An Analysis of Fire Performance of Small-scale Canadian Heritage Hardwood and Softwood

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Abstract

A common consideration in the rehabilitation of historic timber structures is addressing the concerns for fire safety. Heritage structures can have softwoods but depending on the time they were built they may also have hardwoods present. Currently there is a lack of knowledge on the char rate of heritage hardwood and softwood. This study presents initial findings into the charring of these historic materials as they would be encountered in practice through samples taken from pre-existing aged timber structures in Canada (>100 years). The materials are tested in a cone calorimeter following a modified ASTM 1354 procedure. Hardwood samples typically exhibited a faster charring rate than the softwoods but the charring rates converged at 1.05 mm/min when exposed to higher fluxes of 50 kW/m2. As rehabilitation and readaptation may require performance-based approaches such as structural fire modelling, a provisional framework for a numerical model using LS-DYNA for historic timber members is presented. The objective is to identify future research and testing areas to develop a higher certainty model. In the a-priori model presented, results showed conservative charring rate results with charring trends seen in the experiment generally being followed.

Keywords: Heritage Timber, Hardwood, Thermal Analysis, Finite Element Analysis, Cone Calorimeter

Table of Contents

1. Introduction

Due to the global demand for sustainable building design for the reduction of embodied carbon (see A1 for further information), wood has been seen as an attractive material choice due to its ability to sequester carbon[1] and it is a renewable material. To further its use in modern construction, engineered timber products such as glued laminated timber (glulam), and cross-laminated timber (CLT) are available. These products are typically made by joining dimensional lumber together with adhesives. This process allows for dimensional lumber to be used in taller buildings such as Brock Commons at the University of British Columbia (see A2 for further information). However, wood has been used as a structural material long before the renewed demand for sustainable building design. Many historic structures, particularly in Canada, make use of wood as their primary structural material. Reference [2] reviews 61 historic structures over five storeys tall in Canada that make use of heritage wood members.

A key difference between historic timber and contemporary timber is that while both contemporary and historic timber buildings frequently use softwoods, it has been observed both in Canada and internationally that historic timber structures may contain old growth hardwoods as primary structural systems. While all species of wood are physically different, hardwoods and softwoods can have notable differences in their thermal properties and therefore in their overall fire performance characteristics[3]. Work has been performed to better the understanding of the pyrolysis of wood and the current capabilities towards modelling this process. Some examples include Reference [4] who simulated the pyrolysis of white pine in GPyro. Additionally, Reference [5] who performed a literature review of the fire processes in polymers. Reference [6], performed a 1-D thermal model of an engineered wood product. Finally, Reference [7] experimentally studied how a softwood shrinks and cracks as it undergoes pyrolysis. While there is active work towards better understanding the combustion of wood, these studies appear to focus on softwood and rarely address heritage and aged timber members. It is important to recognize the difference of heritage and contemporary wood. Mass heritage timber members are not the engineered wood products seen today. They are made of large sawn lumber rather than a composite of dimensional lumber. Additionally, heritage wood is aged, it may have significant defects in the member's structure such as cracks and likely has a notable oxidized layer. Motivated by several recent fires in heritage buildings (ex. Notre Dame in Paris and St. Mark's Church in the UK), this article serves to explore this topic by quantifying differences in fire performance of aged softwood and hardwood samples experimentally and numerically. A provisional model framework that could be considered for future use in designs aiming to meet the performance objectives of the current building code is also presented. In the author's jurisdiction, Canada, the current building code allows designers to develop a design based on first principles rather than prescription that is equivalent to the accepted prescriptive design, also known as an "alternative solution". Many jurisdictions are similar and are moving towards a performance-based building code. While the authors will focus on heritage samples commonly found in Canada, this research can be extended for universal applicability to heritage buildings in other jurisdictions.

Another difference that should be highlighted between heritage and modern wood when undertaking a comparative study is the scarcity of materials and resulting data. Heritage wood is a limited availability material. Heritage structures are not all conserved to the same extent, resulting in a spectrum of heritage structures ranging from well-kept sites to decayed and condemned. When searching for heritage materials for research purposes it is important to use materials that are representative of existing heritage structures which are intended to be well maintained and to be in use in some capacity. However, the necessary research materials are then typically part of these well-maintained structures and removing them for destructive testing also reduces the heritage value of the structure/building. Therefore, research involving experimental testing of heritage materials, such as in this work, has the significant challenge of having access to a very limited stock of samples for experimental testing. Thus, creating and validating appropriate numerical models for fire performance would help to alleviate future needs for procuring wide ranges of additional samples. Additionally, heritage structures made use of both softwood (conifer) and hardwood (deciduous) trees. This is significant because broadly speaking, hardwood trees typically grow at a slower rate than softwood trees. This results in a denser material. It has also been found that softwood trees typically have a higher lignin content (26-34%) when compared to hardwood trees (23-30%)[8].

This study is organized to provide designers with necessary information regarding the additional considerations required for heritage design work when compared to contemporary design. This study highlights fire performance considerations in heritage design, examining the charring rate of heritage timber in a fashion similar to that used in determining the fire performance of contemporary timber members. The current state of timber modelling will be explored, to better identify tools which can be used by designers for fire modelling of timber. Finally, certain important research gaps are identified which, with further investigation, can reduce uncertainty in the set-up and use of such models.

2. Methodology

Heritage structures are normally perceived differently to contemporary structures due to the value that they hold to a community's heritage. This is not to say that a contemporary structure cannot hold cultural or societal value (Lloyd's building in London for example is a Grade 1 listed building in the United Kingdom despite being built only 40 years ago), but from a construction perspective a heritage structure is irreplaceable due to either materials that are no longer commonly available or are very expensive or a construction practice which is no longer performed. This section serves to provide the reader with the background knowledge required to understand heritage work.

2.1 Best Practices for Heritage Design

Before explaining the best practices for heritage design, it is important to understand what is considered heritage. Worldwide heritage sites can be noticeably unique from each other. Historic sites can be as vast as castles, cathedrals, or districts of a city. However, heritage does not need to be monumental. Heritage can be smaller structures such as residential spaces from different centuries which provide insight into the history of a community. This paper focuses on Canadian heritage; however, the principles are relevant to other jurisdictions.

In Canada, the conservation of a historic site is the general term for protecting these character-defining elements. Specific strategies are preservation, rehabilitation, and restoration[9]. Preservation is meant to preserve the current state of the historic site. This is recommended to be performed when the heritage value is more tangible, and the character-defining elements are in good condition[9]. Rehabilitation is performed either when the character-defining elements need repairing or if the historic site is being adapted for a new use. It should be noted that when repairs are performed it may not be possible to perform a 1-to-1 repair, there is some freedom to allow new materials or designs to be used on the basis that it does not detract from the heritage value of the site[9]. Finally, restoration is the act of restoring a specific era of the historic site. This can involve removing other potential character-defining elements that were added after the important period which is being restored[9].

From these definitions, an active consideration of fire safety may only be involved in rehabilitation projects as that technique is the most accepting of introducing new materials and designs. Nevertheless, it is important to understand the behaviour and performance of heritage mass timber. If a historic site is undergoing preservation or restoration work and the character-defining element is the exposed mass timber structure, this can still have major impacts on the life safety and resilience of the structure.

Stating that this study will focus only on a Canadian heritage context leaves room for interpretation. Within Canada, a site can be designated heritage at several different levels: municipal, provincial, federal, and international (although this is decided by UNESCO and is not a Canadian body). Not all levels of heritage protect a heritage site to the same extent. Additionally, just because a site is deemed heritage at one level does not mean it is considered heritage at any other level (ex. a provincial heritage site may not be considered heritage by its municipality or federal). Many heritage values are intangible by nature, however, the elements of a site which demonstrate these values are typically tangible and are referred to as the character-defining elements. Different levels of government bodies may hold different values to the heritage of a site.

Additionally, a governing body may recognize a site to be historic due to tangible heritage values such as the construction methods or materials used. Therefore, in some heritage sites, the timber elements may be deemed irreplaceable due to their value.

For this study, heritage will be considered from the Canadian perspective but will not specify what level of heritage. Rather this study will follow the intent of the Standards and Guidelines for heritage conservation in Canada[9]. This is because, while a site may not be formally recognized or protected as heritage it may still hold value to the community it resides in. By following the Standards and Guidelines for heritage conservation in Canada, it ensures that this value is not lost.

2.2 Performance in Fire of Heritage Mass Timber

If exposed mass timber is a character-defining element for a site, it will ideally remain exposed to protect the heritage value of the site. At the same time, timber is a combustible material. Therefore, a fully developed fire in a structure poses a major threat to public safety and, if not contained properly, risks further fire spread. For this reason, in preserving historic legacy, it is important to understand the fire performance of heritage mass timber and differences from contemporary mass timber. This will facilitate understanding the potential of leaving heritage mass timber exposed in preservation or restoration work and will allow appropriate design whether in the context of rehabilitation or in the development of a fire safety plan for a heritage site.

The importance of this knowledge is summarized through literature review of 125 studies on heritage structures ranging from 1985 – 2022[10]. In the review, it was found that the studies could be separated into six general categories. The distribution is as follows: 11% fire safety regulations, 23% fire risk assessment, 23% fire protection and mitigation measures, 12% spread of both fire and smoke and evacuation, 17% thermomechanical behaviour of historic structures or materials, and 14% fire safety engineering design[10]. Of the 125 studies examined, 64 were related to heritage timber. Of those 64 studies, 5 investigated the thermal and thermo-mechanical performance of the timber. In general, the examples demonstrated that there are deficiencies in the understanding of how fire spreads in a heritage structure and likewise how the heritage structure performs. It was concluded that the fire performance of heritage timber is unclear, signifying the need for the present studies to take place[10].

It has been observed that while the design of heritage structures differs from conventional wood design (large members versus adhered dimensional lumber), the behaviour of the structural elements in a fire scenario is comparable[3,9]. This is because both forms of design utilize large mass timber elements as opposed to dimensional lumber found in small residential structures. However, in small-scale testing, variance in the fire performance of contemporary and heritage wood has been observed. Through cone calorimeter tests at 50 kW/m^2, Reference [11] observed that historic wood charred at an average rate of 0.85 mm/min, whereas contemporary glulam charred at an average rate of 0.68 mm/min. The moisture content of these samples ranged from approximately 7-8%[11]. In terms of flame spread testing, Reference [11] observed that heritage wood outperformed contemporary glulam in a Lateral Ignition and Flame Spread Test (LIFT) with regards to char depth and that the flame stopped spreading sooner on the historic specimens. However, the glulam had a less extensive char front as well as a slower rate of flame spread. While heritage timber has been observed to behave and perform similarly to conventional timber, in terms of structural design, heritage and modern timber should not be considered the same material. As a natural material, the methods used to cultivate the material in combination with its environment can affect the way the wood grows. Reference [12] found that when the growth rings in Larch trees were thinner than 2.5 mm, the density of the wood increased; when the growth rings were greater than 3 mm, the density decreased. As thermal properties such as density are impacted by the growth of the tree, the thermal inertia of the wood is also affected[3].

One of the more obvious differences between contemporary and heritage timber is the current level of deterioration each is at. Even if a heritage material is considered well maintained and of high quality, it does not mean that the material is free of defects or damages. Heritage wood members that are in use may have discrete cracking occur over their lifespan. Reference [13] investigated the effects of radial cracks formed from moisture changes over time (from moisture changes with time) on the fire performance of heritage timber. In full-scale member tests, it was observed that pre-existing cracks increased in width during a fire and that the crack impacted the development of the pyrolysis and char front. Char depths which occurred away from the crack were 64% less than char depths observed at the crack. Therefore, the damages and defects present in heritage timber can have a significant impact on the material's fire performance.

To supplement the lack of heritage material available for experimental testing, numerical modelling may be performed to study the fire performance of heritage timber. It may also be used to help frame equivalent design solutions that can satisfy the building code in a performance environment. However, numerical modelling is not without its own challenges. To create a validated model, there needs to be a thorough understanding of the material to be modelled as well as experimental data against which to validate the model. Therefore, to create a valid numerical model experimental studies must still be conducted using the limited stock of materials. In addition to the general challenges of numerical modelling, modelling fire performance of heritage timber poses several of its own challenges. These challenges include strategies to account for the effects of moisture[14] as well as the temperature dependent thermal properties of the material.

One example of the use of numerical modelling is the study performed by Reference [15] in which the researchers modelled a historic timber jack ceiling. A timber jack ceiling is a series of vaulted brick ceilings supported by timber joists. The purpose of the model was to address the complex geometry of the ceiling and determine accurate temperature gradients for the timber joists. From this, a mechanical analysis could be performed to determine the remaining strength of the floor system post-fire. Within the model, three different time-temperature exposure curves were simulated. The time-temperature curves were the ISO 834 standard fire[16], parametric fire curves, and two-zones models (produced by OZone). While this study has a significant focus on the use of different time-temperature curves on the model results, it highlights the importance of understanding the properties of historic timber. While it was believed that the standard fire curve would lead to higher char rates due to being the only curve with no decay phase, the opposite was true[16]. Therefore, the results from the parametric and two-zone models may not be accurate, highlighting the need for further understanding of the behaviour and performance of heritage wood in fire.

Herein, this study aims to determine the difference in charring characteristics of historic hardwoods versus historic softwoods. Better understanding of whether there is a difference in charring behaviour, and if so to what extent, will aid designers in properly accounting for fire safety during conservation of historic timber structures. Determination of the char rate and depth form the basis for a common approach to determining the structural integrity during a fire, and the remaining strength of a timber member post-fire, as illustrated in standards such as CSA O86 Annex B[17]. Finally, a provisional (1st stage) model is developed to analyse these tests and further illustrate the need for a fundamental understanding of the fire performance of heritage timber.

3. Experimental Fire Performance of Heritage Timber

In the present study, a cone calorimeter available at the University of Waterloo Fire Research Laboratory is used to investigate differences in the charring behaviour between heritage softwood and hardwood. The cone calorimeter consists of a cone-shaped radiant heater which is used to expose small samples (100 x 100 x 45 mm) of materials to a uniform surface heat exposure under well ventilated (constant oxygen availability) conditions. Concentrations of O_2, CO_2, and CO are measured in the exhaust[18] and used to estimate the effective heat release rate from a material. Some calorimeters are equipped to determine concentrations of other species, such as HCN, HCL, HBr, SO_2, and NO_x [18]. As a cone calorimeter provides a stable and repeatable environment and can analyse products of a fire it is used for standardized pass/fail tests and used to collect data for fire models. Recently, the cone calorimeter has been employed for studies of the fire characteristics of a wide range of polymers (of which wood is) [18]. The experimental setup used in the present study can be seen in Figure 1. While the radiant exposures available with the cone calorimeter are lower than those which might be experienced by a timber member engulfed in a fully involved compartment fire, the heat exposures are consistent and repeatable. Additionally, these radiant exposures simulate values which might be encountered by exposed heritage elements during the early stages of fire growth. In addition, as a standard test method, the cone calorimeter is designed to provide data by which different materials can be compared with respect to their overall fire performance characteristics. Furthermore, the cone calorimeter has proven to be an useful research tool as it can allow for small samples of heritage hardwood and softwood to be systematically compared under different intensities and durations of heat exposure with other conditions held constant. This provides a dataset useful for experimental validation of models and sub-models of the thermal response of those materials to early fire exposure.

Figure 1: Cone calorimeter device with specimen circled in red (left) and sample ignited (right)

3.1 Methodology

The softwood heritage samples were sourced from joists whose dimensions were 350 x 70 mm of spruce species circa approximately 1830. The building, from which the samples were extracted, was undergoing redevelopment and the timber members were carefully removed by the developer and demolition crew (see supplemental Figure S-1). The hardwood samples were taken from a decommissioned farm structure beam circa 1880 and were of oak species.

The samples species were all identified through the assistance of an experienced horticulturist employed by the author's university affiliation. Once timber samples were located, they were inspected for signs of defects or deterioration such as rot, moisture damage, and pests. Only samples without defects were chosen and subsequently were stored together to reach equivalent moisture contents (23 ^{o}C and 50% relative humidity). For use in the cone calorimeter tests, the heritage members were cut to 100 x 100 x 45 mm. 45 mm is the maximum that can be accommodated in the standard cone calorimeter configuration. Individual specimens were cut to avoid the presence of knots or other defects in order to limit outliers in data due to the significant impact defects can have on charring behaviour. For consistency and to promote controlled comparison across tests, specimens were prepared and mounted in the sample holder with a fresh-cut side exposed to the heating element to avoid uncertainties in the results due to the surface oxidation of the timber members. Additionally, specimens were cut so that the exposed face was always oriented perpendicular to the grain to avoid known differences in fire performance of samples oriented parallel or perpendicular to the grain. Figure 2 illustrates the exposed face for each species. After being prepared, two hardwood and four softwood samples were slowly dried in a furnace for 24 hours at 108 °C to determine their moisture content, bulk density, and dry density. Samples were weighed before and after drying in the furnace. Samples were of similar, but drier than service conditions. The softwood samples were found to have an internal moisture content of 6.97% and an average bulk density of 355.95 kg/m^3. The hardwood samples were found to have an internal moisture content of 8.665% and an average bulk density of 565.91kg/m^3.

Figure 2: Grains of the hardwood (left) and softwood (right) specimens

The cone calorimeter tests were performed following a modified ASTM E1354 procedure[19] with no external spark ignition to imitate a real fire where the exposed wood would self-ignite without external ignition[11]. Individual wood specimens were tested at either a low heat exposure of 30 kW/m^2 or a high heat exposure of 50 kW/m^2. Each test specimens were removed from the apparatus after a specified exposure time of 3, 6, 10, 15, or 30 minutes and immediately extinguished with water. The use of water was to halt the smoldering and combustion processes. This was to prevent continued charring of the wood specimen after the test had concluded to facilitate cooling and storage for later measurement of char formation. The water evaporated in contact with the wood, and the specimens were kept in a temperature and humidity-controlled environment after the test.

Two softwood and two hardwood specimens were tested at both levels of heat exposure, for each duration of exposure. This resulted in 20 softwood tests and 20 hardwood tests for a total of 40 tests. Softwood samples which were tested for 3, 6, 10, and 15 minutes and one set of data for the hard wood samples was collected by Reference [11].

Measurements from each test included the char depth and average char rate of the samples. Char measurements were recorded once the specimens had cooled back to ambient temperatures. The specimens were cut in half and the distance from the unexposed face to the blackened char, past the discolouration from pyrolysis, was measured (+/- 1 mm). Figure 3 displays where the measurement of the uncharred wood was taken. This measurement was subtracted from the original thickness to determine the char depth. Char rate assumed that the char progressed at a steady rate and was determined by the final char depth divided by the length of time of the test. Due to the uniform surface heating, a level char front of a sample was observed in all samples. The assumption that the char rate is uniform and steady follows design procedures for the charring of structural timber in standards such as CSA O86 Annex B [17].

As a final note, it should be reiterated that a timber element fully immersed in a post flashover compartment fire would be exposed to heat fluxes and potentially fire durations much greater than those considered in this research. These fire exposure profiles should also be considered in the future. However, the heat fluxes employed are appropriate to the early stages of compartment fires and facilitate systematic comparison of the early thermal responses and charring of exposed timber under such conditions.

Figure 3: Cross-section of a sample with dimension indicating where uncharred depth is measured

3.2 Experimental Results

Once the samples were tested several qualitative observations could be made based on the final charring patterns characterizing the samples. The first was the cupping of the samples and increased char depth on the edges, relative to the centre, of the samples. The cupping of the wood is an expected and common behaviour of polymers exposed to fires[20]. Further, once the samples begin to cup, the outer edges have the potential to become directly exposed to the heat which results in the deeper localized char depths. The second, distinct, visual observation is the difference in charring between the hardwood and softwood samples. Figure 4 shows the visual difference between the char formed on hardwood and softwood when exposed to 50 kW/m^2 for 30 minutes. The hardwood formed a tight, scaly char with a series of grid-like cracks. In contrast, the char texture in the heat exposed softwood sample appears more "expanded" than that for the hardwood. Based on the significantly different visual appearances and textures of the char, it can be surmised that the char from each species may not provide the same level of thermal insulation. However, further testing is required to provide evidence for the validity of such an assumption. Potential reasons for the difference in charring between these species include a difference in thermal properties, material composition, and environmental exposure of the materials. It is known that these species have notably different densities compared to each other, however the details of the composition, the conductivities and specific heat capacities of these specific specimens are not known and would impact the combustion process. As noted by Reference [8], softwoods and hardwoods have a different composition of lignin which leads to different compositions of reactants involved in the combustion process. Finally, the history of the specimens is not documented, and it is uncertain what environments they have been exposed to. While this introduces variability in the study, it is the reality experimentally determining fire performance characteristics of historic materials.

Figure 4: Sample images of the char produced by the hardwoods (left) and softwoods (right) when exposed to 50 kW/m^2 for 30 minutes (author's photos)

Prior to investigating the data collected from the testing, it should be noted that all samples exposed to 50 kW/m^2 ignited within one minute of heat exposure. In contrast, the samples exposed to 30 kW/m^2 did not ignite. From the cone calorimeter tests, data was collected to determine the char depth and average char rate for hardwood and softwood specimens when exposed to two different heat fluxes. Figure 5 illustrates the average char rate of the hardwood and softwood under 3, 6, 10, 15, and 30 minute exposure to heat fluxes of 30 kW/m^2 and 50 kW/m^2. From Figure 5 several observations can be made about the charring behaviour of the softwood and hardwood specimens. The first observation is that the average char rates will peak in the early stages of heat exposure (< 10 minutes), although the profile of char rate with exposure time during this period may depend on the level of heat exposure. This aligns with the fact that charred wood provides thermal insulation to the inner area of the cross-section. This is more apparent under the high heat exposure as the wood surface can quickly increase in temperature until an established char layer is formed. Secondly, it can be observed that typically the hardwood samples maintained a higher average char rate regardless of the level of heat exposure or length of exposure. The two exceptions being the average char rates measured for the specimens at 3 minutes and 30 minutes when exposed to 50 kW/m^2. In these cases, the average char rates are approximately equal for both the softwood and hardwood specimens. The fact that the averaged char rates appear to be consistent after 30 minutes of exposure may point to similar averaged charring rates over longer duration of high heat exposures between the species. Prior to making this conclusion, however, additional testing would be required for durations longer than 15 and 30 minutes under a range of higher heat flux conditions.

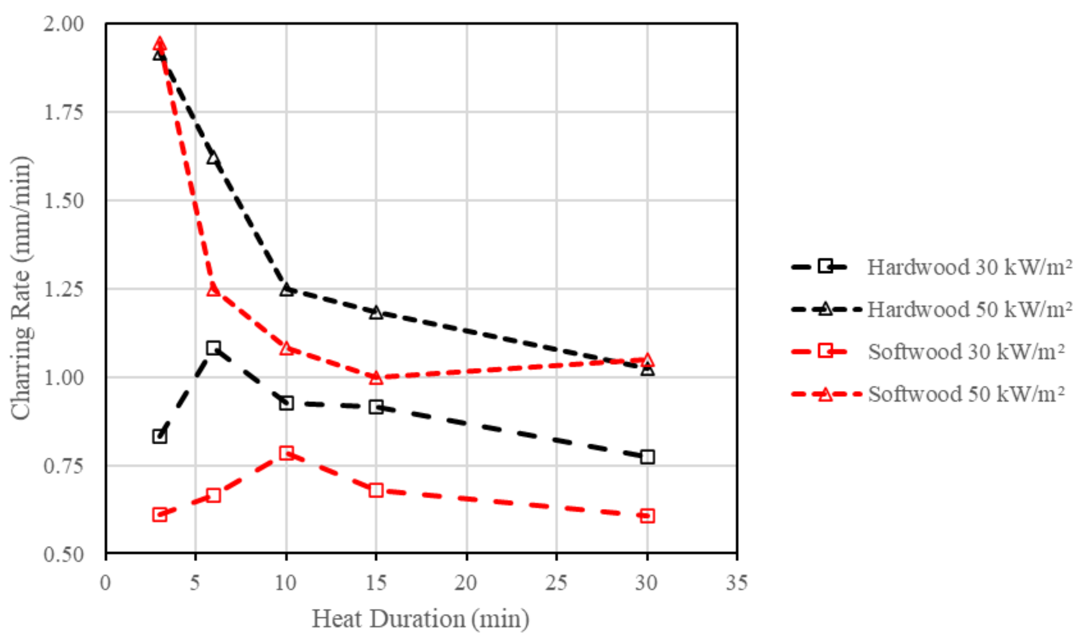

Figure 5: Average charring rate of wood samples at 30 kW/m^2 and 50 kW/m^2

Figure 6 illustrates the measured char depths for each specimen exposed under 30 kW/m^2 and 50 kW/m^2 incident heat flux with dashed lines representing a linear trendline. From Figure 6, results consistent with the average charring rates can be seen, namely that the hardwood specimens typically have a greater char depth than the softwood specimens. Further, the char depths exhibit a linear trend with exposure duration which is also observed in contemporary wood and is assumed in prescriptive designs such as Annex B of CSA O86[17]. However, caution should be taken if using the trendlines to determine the char depth at all heating durations under specific heat fluxes. Additional testing is required at different heating durations is required to fully understand the charring behaviour. Sample to sample comparison suggests that the softwood chars more uniformly and thus char depth results are more consistent. Whereas the hardwood samples show a greater variability in char depth across samples. As stated previously this may be due to wood being a natural material that may have greater uncertainty in performance due to variability in the material. The variability in the material is especially true for heritage wood which is not graded based on an established standard. To confirm these observations and obtain more useful statistics on specific trends in the charring data more samples would need to be tested at all testing criteria. This was not feasible in the present research as heritage wood suitable for destructive testing was a limited resource.

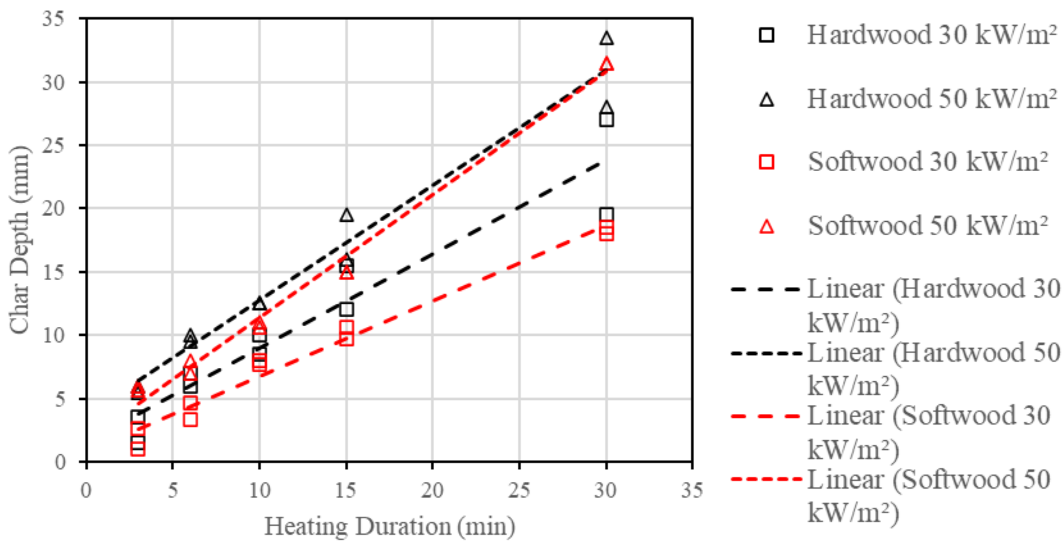

Figure 6: Char depth of samples exposed to 30 kW/m^2 and 50 kW/m^2

Finally, heat release rates (HRR) were collected during the tests. Figure 7 illustrates the HRR vs time curves for several samples which were exposed to heat for 30 minutes. From this, several observations can be made. The first is that both the hardwood and softwood samples exposed to 50 kW/m^2 ignited early in the test (typically within 40 seconds), whereas samples exposed to 30 kW/m^2 did not ignite. This pattern was typical for all samples tested. The hardwood samples reached a peak HRR of approximately 200 kW/m^2, whereas the softwood samples reached a peak HRR of approximately 185 kW/m^2. Another observation is that following the initial peak the HRR appears to decay and stabilize without a second peak. However, one sample of the softwood did appear to increase in HRR after approximately 1400 seconds (Softwood: 30 kW/m^2 Sample 2 in Figure 7) possibly due to some loss in integrity of the char layer. The final observation is the potential heat release rate from the heritage wood in the event of a fire. In the early stages, because a char layer has fully formed it is evident that there can be a relatively high heat release rate from unexposed timber surfaces. Following this, the HRR appears to stabilize at lower values of between 25 and 60 kW/m^2 under sustained exposure to heat. The hardwood reached a higher plateau in heat release rate of approximately 55 – 60 kW/m^2 in contrast to the softwood which was closer to 25 kW/m^2. This clearly indicates that the additional generation of heat possible from exposed structural wood should be accounted for in an analysis of structural timber in fire.

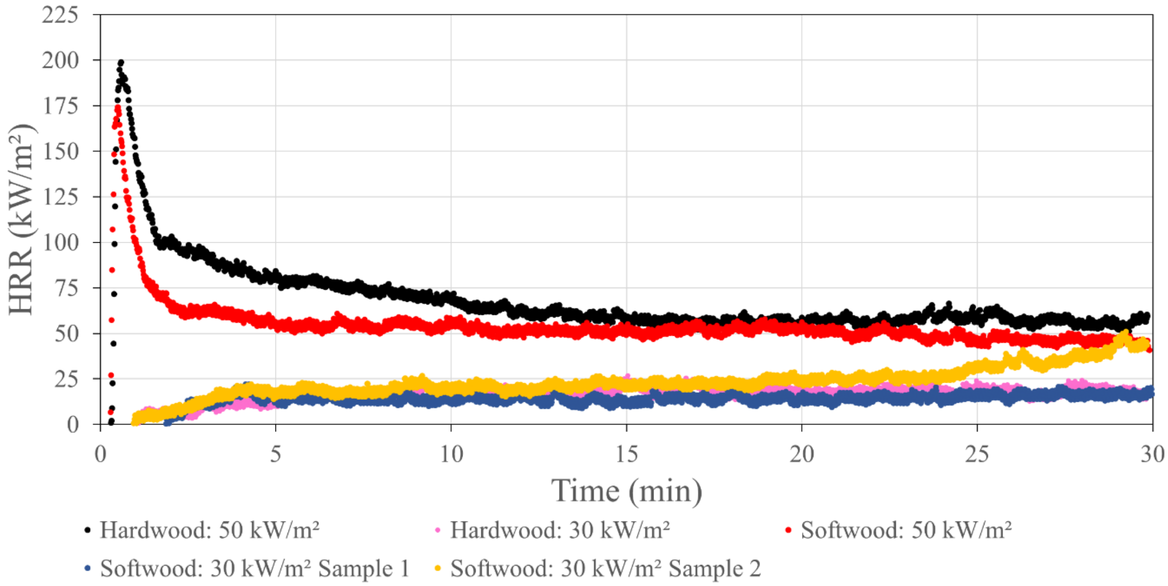

Figure 7: Heat release rates for samples exposed for 30 minutes

To generate the HRR data, the concentration of O2, CO2, and CO are for the same samples shown in Figure 7. In all cases, levels of CO2 above ambient values are observed during flaming combustion or due to steady oxidation via smouldering for samples exposed to 30 kW/m2. Supplemental Figure S-2 shows the concentrations in O2, CO2, and CO for the samples shown in Figure 7. Variations in the oxidation process for differing levels of heat exposure may lead to different overall compositions of the char layer as well. Further studies should be performed to address any impact this might have on the thermal properties of the char product.

4. Current State of Timber Fire Modelling

Heritage timber is a limited resource. Therefore, it is difficult to obtain such material for experimental testing particularly during the adaptation of a heritage building. As a possible solution, the authors explored the validity of modeling heritage timber as a tool to help understand thermal properties. Reference [21] previously developed a default timber model by validating it against two benchmarks (glulam beams and heritage timber members), and then applying it to a cross laminated timber ceiling. This default methodology was used to model the new scenario herein; note that the previous heritage timber model by Reference [21] differs from this study since the comparative data had been obtained from a methanol pool fire exposure to a larger heritage specimen. This provisional modelling study will be used to determine the default model's applicability, as well as identify factors requiring further research and testing with the aim to develop the model more fully so that a higher certainty model can be created.

LS DYNA, a finite element analysis software was used as the numerical solver. This software was chosen because of its common use in the industry and academia for fire safety engineering analyses[22,23]. While LS DYNA is extensively validated to model steel and concrete behaviour in high temperatures, its ability to predict timber behaviour is a relatively new research endeavor and therefore considered herein in lieu of other software packages. The ABAQUS software package for modelling timber degradation in fire has also been considered in the past[24], and in general the research areas proposed here will be broadly applicable across many finite element package types.

A one-dimensional model of the hardwood and softwood samples was developed to show the heat transfer from the cone calorimeter to the specimen. Because the model was relatively simple, the geometry was built in Primer with material and thermal properties manually input. The model was then run through LS DYNA and results were displayed and exported using D3PLOT and T/HIS to Excel. The model assumes ideal conditions, such as having constant oxygen supply, to best reflect the conditions encountered in the cone calorimeter tests.

4.1 Modelling Challenges and Research Gaps

Timber as a combustible material presents a variety of new modelling challenges when compared to traditional materials such as concrete and steel, including the presence of moisture and the formation of the char layer. The moisture within the material affects the ignition time and intensity required for ignition. As the temperature increases, the water will begin to evaporate which requires energy[14]. This energy loss must be accounted. As well, the thermal properties of timber will change over time and temperature. These include its thermal conductivity, specific heat capacity and density. While LS DYNA can input functions of thermal conductivity and specific heat capacity, the user cannot change the density directly. Instead, the software takes in a single value for the duration of the simulation. This also means that the material properties cannot be simply or directly changed. Therefore, while timber changes into ash and an insulating char layer, the software only models the wood material with its associated properties. Given the configuration, it will err on the conservative side of calculating charring rate as the insulating layer will be absent.

Additionally, timber is an anisotropic material. This means that its structural and thermal properties are dependent on the grain direction. Studies show that char rate and conductivity will differ based on the orientation of the grain[25]. Finally, the inclusion of heritage wood is a challenge in the modelling process. The model requires accurate input data (such as density, specific heat capacity, and thermal conductivity) to produce accurate results. Since, the behaviour of heritage timber can be inconsistent and other variables present with heritage timber are not included as direct input to the model. Overall, modelling heritage timber has an additional layer of variability that is not usually present.

4.2 Model Methodology

4.2.1 Mesh and Time Sensitivity Analyses

Initial steps taken to create the model included completing a mesh and time sensitivity analysis. Mesh sizes of 1, 3 and 5 mm were compared, as well as timesteps of 1, 5 and 10 seconds. The objective of these analyses was to choose the largest possible mesh and timestep size to reduce computing time, while maintaining the accuracy of the results. Overall, the analyses were completed using the 3-minute, 30 kW/m^2 heat flux test; results indicated the use of a 1 mm mesh size and a 10-second timestep were ideal (see supplemental Figures S-3 and S-4 for further details). This can be seen through the discrepancies seen between results with 1, 3 and 5 mm, and the lack of discrepancies between the various timesteps. Note that although the timestep is relatively large, LS DYNA will decrease the timestep if the temperature change per timestep is greater than a user inputted threshold (50 K in this case). A maximum and minimum thermal timestep of 1.0E-6 and 30 seconds respectively were also inputted.

4.2.2 Materials Properties

The models herein are based on the previously validated model in Reference [21]. A summary of the material property input parameters can be found in Table 1 below.

Table 1: Material property input values

Property	Value	Source
Density (Hardwood)	565.91 kg/m^3	Moisture Content Test
Density (Softwood)	355.95 kg/m^3	Moisture Content Test
Specific Heat Capacity Curve	-	Eurocode 5 [27]
Thermal Conductivity Curve	-	Eurocode 5 [27]
Phase Change Temperature	373.15 K (100 °C)	References [21, 28]
Latent Heat (Hardwood)	195.83 kJ/kg	References [21, 28]
Latent Heat (Softwood)	157.52 kJ/kg	References [21, 28]

The material properties (density, specific heat capacity, thermal conductivity, phase change temperature and latent heat values) were assigned using the results from a moisture content test previously described. As aforementioned, LS DYNA can only utilize a single density value during a simulation, therefore, the bulk density was used.

The material type was set to be thermal isotropic, which allowed thermal conductivity and specific heat capacity curves with respect to temperature from Eurocode 5 [27] to be used. This specific heat capacity curve has a discontinuity in which the specific heat capacity has two values for single temperature values (at 99 and 120 °C). This is to account for the energy absorbed when the water in the timber member evaporates. However, LS DYNA is unable to process this discontinuity. Therefore, following References [21, 28] the larger values were removed, and phase change temperature and latent heat values were implemented to account for the moisture evaporating. The phase change temperature was set to 373.15 K (100 °C), and the latent heat to 195.83 kJ/kg for the hardwood, and 157.62 kJ/kg for the softwood. The latent heat value was calculated using the same method as in Reference [27] by multiplying the moisture content of the sample by the heat evaporation of water (2260 kJ/kg). It is also important to note that the Eurocode 5 thermal conductivity and specific heat capacity curves are for softwood (there are no curves for hardwoods) [27]. As these were used for both the softwood and hardwood models in the study herein, the authors understand this is a source of inaccuracy.

4.2.3 Thermal Properties

The initial temperature was set to be ambient temperature, 293.15 K (20 °C) as per Eurocode 5[27]. This is the temperature of the specimen at the start of the simulation and was assumed from the experiments. As per the cone calorimeter test methodology, the heating side had a boundary condition of 30 or 50 kW/m^2 heat flux, and the insulated side a boundary condition of 0 kW/m^2 heat flux for durations of 3, 6, 10, 15 and 30 minutes.

4.3 Comparison of Model Results to Experimental Results

Figure 8 below, shows the temperature distribution through a wood sample at the end of the three-minute model simulation at 30 kW/m^2 heat flux. The maximum temperature, 1242 K (968.63°C) is at the top of the specimen where the heat source is located. The minimum temperature, 293 K (20°C), is at the bottom of the specimen, where the heat has not transferred yet. As aforementioned, the simulation is a one-dimensional heat transfer under idealized conditions. Therefore, the temperature distribution is also idealized with constant temperatures along any horizontal line.

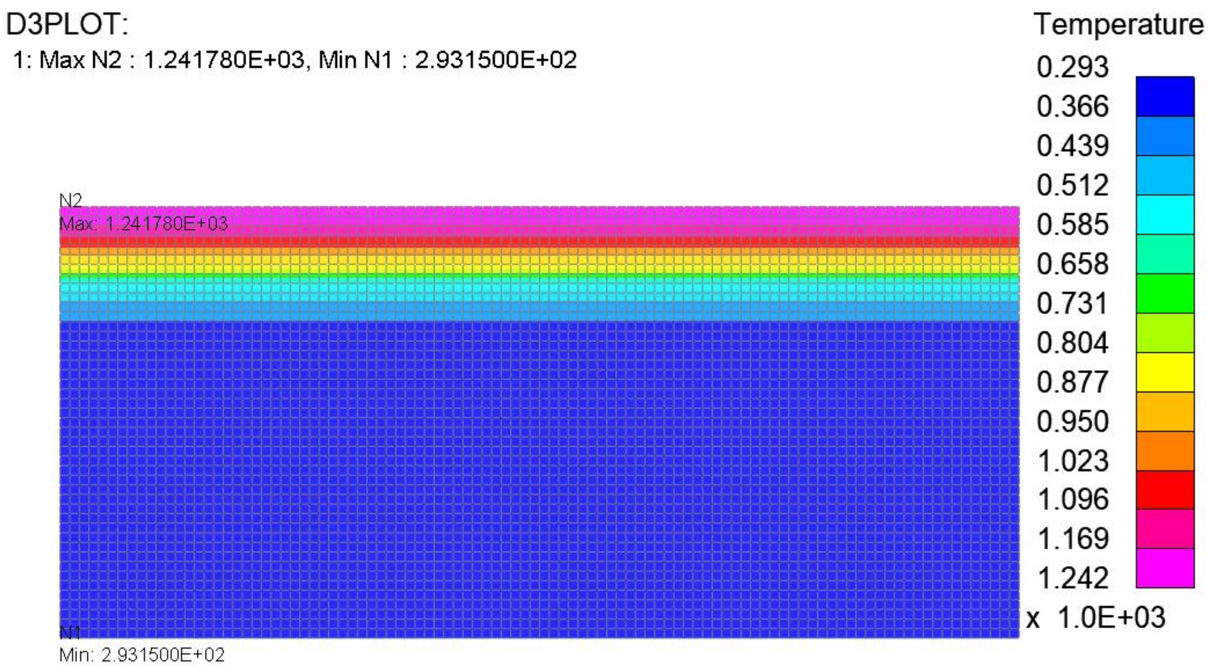

Figure 8: Temperature distribution at the end of the three-minute 30 kW/m^2 heat flux simulation

Figure 9 shows the experimental versus simulation char rate results for the hardwoods. For the model, the char rate is defined as the depth of the charring, divided by the time. As per References [29, 30], charring is considered to begin when the temperature reaches 300°C. The hardwood modelling estimates are approximately double the experimental results on the conservative side, with the maximum model char rate of nearly 4 mm/minute. The softwood charring rate was calculated using the same method as the hardwood. Results from the model show conservative charring rates with the highest charring rate being nearly 6 mm/minute (see Figure 10). The trends for the 50 kW/m^2 flux were followed in the model, but not for the 30 kW/m^2 heat flux.

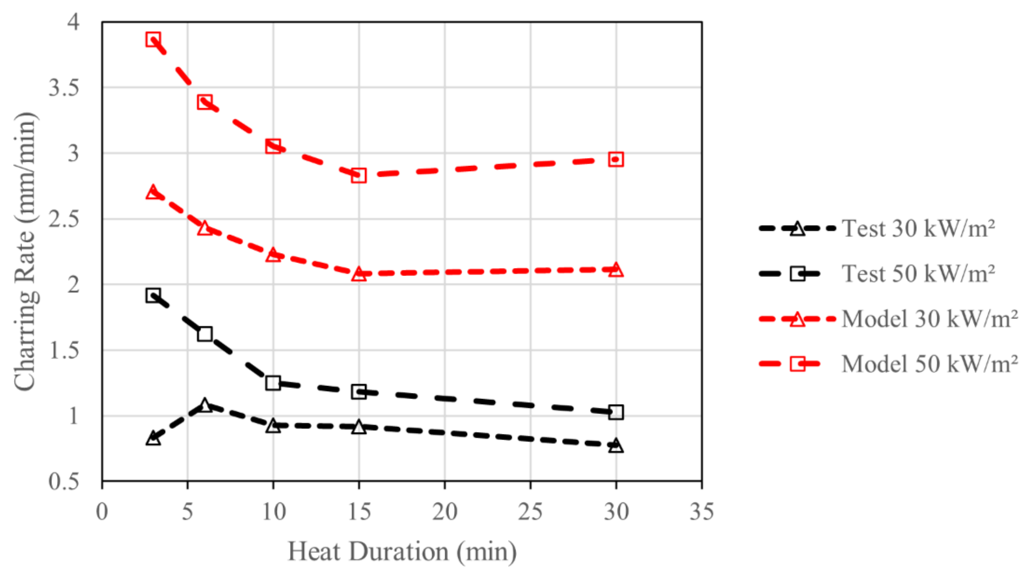

Figure 9: Experimental versus model charring rate for Hardwood

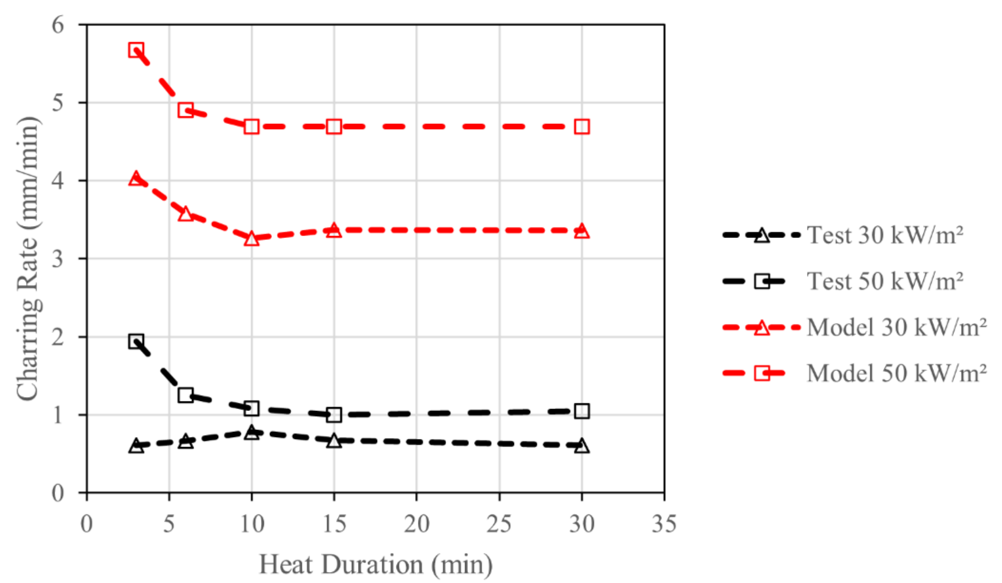

Figure 10: Experimental versus model charring rate for Softwood

It is important to note that while the current models are showing conservative results, this may not always be the case for other specimens and needs further refinement and more careful research attention. A study Reference [31] compared experimental and model results of a timber beam in fire using another finite element analysis software ABAQUS. Results from this study showed an overestimation of temperatures over time and therefore char depths for one furnace experiment, and the opposite (an underestimation) for a second experiment of similar size. Whether this is an artifact of the model or the experiment itself needs further investigation.

There are several reasons for the differences between the model and experimental results which will need addressing in second stage modelling. A likely explanation is the material properties are not fully appropriate for the charring process taking place and the level of heat flux exposure considered in this research. The thermal properties, specific heat and thermal conductivity, follow the relationships provided in EN1995-1-2[26] which were developed for softwood. Because no hardwood data was available, these were used for both the hardwood and softwood simulations. This may explain why the softwood has higher charring rates than the hardwood in the modelling data, whereas the opposite was found in the experiments. By using the same specific heat and thermal conductivity values, the differences between the hardwood and softwood models were the inputs for density and latent heat. To investigate how much variation in the density of the material impacts the results, an initial density sensitivity analysis for the hardwoods was conducted. Using the measured average bulk density for the hardwood specimens, the charring rate for the 3-minute, 30 kW/m^2 simulated exposure was 2.70 mm/min. Using the average dry density, a lower density value, the charring rate for the same simulation increases to 2.92 mm/min. Therefore, density and the charring rate are inversely proportional; as the density decreases, the charring rates increase. Since the softwood had a smaller density compared to the hardwood samples, this could explain the higher softwood charring rate seen only in the model.

Another aspect that was considered as a possible explanation for differences between the model and experimental data is that the density in the model is fixed at a constant value. As aforementioned, there are no provisions in LS DYNA to vary density values with respect to temperature changes. In a realistic scenario, the density would change from bulk to dry density as moisture evaporates. From the density sensitivity analysis, it was discovered that the charring rate would be more conservative than seen in this study. Therefore, while density changes do not explain the difference between the model and experimental data, it shows that density has a significant impact on the charring rate, demonstrating the importance of correctly inputting this parameter.

Other sources of error include the inability of the current model to account for changes in the material characteristics as the temperature changes as would be seen in timber undergoes pyrolysis and changes to char. Therefore, there is no provision in the model to account for the development of the insulating char layer that would limit heat transfer through the virgin wood and temper such rapid charring. In addition, the formation of the char layer varies. Since this variability is not easily quantifiable as input into a numerical model, while it is recognized as being important, it is not being considered at the present time.

Finally, the process of moisture transfer and evaporation in the specimen is also unknown. Following Reference [21], the discontinuity in the specific heat capacity curve from Eurocode 5[27] was removed. It was replaced with a calculation related to energy absorption based on the latent heat of evaporation for water. In doing this, the intent of the specific heat capacity curve as included in Eurocode 5[27] is changed and may thus be less representative of the material. One possible method for correcting this is to adjust the values of both the specific heat capacity curve and to the density value. Not only is this difficult with the requirement for constant density with the current model, but preliminary results indicated even more conservative charring rates. This, as well as the other factors influencing the accuracy of the model, will form the subject of future research.

Overall, while models may never be able to reflect all the nuances of pyrolysis of heritage timber, the aim is to develop a model that can be used to predict conservative char rates with a reasonable error margin. With a working default model, the behaviour of timber in fire can be a possible solution when experiments are not feasible. This is important for heritage timber, since it is a limited resource, and can be difficult to source.

5. Recommendations for Future Research

From the study conducted, it is evident that more experimental data is required to understand the specific behaviour of heritage timber in fire. This more accurate information can then be implemented into a revised model to create a higher certainty of results. Areas which require more research include the detailed mechanics of formation of the charring layer and the method by which moisture moves and evaporates through timber during exposure to differing levels of heat. In terms of progression in the model, methods to change material properties over time as a char front propagates in space need to be implemented. The charring layer forms and insulates the underlying timber, thus slowing the charring rate. Therefore, the model needs to be able to predict and accommodate changes in the material from wood, to char, to ash.

Prior to implementation changes in material types within a revised model, a consensus must be reached on when these material changes occur. It is known that water evaporates at 100 °C and it is generally accepted that wood converts to charcoal (chars) at 300 °C, however the process of pyrolysis is not well understood. A thermogravimetric analysis (TGA), which measures the mass loss vs temperature of a specimen, should be performed to identify temperature ranges during which the heritage wood may be changing its composition.

Further study should also be conducted to improve understanding of how moisture transfer within wood impacts the conductive heat transfer through the material under exposure to heat. While it is known that as it evaporates, moisture will locally delay heating of the wood. However, the impact of moisture migration to an exposed face resulting in non-uniform distribution of moisture is less clear. A study could be specifically designed to identify when and where in the cross-section evaporation is occurring throughout the heating process.

To have increased confidence in the capabilities of a numerical fire model, additional data sets to validate against are required. One such dataset is the temperature gradient through a timber specimen during exposure to fire scenarios. A method of collecting this data is to install a line/array of thermocouples into the specimen. It should also be noted that when thermocouples are installed into wood, they are typically placed in holes drilled from the unexposed face. However, if moisture migrates to the thermocouple hole during the fire, the possibility exists that moisture escapes the wood and coats/evaporates on the thermocouples. This could affect the accuracy of the temperature data in testing and is not discussed in literature. Further investigation into this should be made prior to an in-depth analysis of the heat transfer through wood if thermocouples are to be used.

Finally, studies should be performed to understand how the species of wood and duration/intensity of heat exposure affect the thermal properties of char. From visual inspection and data on oxidative exposure of wood, there are indicators that the char formed is different when these variables are altered. However, the data collected in this study is not sufficient to state the impact that specific species and heat exposures have on the thermal properties of the char layer.

6. Conclusions

As noted previously, one aspect of heritage wood structures which makes them unique is the use of hardwoods which is no longer as common for structural purposes. As observed through the experimental test series, the heritage hardwood typically charred at a higher rate than the heritage softwood. From a practical point of view, designers may be used to working with softwoods, as it is the type of wood used today, and assume similar values for heritage hardwoods. However, this would overestimate the strength of the wood member both during and post-fire as a slower char rate would be inferred, resulting in a greater residual cross-section than might actually exist. Future studies into longer durations of heat exposure (> 15 minutes) are required to examine if char rates between hardwoods and softwoods converge. Additionally, it was found that some samples did ignite and generate significant rates of heat release which have to be taken into account in assessing potential performance of a heritage structure during a fire. It was also observed that there is a variability of the behaviour and charring characteristics of the timber specimens at high heat exposures. While it may be simple to say that more tests can lead to greater confidence in estimating the charring behaviour of heritage timber, it is difficult to obtain suitable specimens. Therefore, LS DYNA was used to attempt to model the behaviour without the need for more specimens. Current default practices were used to build the model and results showed overly conservative charring rates in comparison to experiments though in most cases, replicated trends well. This demonstrated the need for future research into the impact of material properties on modelled results, into how to implement changing material properties with temperature, such as density, into how to account for the char layer which forms and insulates the sample , and into properly accounting for moisture evaporation within the software, areas currently being investigated by the authorship team.

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Statement of Authorship

All persons who have met authorship criteria in this manuscript are listed as authors. These authors certify that they have participated sufficiently in the work to take public responsibility for this manuscript's content, including the participation in the concept, design, analysis, writing and revision of this manuscript. Those that do not meet these criteria are listed in the acknowledgements.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Further Information

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