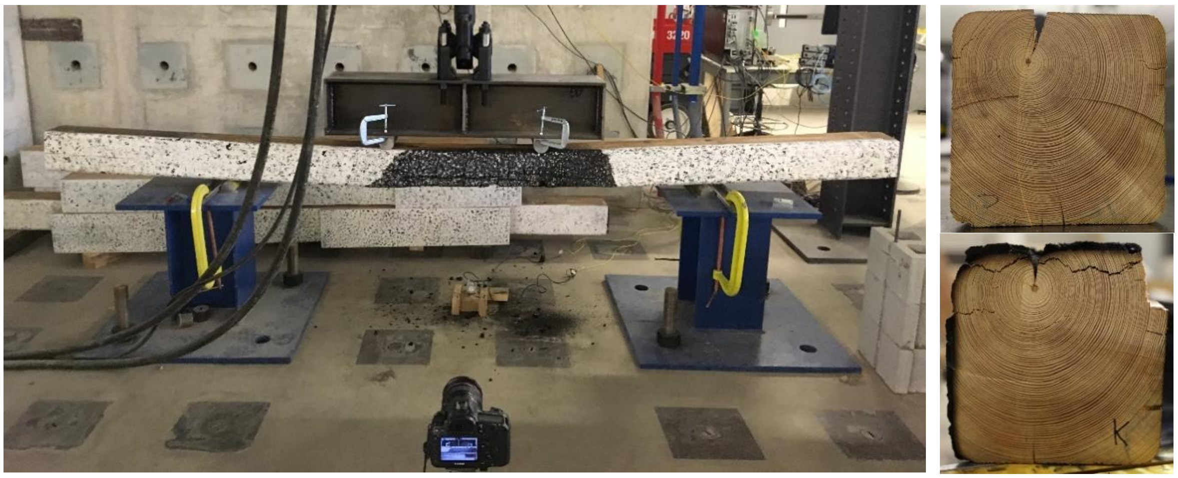

Figure 6. Loading test setup (left) and member cross section slices (right, top- towards the end of the member, bottom- towards the centre of the member).

After the timber members were loaded until failure, they were cut into 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 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.

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 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 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). The 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 [41] shown in Figure 7. The ASTM E1354 procedure was modified in that no spark ignitor was used, and that the samples were removed from the apparatus after the desired heat duration and extinguished with light amounts of water. ASTM E1354 indicates that exact irradiance levels or use of external ignition is not prescribed, and that these should be determined separately for each product [36] Thus, a spark ignitor was not used, representing a scenario in which the timber would self ignite (a plausible scenario in a structural fire).

All samples were exposed to a heat flux of 50 kW/m^2, for varying exposure durations. The cracked and solid samples were exposed to the heat flux for 6, 15, and 30 minutes respectively (with duplicates of the 6-minute tests to confirm test repeatability). The primary purpose of the Cone Calorimeter tests was to induce a repeatable thermal exposure on the timber, such that the effect of the crack on the fire performance of the samples could be assessed. As such, 50 kW/m^2 was therefore chosen as a heat flux that was great enough to induce significant char depths but not so high as to run the risk of charring through any specimens completely at 30 minutes [42].

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 [42]). 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 [15], 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 7. Cone calorimeter test setup.

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 [43], and the expected crack width could be impacted by this effect.

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.

4.1 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 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 was taken as the average of 4 measurements, taken at 1/5 points on the width of the beam (excluding the center measurement, which represents the maximum char depth due to the crack). Cracks included in consideration of Table 3 include the existing cracks on the soffit for member Heritage 1 and side A for Heritage 2. Figure 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 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 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 9 represents the char measured on the soffit of the member, while Figure 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 [21].

Figures 9 and 10 therefore give an idea of the location of the 300 °C isotherm along the length of the member.

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

Figure 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).

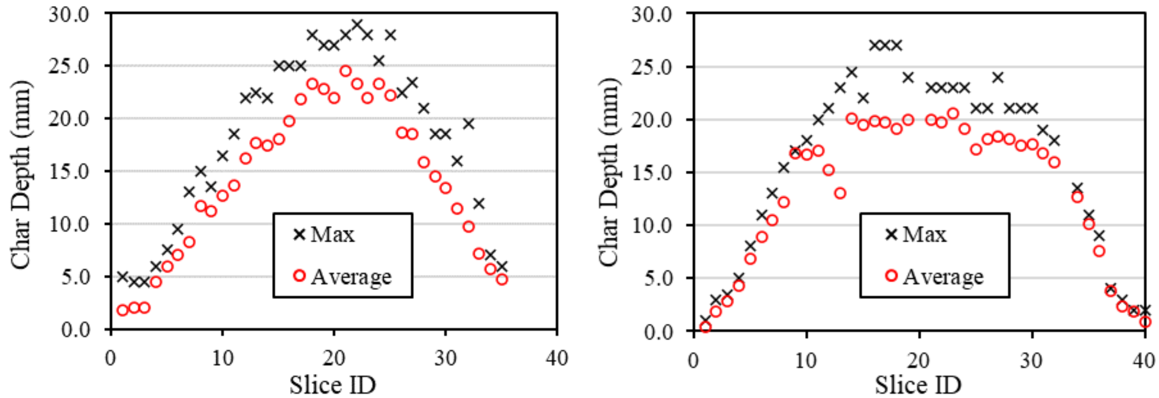

Figure 9. Char depths after loading on soffit of Heritage 1 (left) and Heritage 2 (right), where Max is the maximum char depth around the crack, and Average is average char depth away from the crack.

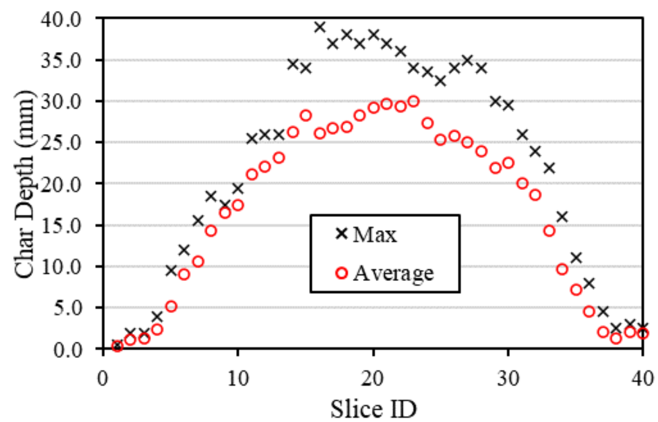

Figure 10. Char depths after loading on the sides of Heritage 2, where Max is the maximum char depth around the crack, and Average is average char depth away from the crack.

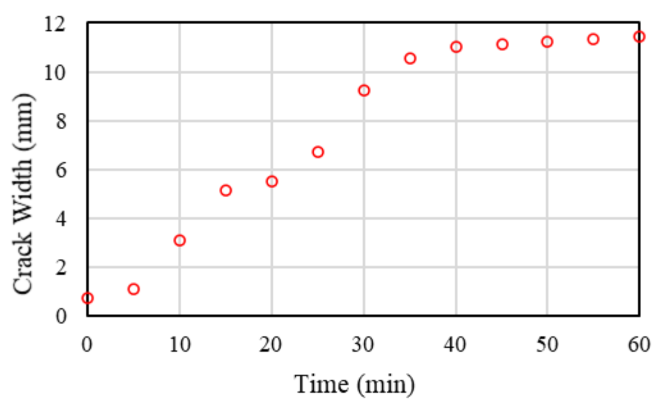

Figure 11. Crack expansion over time during the 30 minute pool fire and 30 minute cooling phase on Side B of Heritage 2.

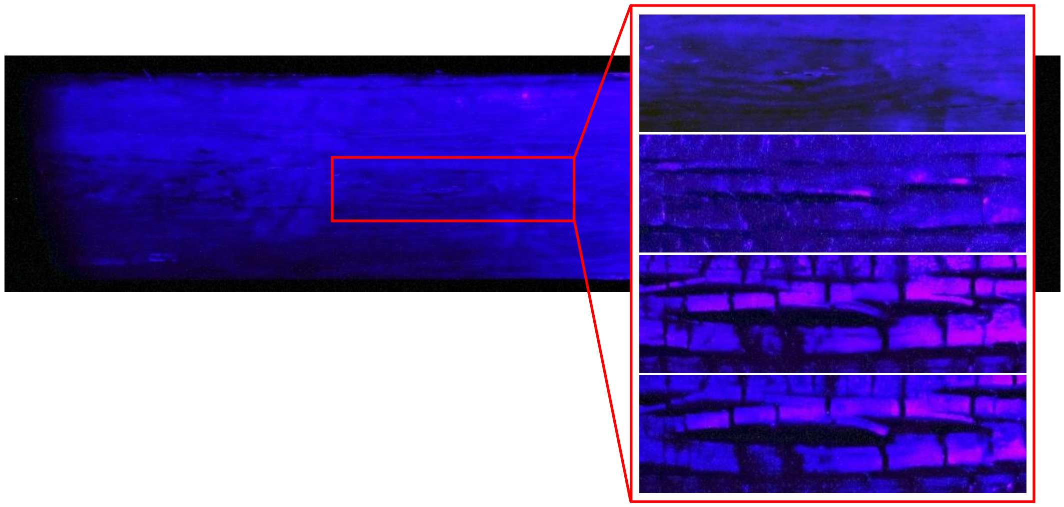

Figure 12. Crack expansion during heating at 0, 15, 30, and 60 minutes on Side B of Heritage 2.

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 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 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 11 and 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 11 and 12 show that the crack did continue to increase in width after the heating phase was complete. Figure 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.

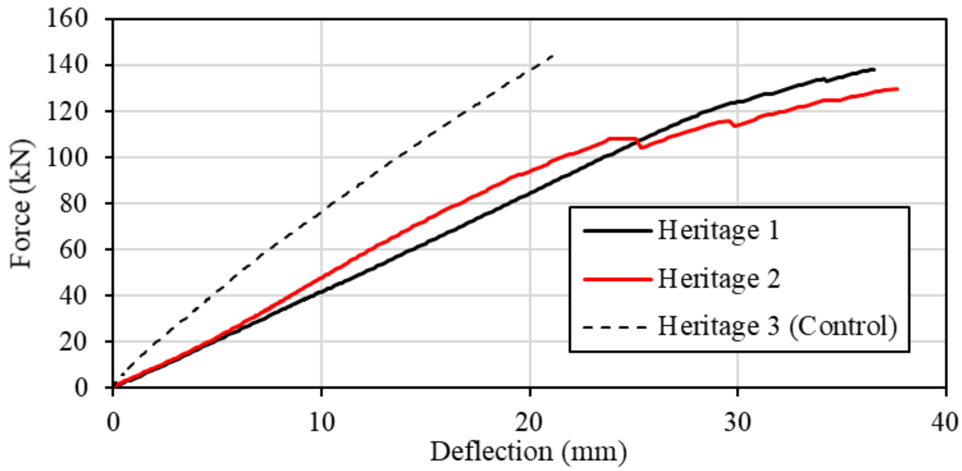

Figure 13. Force vs deflection for the charred heritage and control members.

4.2 Cone Calorimeter Tests

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

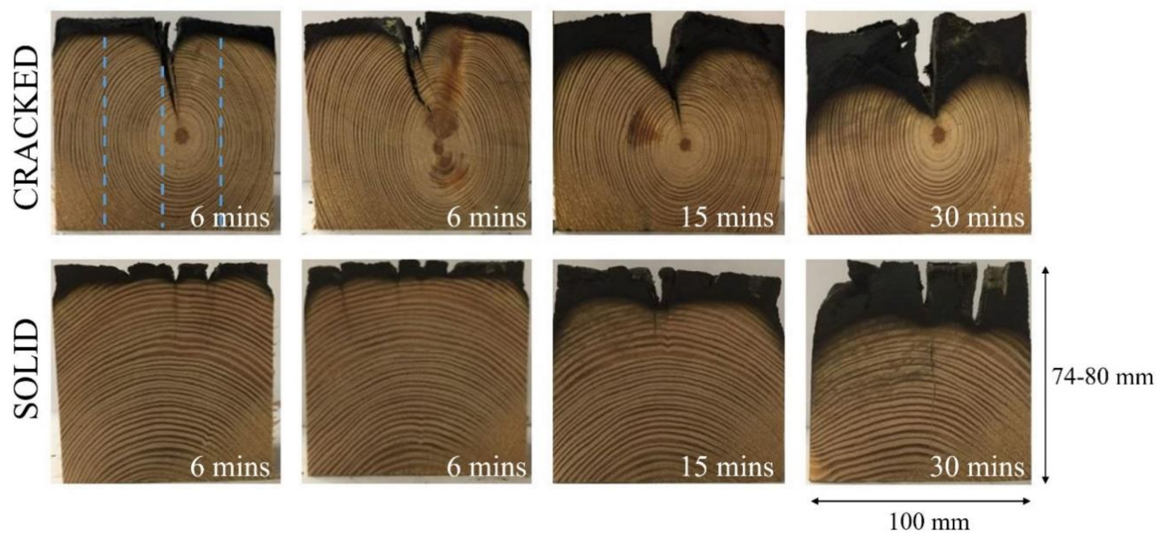

Figure 14. Char depth of cracked (top) and solid (bottom) timber samples at various exposure durations. Blue dotted lines indicate where char measurements were taken, and original dimensions of all samples are illustrated in the bottom right corner.

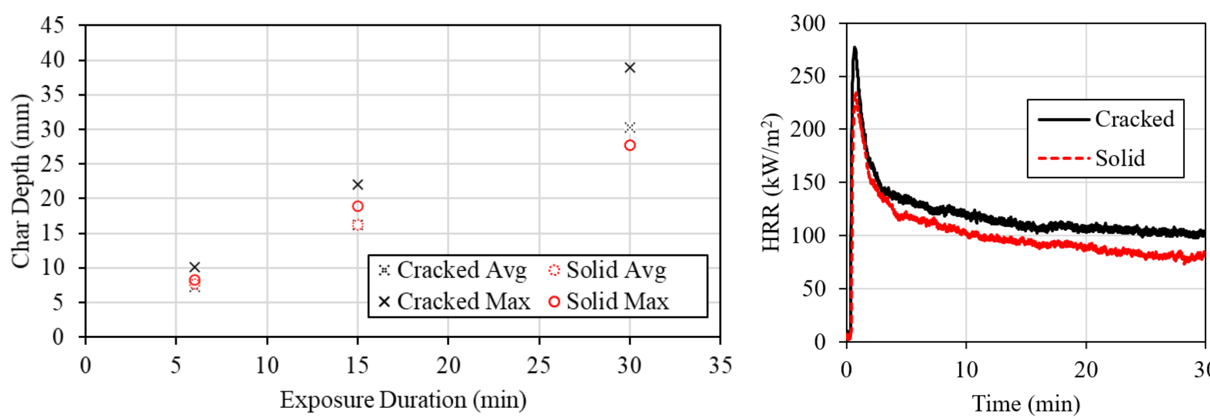

Figure 15. Average and maximum char depth of cracked and solid specimens, and heat release rates of cracked and solid samples tested to 30 minutes.

Table 4. 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)	Peak Heat Release Rate (kW/m^2)
C1	647	8	9	29	270.2
C2	667	8	10	25	303.6
C3	619	10	13	29	277.1
C4	630	11	15	19	277.5
C5	648	1	1	19	282.5
C6	633	1	1	32	280.6
C7	632	2	2	21	268.6
C8	635	2	2	23	234.8
Cracked Average	641	9.25	11.75	25.50	282.1
Solid Average	637	1.50	1.50	23.75	266.6

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 16 kW/m^2 (6 %) 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). Despite the differences, the small sample size of the cracked and solid samples makes it difficult to draw firm conclusions regarding the heat release rates, re-emphasizing challenges in obtaining heritage materials suitable for testing. Although the peak heat release rates do not appear to be statistically different, more comparative test data for cracked and non-cracked specimens and further study are needed to draw substantiated conclusions regarding the effect of cracks on 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, 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.

5. Discussion

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 [18]. 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 194 mm, as discussed in the methodology (Section 3.2). Although the pool fire was centered along the member, the off-centered charring was due to an uneven fire spread once the beam ignited, spreading to one side of the beam over the other. This could have been caused by ventilation in the room, or a heat channel caused by the existing crack on the soffit. It did not have a significant effect on the loading results however, with Heritage 1 and 2 performing similarly.

The loading tests revealed a similar ultimate capacity between the control and charred members, where the ultimate capacity of the control was only 7.2% larger than the average of the charred members. The most significant difference was in the stiffness, where the control member was much stiffer than the charred members, with the charred members experiencing a maximum deflection of 43% more than the control members on average. Considering the reduced cross section taken by subtracting the maximum observed char depth on each side and the soffit of the member from its initial dimensions, calculated strengths were determined from the CSA O86-19 procedure for bending capacity of sawn lumber [44], which considers the bending strength of the wood, the dimensions of the section, as well as a series of modification factors. As the maximum char depth was used, the calculation method provides a worst-case scenario as the entire length of the members was not charred, however it is assumed that in these calculations the minimum cross-sectional dimensions would be used. As well, the charred area occurs in the region of highest moment under this loading configuration which is the predicted failure mode per the calculations. The strength of the beams was taken as the bending strength for Pine species, Select Structural grade, as listed in CSA O86-19 as 12.7 MPa. 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 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 O86-19 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 experimental structural capacity of the cracked and charred members had been worse than that predicted, the presence of cracking would need to be considered well beyond the char layer in calculation methods. . 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.

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 [21]. 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 [17]. 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 an 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, 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.

6. Conclusions

Under the thermal exposures considered, this research has shown that increased char depth should be expected in timber members with pre-existing radial cracking as opposed to without. This may have an adverse effect on member stiffness, and up to a lesser extent on strength. Consequently, heritage and historic timber structures are likely to be more vulnerable to fire than modern counterparts. To mitigate the increased vulnerability requires additional detailing to passive fire protection strategies in conjunction with administrative actions to reduce the probability of fire risk and minimize additional deterioration through attention to humidity and building control. With a technique developed herein for gathering heritage timber materials properly, future researchers can improve upon the above guidance in second stage research with additional testing and numerical methods that can better quantify the strength and stiffness reductions of timber expected post-fire. Ultimately this study benefits a range of practitioners (i.e., conservation authorities, building scientists, fire fighters, insurers, and fire engineers etc.) who require a body of research on what fire risks are associated to heritage timber buildings – i.e., radial cracking is a concern.

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 [45].

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 full- scale samples. Key findings of this first stage 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 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.

Statement of Authorship

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript.

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