A Holistic Approach to Mass Timber Design

Ethan Philion

A thesis submitted to the Faculty of Graduate Studies in partial fulfillment of the requirements for the degree of Master of Applied Science

Graduate Program in Civil Engineering

York University

Toronto, Ontario

August 2023

Abstract

As a new material, there is a significant lack of knowledge of the performance of mass timber, especially in fire. This research investigated the current understanding of modern mass timber, the performance of heritage mass timber, and the state of diversity of the industry itself. Findings include heritage hardwoods typically charred at a higher rate than the heritage softwoods but the species converged at a rate of 1.05 mm/min when exposed to 50 kW/m^2. Gender distributions of the survey (16% women, 81.7% men) mirrored industry statistics. It was also found that 71.4% of the women were ages 44 and under compared to 39.1% for men. The findings of this thesis can be used to further the design of mass timber structures and direct where future research for mass timber is needed most.

Acknowledgements

First, I would like to thank my supervisor Dr. John Gales for his support and guidance throughout this degree and the beginning of my career in fire safety. Without him, I may have not found a career path I can say I have passion for.

I would also like to thank the members of my team who have helped me over the past few years. Thank you to Chloe, Tim, Anne, Hannah, and Katie. I also want to thank Riad Rajab and Sindy Mahal for their support during my degree. Thank you to Beth Weckman and her team at Waterloo for access and training to their testing space and equipment.

I would like to thank Panos Kotsovinos for his aid and mentorship in my research. I would like to thank Arup, the Canadian Wood Council, and NSERC for their support of the research projects I undertook. Thank you to Bronwyn, Chloe, and Katie for their support and guidance through my first publications.

I would also like to thank my family for their support and understanding of the career path I have chosen to follow. Finally, I would like to thank Emmalene for her support and encouragement throughout every challenge I've faced.

Declaration

The work presented within this thesis has been adapted from work which has been published, submitted to a journal, or has been presented at a conference. This thesis is written as a modified manuscript where each chapter is based on and adapted from one of the research articles. The thesis author was the primary author of each of these research articles, which were all written during the author's studies for this master's program. First authorship is defined as the author who participated sufficiently to take ownership of the article. Below outlines what research article each chapter is adapted from:

Chapter 2 is adapted from the following journal paper:

- **Philion, E.**, Chorlton, B., Gales, J, and Kotsovinos, P. (2022) Fire Modelling Strategies for Exposed Mass Timber Compartments and Experimental Gaps for Model Validation. Journal of Performance of Constructed Facilities (ASCE), 36(6), DOI: 10.1061/(ASCE)CF.1943-5509.0001761.

Chapter 3 is adapted from the following conference paper:

- **Philion, E.**, Chin, K., Chorlton, B., Kotsovinos, P., and Gales, J. (2023) Fire Performance of Heritage Hardwood: Conservation and Adaption of Existing Timber Structures. CSCE Annual Conference (2023). Moncton.

Chapter 4 is adapted from the following submitted journal paper:

- **Philion, E.**, Jeanneret, C., and Gales, J (2022) A Link Between Canadian Timber Professional Engineering and Gender-based Equity, Diversity, and Inclusion. Canadian Journal of Civil Engineering (cjce-2022-0419).

Table of Contents

Abstract ii

Acknowledgements iii

Declaration iv

Table of Contents v

List of Tables viii

List of Figures ix

Chapter 1 : Introduction 1

1.1 General 1

1.2 Motivation 3

1.3 Scope of Thesis 6

1.4 Research Objectives 8

1.5 Outline of Thesis 8

Chapter 2 : Current State of Fire Modelling of Timber 11

2.1 General 11

2.2 Current Methodologies of Timber Design 14

2.2.1 Compartment Fire Dynamics 14

2.2.2 Performance of Timber in Elevated Temperatures 17

2.3 Current State of Timber Modelling 21

2.4 Summary 31

Chapter 3 : Fire Performance of Heritage Hardwood and Softwood 33

3.1 General 33

3.2 Review of Design on Heritage Structures 34

3.2.1 Best Practices for Heritage Design 34

3.2.2 Performance in Fire of Heritage Mass Timber 38

3.3 Experimental Fire Performance of Heritage Timber 42

3.3.1 Experimental Results 46

3.3.2 Model Results 53

3.4 Conclusion 54

Chapter 4 : Gender Diversity within the Field of Timber Professional Engineering 56

4.1 Introduction 56

4.2 Background 58

4.3 Methodology 64

4.4 Survey Results and Discussion 68

4.4.1 Gender Non-Specific Results 68

4.4.1.1 Demographic of Respondents 68

4.4.1.2 Experience and Education of Respondents 70

4.4.2 Gender-Specific 75

4.5 Future Research and Limitations 77

4.6 Recommendations and Conclusions 79

Chapter 5 : Conclusions and Recommendations 82

5.1 Summary 82

5.2 Limitations 84

5.3 Conclusions 84

5.4 Design Recommendations 86

5.5 Research Recommendations 87

References 90

Appendix A: Structural Fire Modelling Strategies for Exposed Mass Timber Compartments and Experimental Gaps for Model Validation 97

Appendix B: Informed Consent and Survey used in Chapter 4 128

Appendix C: Certificate of Human Participants Review Sub-Committee Approval of Research Project 135

List of Tables

Table 2.1: Literature Review Summary... 30

List of Figures

Figure 1.1: Image of CLT panels for demonstration purposes (Author's photo)........................... 1
Figure 1.2: CWC Field Test performed in Ottawa (Courtesy of the Canadian Wood Council [11]) 5
Figure 2.1: Drawing of a charred timber member illustrating the char depth, residual cross-section, and zone where timber strength may have been affected 12
Figure 2.2: Different design fire examples including (Left) the standard fire, two-sample parametric fires and (Right) a sample travelling fire as it progresses through a fixed dimensioned compartment of 20 x 20m (Adapted from Gales et al. [40]) 16
Figure 2.3: Plot of specific heat based on temperature based on values published by Eurocode 5 [47].. 19
Figure 3.1: A federal (top) and municipal (bottom) plaque recognizing the heritage of Port Stanley, Ontario (Author's photos).. 37
Figure 3.2: A heritage timber column with a check along the centerline (Courtesy of John Gales) 40
Figure 3.3: Cone calorimeter device with specimen circled in red (left) and zoomed-in image of specimen ignited during a test (right) (Author's photos)... 43
Figure 3.4: Samples of heritage timber before being prepared for the cone calorimeter (Courtesy of John Gales) 44
Figure 3.5: A hardwood sample after being tested (Author's photo) 46
Figure 3.6: A hardwood (left) and softwood (right) sample exposed to 50 kW/m^2 for 30 minutes each (Author's photos).. 47
Figure 3.7: Average charring rate of wood samples at 30 kW/m^2.. 48
Figure 3.8: Average charring rate of wood samples at 50 kW/m^2.. 48
Figure 3.9: Char depth of samples exposed to 30 kW/m^2... 49
Figure 3.10: Char depth of samples exposed to 50 kW/m^2... 50
Figure 3.11: Heat Release Rates for Samples Exposed for 30 Minutes 51
Figure 3.12: Oxygen concentrations in exhaust for samples exposed to 30 minutes 52
Figure 3.13: Carbon dioxide concentrations in exhaust for samples exposed for 30 minutes...... 52
Figure 3.14: Carbon monoxide concentrations in exhaust for samples exposed for 30 minutes.. 53

Figure 3.15: Experimental vs model results of hardwood char rate 54
Figure 4.1: Selected Mass Timber building in the Greater Toronto Area (Courtesy of John Gales) 57
Figure 4.2: Survey Recruitment.. 67
Figure 4.3: Population Identification of Respondents 69
Figure 4.4: Age of Respondents.. 70
Figure 4.5: Timber Educational Experience of Respondents 71
Figure 4.6: Source of Experiential Motivation to pursue Timber-based design........................... 72
Figure 4.7: Type of Experience of Respondents... 72
Figure 4.8: Personal Motivation to undertake Timber by Respondents 73
Figure 4.9: Highest level of education of participants.. 76

Chapter 1: Introduction

1.1 General

There is a current demand for sustainable construction worldwide. This is a response to the ongoing push to reduce the rate at which climate change is occurring, in which the construction industry has the potential to make a significant impact. Currently, the construction industry contributes approximately 13% of total carbon emissions [1]. Note that these emissions are for the embodied portion of a structure (materials and construction) and not the building operations. One way to combat this is to use low-carbon materials such as timber. Due to its ability to sequester carbon [2], when responsibly managed timber has the potential to create net negative carbon structures. Timber construction has additional benefits such as rapids rates of construction and biophilia. With the push to use timber as a structural material, engineered products such as glue-laminated timber (glulam) and cross-laminated timber (CLT) have been designed to allow for large timber buildings. Figure 1.1 displays how CLT uses dimensional lumber to make timber slab elements.

Figure 1.1: Image of CLT panels for demonstration purposes (Author's photo)

While there are several benefits to the use of timber, one notable limitation is that it is a combustible material. Conventional construction typically makes use of non-combustible materials such as steel or concrete. While these materials are not impervious to any deficiencies in a fire, there are significant concerns which need to be addressed when the main structural material may weaken in a fire while simultaneously acting as a fuel and adding to the intensity of the fire and allowing for the fire to spread.

An additional difficulty in validating the fire safety of timber elements in a structure is that current methodologies for testing were developed when structures were made of non-combustible materials. As wood contributes to a fire it will not produce comparable results from a standardized test as to contemporary materials such as steel or concrete. Therefore, to be able to interpret data about the fire performance of timber and safely implement timber in a structure requires a high level of competency.

It should also be noted that there are limited resources to aid in the fire design of mass timber. Within Canada, Annex B of the standard of wood design CSA O86 [3] provides limited prescriptive methodologies which only address the strength of a timber member exposed to a fire. Annex B does not provide any guidance to account for the impact timber has on the fire dynamics. Those not versed in fire safety design would consult the current published practices and may only consider the impacts on the mechanical strength of members in a fire. As conventional materials are non-combustible there is little experience in the field of considering the impact of a combustible structural material, unless specialized in the field of fire safety.

Further complementing the design of fire safety for timber structures is that historic Canadian structures often made use of mass timber. Work on historic structures often has additional restrictions to be considered. These restrictions are often put in place to preserve character-defining elements (elements of a structure which demonstrate the heritage value) [4]. Therefore, solutions such as the encapsulation of wood in heritage structures are typically against best practices for historic structures as the heritage structural material would be considered a character-defining element. Therefore, a thorough understanding of the fire performance of timber is necessary for historic structures.

There are several criteria to consider what competent design is for structural mass timber engineering. These criteria include understanding the structural mechanics of mass timber, its structural performance when exposed to a fire, the impacts on the fire dynamics of a structure when using a combustible structural material, and an understanding of best practices for heritage structures. These are several specialized fields (structural design, fire safety, and conservation) overlapping. Currently, undergraduate levels of undergraduate engineering programs include little learning for fire safety. Fire safety and conservation typically require further post-graduate studies or experience in the field to become competent. Without systems in place to guide people to these skills it is unlikely for one to navigate all these specializations on their own. As practitioners attempt to become versed in these specializations, they need an industry backing them and providing support. If the industry does not have a strong social net, practitioners will not be able to become competent enough to perform mass timber design.

1.2 Motivation

The motivation of this thesis is to better understand the design of structural mass timber in a fire. Currently, there is a large desire for mass timber structures due to its health and sustainable benefits. The desire for mass timber can be observed through databases such as *"The State of Mass Timber in Canada"* [5] where there has been a 117% increase in total completed timber structures in Canada from 2015 to 2021. However, to meet this demand there needs to be competent engineers with the required knowledge to design for fire safety with the use of a combustible structural material.

There have been several studies addressing compartments utilizing exposed mass timber. One example is the CodeRed field-scale[1] test series which utilized a 352 m^2 sized compartment which was designed to be comparable to a similar test series of non-combustible construction [7]–[9]. A second series of field-scale tests, performed by the Canadian Wood Council (CWC) in Ottawa, consisted of a 2-storey structure (see Figure 1.2 for an exterior view of an experiment setup) which utilized both exposed and encapsulated timber [10], [11]. There have also been small-scale tests used to understand the performance of how mass timber elements perform in a fire without great variability in the fire dynamics during testing [12]–[14]. From research, several prescriptive methods have been developed. There is the residual cross-section method in CSA O86 [3], which provides a quick method to determine the residual strength of a timber member after a fire. New provisions such as the *Encapsulated Mass Timber Construction* was developed and released in Canada which prescribes methods to determine how much wood on different surfaces in a compartment need to be encapsulated. An example of these provisions can be found in an amendment to the Ontario Building Code, O. Reg 451/22 [15]. However, there is still a lack of knowledge to allow for alternative solutions to these provisions.

[1] Scale is defined in in this thesis as material (for basic properties), assembly (for connections and frames), standard (for fire resistance requirements) and field (for larger constructions that do not meet the above classifications). It is noted that the fire engineering community has not defined what scale means through consensus and this is a community consensus need in the field. The reader is encouraged to consult the works of Buchanan [6] regarding Consistent Crudeness discussion in testing.

While it is motivating to see the research being performed to address current demands, conventional mass timber is only one field of timber engineering. In Canada, there are many historic structures which use mass timber as a structural material [16]. Solutions such as encapsulation should not be used as they would affect the character-defining elements of the structure, a thorough understanding of the performance of heritage timber is required by practicing engineers. Furthermore, heritage timber was milled differently and followed different construction practices [17]. However, research is being performed to analyze the effects of historical construction on the fire dynamics of a structure [18]. Furthermore, heritage timber has been aged and weathered resulting in timber members being physically different than modern timber [19]. Although there is an extra level of knowledge required for fire safety design of historic timber there is a lack of research being performed.

Figure 1.2: CWC Field Test performed in Ottawa (Courtesy of the Canadian Wood Council [11])

Finally, it needs to be addressed that there needs to be an industry ready to support the engineers who will perform this work. Part of this is to make people feel that they belong in the industry. It is a known fact that STEM fields, including engineering, are poor in terms of equity, diversity, and inclusion (EDI). Some initiatives and groups actively work to address these issues, albeit typically focused on gender discrepancy. One example is the Engineers Canada 30 by 30 initiative which seeks to increase the percentage of newly licensed engineers who identify as females to 30% by 2030 [20]. Another initiative is Engendering in STEM. Engendering in STEM is a collaboration of several universities and STEM-based associations and companies which seek to reduce barriers faced by girls and women from childhood through to university and early career [21]. However, these initiatives tend to address the whole field of engineering as a whole. There is a lack of studies on a smaller scale such as in specific fields like professional engineering. Studies of this scope can allow industries to develop EDI policies to promote a sense of belonging.

1.3 Scope of Thesis

As noted above, designing mass timber requires fire safety considerations due to the combustibility of the material. There are several aspects to considering the fire safety of mass timber. While researchers have been researching the fields of mass timber described above, there are still fundamental gaps in knowledge and understanding of mass timber. The current state of research is only beginning to study the dynamics of exposed mass timber in large compartments [7]–[10]. Additionally, there is not a large focus of research on heritage mass timber even though a strong understanding of its performance in fire is needed as modern solutions such as encapsulation likely cannot be implemented [4]. Due to the combustible nature of wood, a competent engineer should be able to consider the fire implications of using mass timber and needs the industry to support them in this. The scope of this thesis is to improve the understanding and design of mass timber in fire as a whole. There are two general themes to the thesis to achieve this. These themes are:

1) The behaviour and performance of both contemporary and heritage mass timber in a fire; and

2) Identify areas of improvement needed to address EDI problems within the field of timber professional engineering.

To address Theme 1 both a literature review and a series of small-scale experiments were performed. The literature review examined the current state of knowledge for modelling contemporary timber in a fire to determine if there is enough understanding of the fundamentals. The experiments investigate the performance of heritage timber in fire by exposing heritage timber to high heat exposures. To maintain consistent heat exposure for the timber samples, a cone calorimeter will be used for small-scale tests. Tests will be performed to examine the charring rate of the specimens which is a common metric used in evaluating the residual strength of timber in practice.

To examine Theme 2, a survey was distributed to Canadian practitioners in the field of timber professional engineering. The survey asked participants about their status of engineer license, the highest level of education achieved, previous education in timber, their personal and experiential motivators for working in the industry, and their intent to remain in the industry. The data from this study illustrates where support is required in the industry to allow practitioners to become competent timber engineers.

Finally, it should be noted that true holistic structural design should also include considerations for other considerations such as seismic and wind loading. However, the scope of this thesis will primarily focus on the fire safety of timber structures and the state of the industry. From examining the themes listed above, the point that timber design requires competency in several fields is required will still be made. This is what the “holistic design” the thesis refers to.

1.4 Research Objectives

From the studies performed as per the scope of the thesis, there are several key findings which were intended to be understood. These findings would promote timber design by identifying knowledge gaps for the performance of timber in fire, providing a deeper understanding of heritage timber in fire, and addressing the social needs of the field.

The outcomes in which this research sought to find are as follows:

- Study current methodologies for modelling the fire performance of structural mass timber;
- Examine and evaluate the difference in the fire performance of heritage softwood and hardwood;
- Understand the diversity landscape of the field of professional timber engineering and identify where future studies will have the most impact;
- Summarize where the current state of timber engineering is and summarize the evidence of where further work is needed to ensure competent timber design.

1.5 Outline of Thesis

The thesis takes the form of a modified manuscript style. It has been adapted by the author using text which has been published in conference proceedings and peer-reviewed journals. The text has been altered to fit within the context of this thesis. The first drafts and review edits of these papers were primarily performed by the author of this thesis during their master’s degree. Below is an outline of each chapter within the thesis:

Chapter 2: Current State of Fire Modeling of Timber reviews the state-of-the-art knowledge for fire safety design in timber structures. The chapter contains a discussion of current practices for assessing the performance of mass timber in a fire scenario as well as the impact of exposed timber on the dynamics of a compartment fire. Accepted practices in codes and standards are compared to current studies being undertaken by researchers. This chapter intends to provide a general understanding of currently accepted practices for addressing fire safety when designing with mass timber as well as illustrate the need for competency in the field for experts to address these needs. Additionally, it will be examined how this knowledge has been transferred to use in fire modelling of timber to determine if there are enough fundamentals of timber in a fire that are understood. From this study, several key research gaps were identified to address the use of combustible structural materials in modern design.

Chapter 3: Fire Performance of Heritage Hardwood and Softwood compares the charring of heritage hardwood and softwood samples. While it is important for studies to be performed to understand modern timber construction, many heritage structures in Canada are also constructed with mass timber. This is important to note, as studies performed on modern timber may not be directly applicable to heritage timber. Modern mass timber construction in Canada uses softwoods, however, heritage structures used both softwoods and hardwoods. This is significant as hardwoods and softwoods have generalized different material properties. Material properties such as density will affect the thermal performance of the wood samples. Experimental data is needed to understand the difference in thermal performance of the two classifications. A series of cone calorimeter experiments were performed to compare the charring of heritage hardwoods and softwoods when exposed to high heat exposures. Additional challenges and requirements of studying heritage structures are also discussed in this chapter.

Chapter 4: Gender Diversity within the Field of Timber Professional Engineering focuses on the state of the industry itself. EDI is a known issue within STEM and engineering itself. Chapter 4 consists of a study performed on the field of timber professional engineering to understand its current diversity landscape. The study consisted of a survey distributed to Canadian practitioners who have worked with timber. The survey consisted of questions related to the intersectional identity (age, gender, and race) of current professional engineers in the wood industry in Canada. Additionally, the survey will ask participants about their status of engineer license, the highest level of education achieved, previous education in timber, their personal and experiential motivators for working in the industry, and their intent to remain in the industry. The results of this study identified current deficiencies within the field and produced recommendations for where to target future studies.

Chapter 5: Conclusions and Recommendations summarizes the key findings and novelty of the previous chapters. This chapter also outlines any recommendations for practitioners in the field of timber professional engineering based on the findings. Finally, the chapter recommends areas of future studies which can have the greatest impact on the field of timber professional engineering.

Chapter 2: Current State of Fire Modelling of Timber

2.1 General

The purpose of this chapter is to serve two purposes. The first is to provide an understanding of the current understanding of structural fires and the considerations regarding the use of a combustible structural material. This is to provide the required background information for this thesis. The second purpose is to outline the current state of modelling timber in fire. This review will be used to determine current research gaps in the fire modelling of timber.

While timber itself is not a new structural material, mass timber structural systems are being used in increasingly taller and more complex building designs [22]. Building with timber has several advantages, such as its biophilia effects [23], environmental benefits [24], as well as architectural appeal. These contemporary designs are often concentrated on either the residential (small compartments) or commercial (large open-plan spaces) sectors. In large open compartments, it has been observed in non-combustible structures that non-simultaneous fire propagation across the floorplate is possible which is in disagreement with traditional approaches to fire dynamics for small enclosures [25]. Timber is a combustible material, and the presence of exposed timber will add a fuel source and allow flame spread through the compartment further complicating fire dynamics in exposed timber compartments. Therefore, it is important to have suitable design methods for exposed mass timber compartments.

A prescriptive approach to ensure safety in design is to completely encapsulate all mass timber members. However, often there is a desire in design for the timber to be left exposed. In some cases, the timber can be overdesigned using the Reduced Cross-Section Method. This method accounts for the reduction of the cross-section of a timber member due to charring based on the time exposed to fire. The method assumes that the charred region (plus an additional allowance) will lose all strength while the remaining portion of the cross-section retains its full strength [3]. Figure 2.1, illustrates this method. It should be noted, however, that the reduced cross-section method only accounts for the lower capacity of a timber member after being exposed to a fire. This method does not address elements such as the fire dynamics of having an exposed, combustible surface in a compartment. Therefore, additional criteria, other than only the remaining capacity, should be examined to determine if the timber member should be exposed.

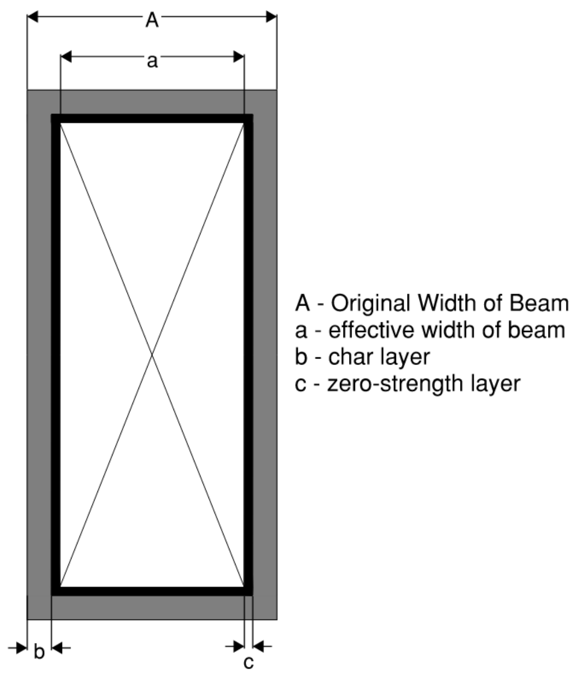


Figure 2.1: Drawing of a charred timber member illustrating the char depth, residual cross-section, and zone where timber strength may have been affected

Encapsulation of a timber member with a fire-rated material typically takes the form of a Type X gypsum [3]. Adequate fire testing and correct implementation on-site are necessary to avoid premature failure of the material [26]. In the event of encapsulation failure, the combustible structure would become exposed to the fire which can impact the stability of the building. Building designs that have both encapsulated and exposed timber structures in the same compartment would need to consider the impact of the exposed timber on fire dynamics and the fire resistance requirements of both the structure and the encapsulation.

Additionally, current design proposals consider high-rise mass timber buildings. Questions have been posed by researchers and designers that current building and fire codes may not be designed with such structures in their scope [27]. Several of these tall timber buildings are designed to be a hybrid of several structural materials, using each material to its advantage. For example, Brock Commons is an 18-storey timber-concrete hybrid structure. The timber components make up the floor slab and columns, whereas the concrete is used to construct the core of the structure [28]. Other hybrid designs such as a CLT slab with steel beams are also being used due to the environmental and speed of construction advantages [29].

For the design of buildings which may not fall within the parameters of current prescriptive methods, alternative solutions are required. A typical approach that, when properly validated, can be used to analyze an alternative solution is numerical modelling and more specifically finite element modelling. Finite element modelling can allow practitioners to analyze proposed alternative solutions for designs that include irregular geometries and unusual boundary conditions. Furthermore, after a model has been validated against experimental data, the model can be used to analyze the effects of minor changes to determine what criteria govern the design. Once the behaviour and governing criteria of the systems and materials are better understood, generalized solutions can be developed for these complex designs. Numerical modelling can also be used to guide the development of an experimental program.

As engineered timber is being used with newer design constraints, such as leaving it exposed, additional knowledge about the performance and behaviour of timber in these designs is required to ensure safety in the event of a fire. As these applications of timber are new, there have not yet been many research programs to address the performance of timber. While the use of a validated model can be a method of addressing these knowledge gaps, due to the lack of research programs there are not many data sets to validate the model against. Therefore, these knowledge gaps must be addressed through experimental study, at least until models will be able to be validated with confidence. The results of this review will highlight current gaps in the knowledge base which are preventing more accurate models from being validated so that can be extensively used by practitioners as another tool to analyze the performance of an alternative solution when prescriptive routes are not desirable.

2.2 Current Methodologies of Timber Design

Regarding modelling timber in fire, two knowledge areas need to be understood that are interlinked due to the combustible nature of the timber. The first is compartment fire dynamics and the thermal exposure to the structure. Secondly, the thermal and mechanical response of the structure.

2.2.1 Compartment Fire Dynamics

As opposed to other contemporary structural materials, timber is combustible. Therefore, when timber is exposed to a fire, it will contribute fuel to its own burning as well as allow the flames to propagate and overall increase the severity of a fire [30]–[32].

For a conventional compartment fire, there are three main phases the fire can experience, the growth phase, the fully developed phase, and the decay phase. Many fires begin with a growth phase (although some growth fires feature prolonged smouldering). During the growth phase, the fire begins to spread throughout a compartment. If the flames are not extinguished (by means of either suppression or auto-extinction due to lack of sustained burning), the fire may reach flashover. A definition of flashover describes it as being the point when all temperatures within the compartment achieve at least 600 ^{o}C, or the radiation to the floor of the compartment reaches 15 – 20 kW/m^2 [33]. Regarding the auto-extinction of a fire involving timber, researchers have several opinions on the exact definition. This is because timber will continue to combust, in the form of smouldering, after the end of flaming. Smouldering is a phenomenon that can occur post-burnout of a compartment and is a flameless form of combustion [34], [35]. Due to the presence of multiple forms of combustion, some researchers consider auto-extinction to mean when the flames have been extinguished [36], [37], whereas others consider it to be the termination of any combustion process including smouldering [38]. Wiesner et al. [39] have noted that once in the decay phase of a conventional compartment fire, exposed timber members will continue to deteriorate due to a "… continued propagation of a thermal wave beneath the char layer [39]." Furthermore, Wiesner et al. [39] recommend that designs for tall timber buildings should consider the decay phase of fire when sizing members, even though local prescriptive design methods may not explicitly state to do so.

For a typical compartment when flashover is reached, the fire will have moved into the fully developed phase in which the highest temperatures will be met. Afterwards, the fire will enter the decay phase in which the temperatures and energy release rates will decrease [33]. Although this method alongside a standardized time-temperature curve has been commonplace, designers have recently been utilizing newer, time-temperature curves to better capture the behaviour of fires being observed in compartments which the standard time-temperature heating curve was not necessarily intended to represent [40].

The use of alternative time-temperature curves acknowledges that the standard curve does not represent real fire. Particularly, the standard time-temperature curve does not account for the lowering temperatures of the decay phase of a fire. This impacts contemporary building designs, which are incorporating large open spaces. It has been observed that in large compartments of steel and concrete structures, a fire behaves differently than what is proposed by conventional flashover fire dynamics and the standard time-temperature curve [41]. Rather than an instance where the entirety of the compartment is involved in the fire simultaneously, the fire will grow non-uniformly across the floor plate and/or stories [42]. For longer-duration fires, if a model uses uniform gas temperatures there could be significant errors in the thermal and structural analysis [42].

Figure 2.2 illustrates an arbitrary comparison of the standard time-temperature curve, calculated parametric curves, and travelling fires. The parametric curves are meant to include the heating and cooling phases of different compartment fires. The travelling fire time-temperature curves are meant to represent a localized fire travelling through a compartment. In this scenario, different locations in a compartment will be heating and cooling at different times during the fire.

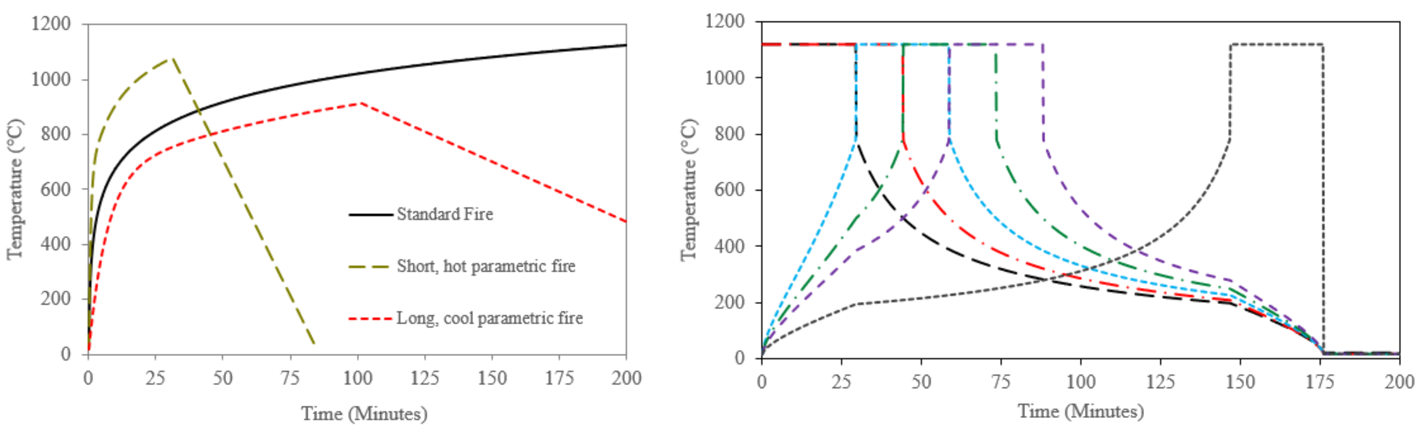


Figure 2.2: Different design fire examples including (Left) the standard fire, two-sample parametric fires and (Right) a sample travelling fire as it progresses through a fixed dimensioned compartment of 20 x 20m (Adapted from Gales et al. [40])

While research is currently being conducted on non-uniform fires in large compartments, very little has focused on the use of combustible materials. The use of exposed timber in large compartments creates several complications in a design. As outlined in Rackauskaite et al. [25] these challenges involve a lack of data for combustible materials, like timber, including fire sizes, fuel load, heat release rate, far-field thermal exposure and near-field heat flux. In the context of this study, near-field represents flames directly impinging on the ceiling from an external source, whereas far-field represents the cooler temperatures away from the direct impingement. However, recent studies have been performed to begin to fill in these knowledge gaps such as the CodeRed test series [7]–[9] and a large ‘field-scale’ timber compartment test performed in Ottawa, Canada [43].

Convection effects in compartment fires are associated with the transfer of heat by the motion of a fluid, which often arises naturally, or is forced when external factors are present, and is the primary mode of heat transfer in the early stages of a fire. The heat transfer convection heat transfer coefficient is related to the heat flux and the difference in temperature between a solid and the surrounding fluid. Most of the available literature regarding timber fire modelling has considered a convection coefficient of 25 W/m^2K, aligning with the standard temperature-time curves which are being modelled. Eurocode 1 Part 1-2 recommends a convection heat transfer coefficient of 25-50 W/m^2K depending on the temperature-time curve considered [44].

Additionally, another approach used in fire design is compartmentation, which is to contain a fire in its room of origin. This approach intends to ensure the fire will decay even if not suppressed. This will allow for safe egress, firefighting access, and resilience to the structure. However, due to smouldering induced by the combustible nature of timber, during what would be the traditional decay phase of a compartment fire, the structure may continue to lose strength.

2.2.2 Performance of Timber in Elevated Temperatures

When designing timber structures, additional considerations are required to account for timber’s combustible nature. Currently, there are a limited number of prescriptive methods to design of timber in elevated temperatures. These methods such as calculating a char depth [3] have the potential to be overly or under-conservative, depending on the impact of timber on fire dynamics. Within the method of calculating a char depth, typically an additional layer referred to as a zero-strength layer is added to the char depth to account for the possible reduction in strength of the cross-section which may have been exposed to high temperatures [3]. While the zero-strength layer does acknowledge that timber will lose strength before reaching 300^{o}C and charring, it does not account for the fact during cooling, heat will penetrate further into the cross-section and potentially reduce the strength of the entire cross-section [45]. Until further research is performed to deepen the understanding of the performance of timber, current prescriptive design methods may not be adequate to account for these uncertainties for exposed timber structures, particularly large compartments where a long decay period is likely.

Often prescriptive methods limit or restrict the design of complex structures. Therefore, designers in these cases need to develop alternative/performance-based designs in which they can demonstrate that these complex structures meet the functional requirements of building regulations. To facilitate performance-based design for timber enclosures, a thorough understanding of the behaviour and performance of timber at elevated temperatures is required.

One important characteristic of timber is that it retains moisture [46]. Once temperatures of a timber member reach 100^{o}C the moisture will begin to evaporate which consumes thermal energy and delays the heating of the timber. Difficulties arise to account for this as once the timber member heats up some of the moisture will migrate making it difficult to identify the amount of moisture evaporation occurring in a given moment. One approach is to increase the specific heat of timber within the range of 99^{o}C to 120^{o}C as described in Eurocode 5 [47]. Figure 2.3 provides a plot of the specific heat values based on temperature for wood based on Eurocode 5. The increase in specific heat accounts for a greater amount of energy required to increase the temperature of the timber member. After 120^{o}C it is assumed that all moisture has evaporated and the artificial increase in specific heat is taken away. Alternatively, designers can follow a latent heat/enthalpy approach [46]. For this, a user-defined moisture content is modelled as latent heat. This allows for a model of the timber element to non-explicitly account for moisture within a member and does not require a peak in specific heat values. Some commercial software can automatically follow this latent heat method while most other packages can have this method implemented.

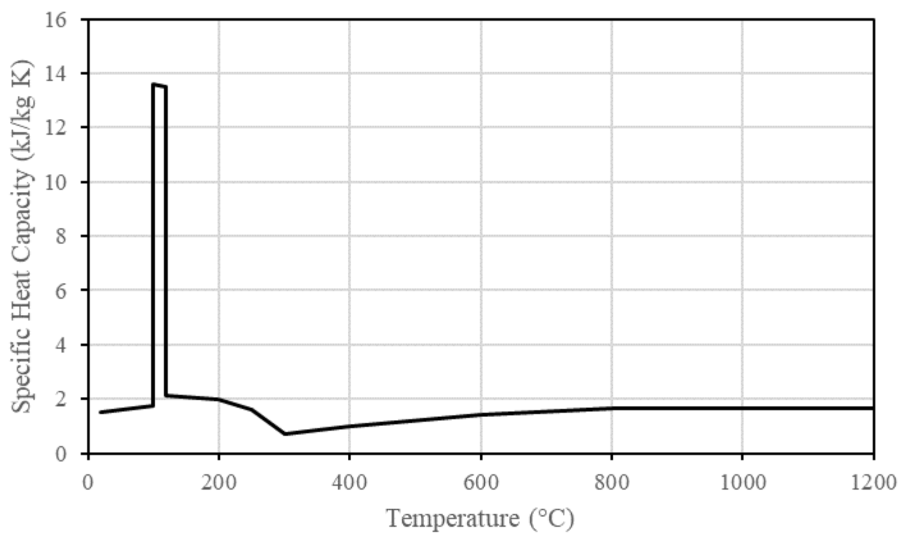


Figure 2.3: Plot of specific heat based on temperature based on values published by Eurocode 5 [47]

Due to the smouldering of timber, additional design considerations are required. Design procedures do not typically account for the performance of timber while it smoulders during the decay phase. When timber burns, it creates its own heat, which in turn has the potential to heat material found deeper in the member. This in turn can cause more material to be included in the combustion process even after flaming combustion has been extinguished. Therefore, timber can continue to combust and potentially fail long after a fire has been considered extinguished in a compartment [45]. While smouldering, the effective cross-section will continue to decrease as the material degrades during combustion until it finally has an assumed zero strength when charred. Additionally, during or after a fire, sections of char can fall off or delaminate from the timber member. Without this protective layer, portions of the cross-section which may have previously not been involved in the fire may now combust due to either a continuing fire or smouldering depending on the current state of the compartment fire [48], [49]. Current prescriptive methods, such as the Reduced Cross-Section Approach from Annex B of the CSA O-86 [3], do not explicitly consider the decay phase of a fire. It has been shown that timber members can fail post-burnout due to the continued combustion via smouldering [45].

Designers have utilized various fire safety strategies which either reduce the risk of a fire growing to the point where it poses a threat to the structure or prevent timber and other combustible materials from becoming involved in the fire. A common approach is to use a fire-rated Type X gypsum to encapsulate any combustible surface [26]. While these methods can prevent the underlying material from becoming involved in a fire, the encapsulation could still fail in a fire if its performance is not adequately tested, or if it is not implemented properly during construction [50]. The drawbacks of encapsulation are its larger environmental footprints due to the use of redundant layers of protection, covering the timber, as well as increasing the time of construction. These drawbacks are opposing the benefits of timber which are its environmental strength, the desire for exposed timber, and its rapid rate of construction. By having a deeper understanding of timber's behaviour and performance in fire, solutions can be developed which allow for complete or partial exposure of the timber surfaces.

2.3 Current State of Timber Modelling

The use of numerical models to assess the performance of timber in fire is a topic of current interest and several studies have been performed to validate this ability of current software packages. Werther et al. [46] found that finite element software such as ANSYS, SAFIR, and ABAQUS are capable of modelling timber, however, some accounted for the moisture content of wood more intuitively than others. Where some software could automatically account for moisture as a latent heat, others would have to be manually set to account for moisture in this method. Otherwise, when accounting for moisture with a discontinuity in the specific heat of wood as prescribed by Eurocode 5 it was found that smaller timesteps (greater computational time) were required to avoid divergence [46]. While accounting for latent heat may produce a less conservative design, it may be more representative of the actual performance of the timber assuming the moisture content used is realistic. From a designer's perspective, accounting for latent heat can lead to more efficient use of the material as there will not be a need to overdesign to account for the unknown heat flowing through the members. From a modeller's viewpoint, accounting for latent heat can reduce discrepancies from the model results to experimental data (i.e., model producing overly conservative results.

The capabilities of modelling the rate of pyrolysis and charring when a timber member is exposed to high temperatures have also been researched. Thi et al. [51] utilized a user-defined subroutine, UMATHT, in ABAQUS to model heat transfer through structural timber members. The model developed by the researchers was capable of identifying the locations of the char layer, pyrolyzed wood, dried wood, and wood at ambient temperatures [51]. Geometric configurations included a small assembly-scale laminated veneer lumber (LVL) sample and a large assembly-scale cross-laminated timber (CLT) beam.

Xing et al. [52] developed a model to determine the char depth and zero strength layer of a CLT panel for both when the char layer remains intact and when there is char fall off under the ISO 834 standard fire [53] or natural fire. The natural fire is based on previous experimental data collected by [54]. Xing et al. [52] found that in most cases the results of the model were in good agreement with the charring rates stated from Eurocode 5 [47]. Overall, the model was considered to adequately capture the performance of the CLT panels.

Quiquero et al. [55] used ABAQUS to develop a finite element model of post-tensioned timber beams under both ambient and fire conditions. In terms of thermal analysis, the temperature gradients and char depths aligned with the results of other experimental studies. A main challenge encountered in the thermal modelling was to adequately capture the effects of moisture evaporation [55]. It was noted that discrepancies at the end of the trials may be due to the model not accounting for the continued combustion due to the smouldering of the timber member. Additionally, as the modelling used experimental data from other researchers' thermocouple placements could not be verified. If model elements were not properly aligned to the real thermocouple placements this could account for some of the uncertainty in model results.

Additional studies into complex timber members have been performed by Kleinhenz et al. [56]. This study investigated temperature-dependent thermal properties of "CLT rib panels". The rib panels are composed of glulam columns (the rib) which are evenly spaced out and sandwiched by two CLT panels. All elements were connected via screwed connections. The tests examined this member type in 4 different scenarios. One where the bottom CLT panel was not used, effectively making the system into a T-section. Then the box or ribbed panel was tested. Then each of the two scenarios were considered with the bottom surface being initially protected with gypsum board [56]. This model used the programming language Python to generate the finite element models and ran the thermal simulations using SAFIR. When accounting for heat transfer in the void cavities, air movement was not considered. When accounting for convection in the voids, the coefficient of convection was the same as what was used for other unexposed surfaces (i.e., 4 W/m^2K). Gypsum and char fall-off were both considered in these simulations. The time at which gypsum would fall off was based on experimental data and to account for it in the model, the elements labelled as gypsum would be removed. Char fall-off was determined to occur once the average temperature between CLT layers surpassed 300^{o}C [56]. Finally, it was observed that the screws did not conduct heat into the timber members and thus the influence of the screws was removed from the thermal simulations. When running the simulations with thermal properties from Eurocode 5 [47] it was found that the model greatly overestimated the char depth and fall off. The potential error was found to be up to 3 layers of CLT when compared to experimental results and analytical results based on procedures listed in Eurocode 5. The models were then rerun with revised values for the thermal conductivity from 400^{o}C to 800^{o}C as well as revising the values for specific heat capacity from 250^{o}C to 300^{o}C. The reasoning behind the revision of the values is to account for an endothermic reaction during pyrolysis as well as to increase the effective insulation of the char layer. The results of the simulations using the revised properties agreed with experimental and analytical solutions [56].

Work has also been performed to develop models capable of analyzing timber-concrete composites (TCC). Bedon et al. [57] tested the capabilities of analyzing a TCC beam-type slab with in-house finite-element software, COMP-WOOD. The slab system used for these tests was composed of glulam beams and a concrete deck. The concrete deck was connected to the glulam via screwed connections. The model was used to analyze both the thermal and mechanical performance of the TCC beam. Bedon et al. [57] found that using the thermal properties of timber and concrete provided by EN 1995-1-2 [47] and EN 1992-1-2 [58] were able to provide results in agreement with experimental data. The in-house software was then compared against commercial software to compare the capabilities of the software. ANSYS, SAFIR, and ABAQUS were used for these comparisons. It was observed that the commercial software was not as capable as COMP-WOOD in producing specific results such as the slip-force curve at the material interface [57]. This is attributed to the commercial software being intended for broad use, whereas COMP-WOOD was intended to be used for composited timber systems [57].

Researchers have also used numerical modelling to simulate heat transfer through complex geometries such as timber jack ceilings (vaulted masonry ceilings supported by timber beams) [18]. Garcia-Castillo et al. [18] used Safir to model the heat transfer through the timber joists of a timber jack ceiling using three different heat exposures. Heat exposures used were the ISO 834 fire curve [53], parametric fire curves, and the two-zones model (performed with the software OZone). The reason behind modelling scenarios with different heat exposures was to examine the variability in the charring of the timber joists during different cases for the decay phase of a fire. The ISO 834 fire curve never experiences a decay phase and is not representative of a real fire, whereas the parametric and two-zone models each consider different modes a decay phase of a fire can take. It was assumed that the standardized fire would be the most conservative approach due to the lack of a decay phase, however, it was found that the parametric and OZone fires produced more extreme charring depths [18]. However, Garcia-Castillo et al. [18] note that the model used values for material properties based on the Eurocode 5 Standard [47] which was developed from data using the ISO 834 fire [53]. Therefore, the heat transfer in the timber from the parametric and OZone scenarios may have not been accurately modelled.

In addition to modelling timber elements, there have been studies on modelling timber connections in a fire. Recently, Palma and Frangi [59] developed a model to evaluate the impact of geometry changes on the fire resistance of steel-to-timber dowelled connections. For this study, a finite element model was used to perform solely the heat transfer analysis portion [59]. Once the temperature gradient of the timber connection was determined from the analysis, a temperature-dependent Johansen [60] based load model was used to evaluate the strength of the connection. Palma and Frangi [59] noted that while it is common to not include heat transfer along the grain's direction for beams and columns, it will need to be considered for timber connections with steel components [59]. This is due to the steel components transferring heat into the timber member where it then transfers in all directions. To account for the anisotropy of timber, Palma and Frangi [59] multiplied the temperature conductivity curve found in EN 1995-1-2 [58] by a value of roughly 4 to adjust the curve to be for values parallel to the grain [59]. However, it was noted that further research is needed to determine a more suitable method of determining thermal conductivity parallel to the grain [59].

Other research performed on modelling timber connections in fire includes the study on the fire performance of self-tapping screws in glulam by Létourneau-Gagnon et al. [61]. When developing the 3D thermal model Létourneau-Gagnon et al. [61] referenced different sources as required to determine the material properties. Steel thermal properties were taken from EN1993-1-2 [62]. For the glulam member, the thermal properties followed the recommendations of König et al. [63]. The initial density and moisture content of the glulam was taken as 480 kg/m^3 and 12% respectively. Finally, the emissivity of 0.8 and coefficient of heat transfer by convection of 25 W/m^2K of the timber were taken from EN1991-1-2 [44]. When generating the geometry of the problem, only a quarter of the specimen was required to be modelled. Additional simplifications of the model followed the findings of Dagenais [64], in which only the shank is required to be modelled (without the threads). By neglecting the threads, the computational time is greatly decreased while preserving the accuracy of the model. Finally, based on the findings of Dagenais [64] and Werther et al. [46], the elements of the shank were modelled using 3 mm hexahedral elements. Through a validation study, it was found that the model could predict the temperature profile of the specimen when a constant heat flux of 50 kW/m^2 was applied for 10 to 15 minutes.

Z. Chen et al. [65] developed a constitutive model which was able to simulate the temperature gradient, deformation, and failure mode of an LVL beam and a glulam bolted connection which were loaded and subjected to elevated temperatures. This model accounts for the post-peak softening of timber in tension and shear, the plastic flow and hardening of timber in compression, as well as a second hardening in compression.

C. Chen et al. [66] developed a model to simulate the thermo-mechanical behaviour of timber in realistic fire scenarios through the use of an open-source framework, OpenSees. Unique considerations of this model include the considerations of layer-based heat transfer and realistic fires. Layer-based heat transfer allows the model to recognize the change of state the timber undergoes while heating up. This allows for material properties to change as wood loses moisture, undergoes pyrolysis, and becomes char. Considerations for realistic fire exposure include simulating a fire through the use of a Fire Dynamics Simulator (FDS). The realistic fire accounted for both the crib fire from the experiment the simulation is adapting as well as the burning of the timber itself [66]. The model was used to simulate a small compartment fire of a timber concrete composite flooring system which is based on the experiments of Hadden et al. [13] Through these considerations the model was able to capture the char propagation and change in material properties, through the timber member during the decay phase of the fire. This is significant to capture in a model as while the char front propagates, the timber section continues to weaken even though flaming combustion has halted. Overall, it was observed that the model can reproduce temperature histories and thermos-mechanical behaviour from validation studies and illustrated the potential for realistic fire modelling of timber. Discrepancies of the model to experimental results are assumed to be due to a lack of material data and model scope [66].

There has been limited research into modelling the smouldering of timber during the cool-down phase of a fire. Gernay [45] developed a numerical model within SAFIR to assess the response of timber columns that experience a standard fire as well as their response to the cooling phase. While the results of the model showed some agreement with experimental data, they also illustrated a delayed heating of timber elements once a compartment fire has entered the cooling phase [45]. The results indicate that this delayed heating in combination with smouldering can elevate the temperature of portions of the cross-section which if checked immediately after a test would appear to be untouched by heat [45]. This model produced by Gernay [45] is beginning to capture the performance of timber members in a fire that is not currently being evaluated with commonly used standardized tests. Once further validated, this knowledge can lead to better capabilities for predicting the failure of timber members.

In addition to the finite element and chemical kinetic models previously described, studies are being performed using a fundamental mechanics approach where material properties are determined through a probabilistic analysis. Wiesner et al. [67] analyzed the capacity of one-way CLT panels in standard and natural fires. To determine the Youngs modulus and Modulus of Rupture for a proposed CLT panel they determined 1000 different potential combinations of these values to account for the variability of timber as a structural material. Within this study, Wiesner et al. [67] used a base value of 24 MPa for the modulus of rupture and Young's modulus with an expected mean value of 11,000 MPa as recommended by CSN EN 338 [68]. To determine an acceptable range of values that can exist in a typical timber product, the Joint Committee on Structural Safety (JCSS) recommends applying a coefficient of variation of 0.25 for the modulus of rupture and 0.13 for Young's modulus [69]. A correlation factor between the Modulus of Rupture and Young's modulus of 0.8 was applied as recommended by the JCSS. Finally, it was assumed that the lamellae on the weak axis have a Young's modulus which is 1/30th of the lamellae on the strong axis as per *PRG 320 Standard for Performance-Rated Cross-Laminated Timber* [70]. In order to determine a neutral axis of the CLT panels during the fires, a Newton-Raphson iterative method was used [67]. The neutral axis was determined once axial equilibrium was met. Results of the capacity of the CLT panels using the semi-probabilistic approach were found to be more conservative when compared to a reduced cross-section method however this was expected by the authors [67].

Another probabilistic model was developed by Garcia-Castillo et al. [71]. This model intends to predict the temperature-dependent strength of timber in terms of both tension and compression. Additionally, the model considers both solid timber and engineered wood products. The probabilistic model uses probability density functions which were developed based on 25 studies with specimens ranging in size, moisture content, density, mode of heating, and loading [71]. Through the creation of this model, one key finding is the need for standardization in testing. It was found that there is a large variability in timber strengths at elevated temperatures. This is in part due to the impact that moisture, density, and size of specimens have on timber in fire. Until we have a more thorough understanding of this, unstandardized testing will produce variability in results which can not be accurately explained [71]. It was also found that the temperature-based function for timber strength proposed by the Eurocode [47] appears to be conservative. Garcia-

Castillo et al. [71] propose that the use of probabilistic models may promote the design of more efficient structures.

There have also been researchers who have approached the thermal modelling of timber with different methods other than finite element analysis. Examples of such attempts include modelling the chemical kinetics of timber combustion. Recent studies of kinetic modelling can be found in [72]–[74]. In addition to the finite element and chemical kinetic models previously described, studies have been performed using a fundamental mechanics approach such as by [67], in which they analyzed the capacity of one-way CLT panels in standard and natural fires.

Table 2.1 provides a brief summary of the literature discussed. As illustrated in Table 2.1, most studies discussed are not applying their models to natural fire exposures. Additionally, it can be seen that there is little done to account for the smouldering of timber within a timber model.

While there have been several research studies to investigate the capabilities of modelling timber, they typically follow conventional compartment fire dynamic theories. With the current demand to construct timber buildings with open-plan, well-ventilated spaces, these models and their results may not be robust enough in considering all possible fires. However, at this time further data and research are needed to understand the fire dynamics for these types of compartments. The current lack of experimental data should be noted when comparing the current state of timber modelling when compared to that of other materials. Materials such as concrete and steel have had large experimental studies such as the fire experiments performed at Cardington [75], [76], whereas exposed timber construction is only currently receiving attention with regard to large field-scale compartment experiments such as those performed recently as part of the CodeRed series of experiments [7]. This lack of experimental data for timber is likely because

Table 2.1: Literature Review Summary

Year	Author	Primary Focus	Thermal Exposure	Thermal Model	Mechanical Model	Pyrolysis	Moisture (Specific Heat)	Moisture (Latent Heat)	Smouldering
2012	Werther et al.	Modelling Heat Transfer	Standard Fire	X			X	X	
2017	Thi et al.	Modelling Heat Transfer	Standard Fire	X		X	X		
2018	Bedon et al.	Timber-Concrete Composite	Standard Fire	X	X		X		
2019	Palma and Frangi	Steel-to-timber Connections	Standard Fire	X	X		X		
2019	Richter et al.	Chemical Kinetic Model of Timber Charing	Constant Heating Rate	X		X			
2020	Richter and Rein	Chemical Kinetic Model of Timber Pyrolysis	Steady Heat Flux	X		X	X		
2020	Quiquero et al.	Numerical Model of Complex Timber Elements	Standard Fire	X	X			X	
2020	Chen et al.	Constitutive Model	Standard Fire	X	X		X		
2021	Gernay	Fire and Burnout Resistance	Standard and Natural Fires with Cooling Phases	X			X		X
2021	Xing et al.	Modelling CLT in natural and standard fires	Standard and Natural Fires	X	X	X			
2021	Kleihenz et al.	Temperature dependant thermal properties	Standard Fires	X		X	X		
2021	Létourneau-Gagnon et al.	Performance of Self-Tapping Screws	Standard Fire and Constant Heat Flux	X		X	X		
2021	Wiesner et al.	Semi-Probabilistic Model of CLT	Standard and Natural Fires		X				X
2021	Garcia-Castillo et al.	Fire Resistance of Historic Flooring System	Standard and Natural Fires	X			X	X*	
2023	Garcia-Castillo et al.	Probabilistic Model of Timber	Constant and Transient Fires	X	X		X*		
2023	Chen et al.	Thermo-mechanical model of timber in realistic fires	Standard and Natural Fires	X	X	X	X		X

* Not explicit in how moisture was modelled but was considered

steel and concrete are being used in complex applications for a very long period of time, allowing researchers to undertake experiments and develop and validate numerical models.

2.4 Summary

With the desire to construct mass timber structures with open-plan, well-ventilated floor plans there is a need to gain a deeper understanding of the performance of timber in fire as well as the fire dynamics of these designs. Finite element modelling offers several advantages in the design and analysis of these types of spaces allowing a better understanding of the resilience of the structure under a range of realistic fire scenarios.

Reviewing the state of the art, it is observed that future research needs for the modelling of timber include the further development of thermal-structural models. These have begun to be addressed by other researchers [45], [55], [65], but additional modelling endeavours considering loaded thermal models could examine different thermal exposures (including nonstandard fires) and structural loading scenarios. This would help to make thermal-structural modelling of timber more established, contributing to the development of these models being used for design. Other properties that are unique to timber could be investigated through modelling. These include the effect of moisture content, including the effect of having varied localized moisture contents throughout the timber caused by moisture migration during heating. Current methods of accounting for moisture only account for the energy required to evaporate the moisture rather than simulate its movement throughout the timber member [46], [47]. Smouldering is also a phenomenon not seen in all structural materials, but that can affect the temperature profile of the section and in turn weaken the member after the flames are extinguished. The development of a model which considers smouldering through software currently used by industry members would contribute towards more accurately modelling the fire performance of timber structures.

Although several steps need to be taken before simplified design methodologies for open-plan, well-ventilated timber structures can be created, the fire research community is beginning to mobilize and address some of these research gaps. Currently, in-progress experiments and analyses are anticipated to help better understand the expected fire dynamics of these types of spaces. By understanding how fires in well-ventilated, open-plan spaces differ from compartment fires recently considered in experimental research, analysis of these types of fires becomes possible, and the creation of methodologies for the design of these spaces becomes more accessible.

This chapter provided a summary of the state of contemporary mass timber design. Through a review of fire modelling of mass timber, it was outlined where current knowledge gaps exist for the fire safety of mass timber design. The following chapter will examine heritage timber and address the differences between heritage and contemporary mass timber.

Chapter 3: Fire Performance of Heritage Hardwood and Softwood

3.1 General

The previous chapter addressed considerations for the fire safety of mass timber and the current state of fire modelling for mass timber. This chapter will examine the differences between historic and contemporary mass timber. This will be performed by outlining the additional considerations required for the design of historic structures as well as an analysis of the different performances of historic mass timber.

Due to global demand for sustainable design [77], wood has been seen as an attractive material choice due to its ability to sequester carbon [24] and the fact that it is a renewable material. To further its ability to be used 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 tall and complex buildings such as Brock Commons at the University of British Columbia [78]. However, wood has been used as a structural material long before the current demand for sustainable design. Many Canadian historic structures make use of wood as the primary structural material. See Koo et al. [16] for 61 historic structures over 5 storeys tall in Canada which make use of heritage wood members.

Another difference between historic timber and modern timber is that while modern timber uses softwoods, historic timber structures are composed of both softwoods and hardwoods. While all species of wood are physically different, the separation of hardwoods and softwoods can have a notable difference in the thermal properties of the wood [34].

One final difference between heritage and modern wood is scarcity. Heritage wood is a limited 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 to test it is important to use materials that are representative of heritage structures which are intended to be well maintained and to be in use in some capacity. However, those materials are typically part of these well-maintained structures and removing them for destructive testing is to remove the heritage value of the structure. Therefore, experimental testing of heritage materials has the unique challenge of having a limited stock to draw upon for experimental testing.

3.2 Review of Design on Heritage Structures

Heritage structures are unique to modern structures due to the value they will hold to a community's heritage. This is not to say that a structure today cannot hold value, but a heritage structure is irreplaceable due to either events which took place there 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.

3.2.1 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 thesis will focus on Canadian heritage; however, the principles can be applied elsewhere.

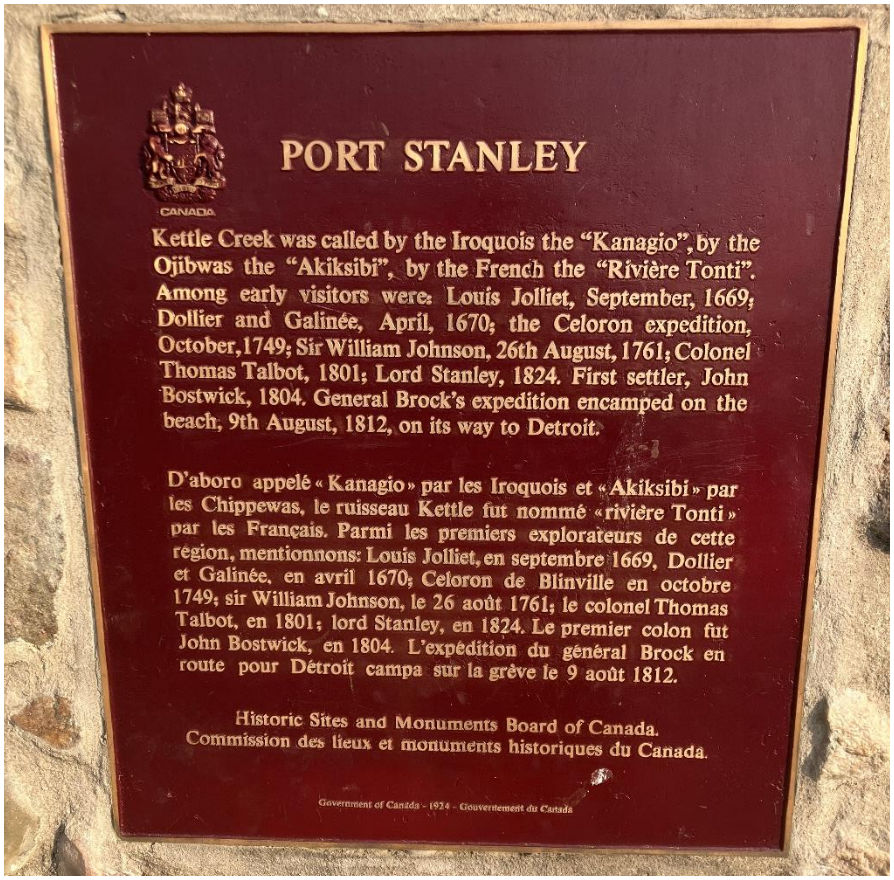
In Canada, the conservation of a historic site is the general term for protecting these character-defining elements. Specific strategies are preservation, rehabilitation, and restoration [4]. Preservation is meant to preserve the current state of the historic site. This is recommended to be performed when the heritage value is more tangible, and the character-defining elements are in good condition [4]. 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 [4]. 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 [4].

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 on Canadian heritage still 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 from affecting the character-defining elements and simply recognize them. 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).

Within Canada, a site is deemed *historic* if it can demonstrate it contains *heritage value*. As per the Standards and Guidelines, "*heritage value* is the aesthetic, historic, scientific, cultural, social or spiritual importance or significance for past, present, or future generations. [4]" Many of these 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. The federal level may view heritage value in a site if it aided in the development of Canada as it is today. The municipal level may see the heritage value of events the site or its people participated in. For example, Figure 3.1 shows a federal and a municipal level plaque for Port Stanley, Ontario. The federal level recognizes those who travelled through the land during the early years of modern Canada. Whereas the municipal plaque recognizes Port Stanley's role in the Underground Railroad. This is to highlight that a site may hold different values to different cultures of people.

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. 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.



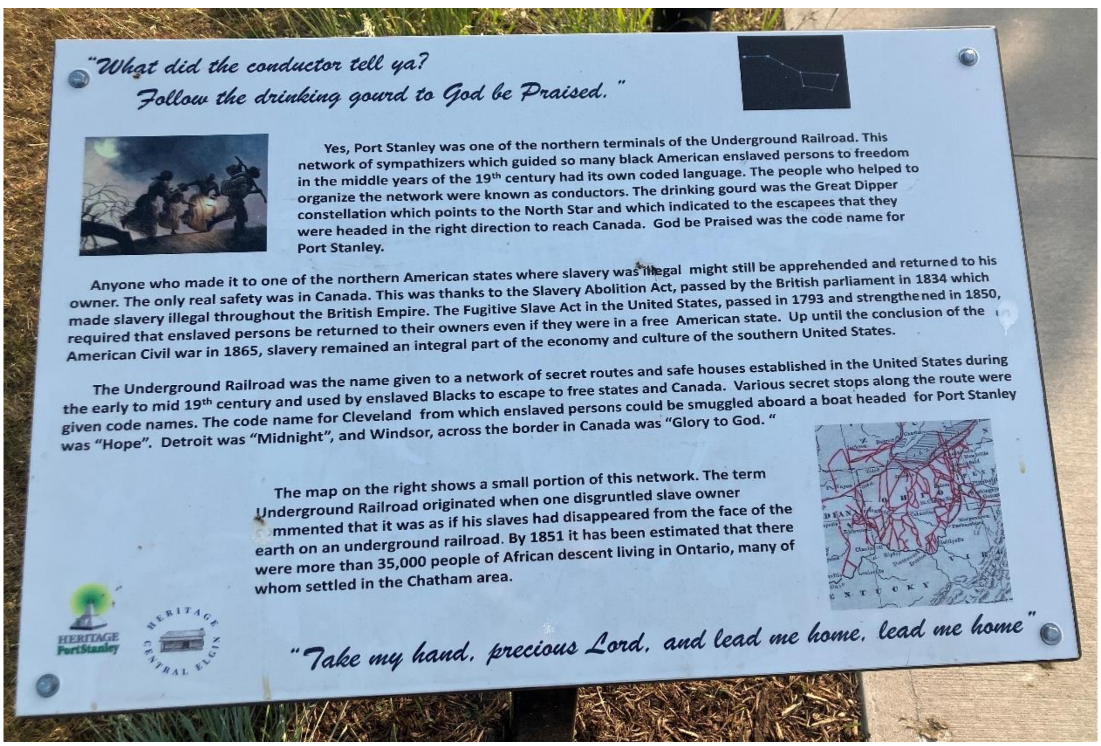


Figure 3.1: A federal (top) and municipal (bottom) plaque recognizing the heritage of Port Stanley, Ontario (Author's photos)

3.2.2 Performance in Fire of Heritage Mass Timber

As noted previously, if exposed mass timber is a character-defining element for a site it will likely be required to remain exposed to protect the heritage value of the site. Furthermore, a fully formed structural fire poses a major threat to public safety and risks spreading further. Therefore, it is important to understand the performance of heritage mass timber and its differences from contemporary mass timber. This can allow for proper design whether in rehabilitation or the development of a fire safety plan by understanding the potential of leaving heritage mass timber exposed in preservation or restoration work.

The importance of this knowledge is summarized through the work of Garcia-Castillo et al. [79] in which they performed a literature review of 125 studies on heritage structures ranging from 1985 – 2022. From the literature 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 [79]. This demonstrates that there is still a deficiency in understanding how a heritage fire spreads and how the structure performs. For further context, of the 125 studies examined in the literature review, 64 were related to heritage timber. Of those 64 studies, 5 of them investigated the thermal and thermo-mechanical performances. From the literature review, it was deemed that the fire performance of heritage timber is unclear, signifying the need for these studies to take place [79].

One of the more obvious differences between contemporary and heritage timber is the current level of deterioration each is at. Heritage materials, which are considered well maintained and of a high quality, does not mean that material is free of defects or damages. Heritage wood members that are in use may have discrete cracking occur over their lifespan. An example of which can be seen in Figure 3.2. Harun et al. [19] investigated the effects of radial cracks formed from moisture changes over time, similar to those shown in Figure 3.2, (from moisture changes with time) on the fire performance of heritage timber. In full assembly-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 char front. Char depths which occurred away from the crack were 64% less than char depths observed at the crack.

It has been observed that while the design of heritage structures differs from conventional wood design (large massive members versus dimensional lumber adhered) their behaviour in a fire scenario is comparable [5, 6]. This is because both forms of design utilized large mass timber as opposed to dimensional lumber found in small residential structures. However, in material-scale testing variance in the performance of contemporary and heritage wood has been observed. Through Cone Calorimeter tests at 50 kW/m^2 Chorlton et al. [81] 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 these samples were tested at ranged from approximately 7-8% [81]. In terms of flame spread testing, Chorlton et al. [81] 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 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. Karlman et al. [82] found that when the growth rings in Larch trees were thinner than

2.5 mm the density of the wood increased and decreases when the growth rings were greater than 3 mm, As thermal properties such as density are impacted by the growth of the tree, the thermal inertia of the wood is also affected [34].

Figure 3.2: A heritage timber column with a check along the centerline (Courtesy of John Gales)

To supplement the lack of material for experimental data, numerical modelling may be performed to study heritage timber. Numerical modelling is not without its own challenges. To create a valid model, there needs to be a thorough understanding of the material to be modelled as well as experimental data to validate a model against. Therefore, to create a valid numerical model there still needs to be experimental studies that does not void using some of the limited stock of materials. In addition to these general challenges of numerical modelling, heritage timber has several of its own challenges in modelling. These challenges include the effects of moisture [83] as well as the thermal properties being temperature dependent.

One example of the use of numerical modelling is the study performed by Garcia-Castillo et al. [18] 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 curves were simulated. The time-temperature curves were the ISO 834 standard fire [53], parametric fire curves, and two-zones models (produced by OZone). While this study has a significant focus on the effects of different time-temperature curves on the model results, it still 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. Part of the reasoning proposed by the authors is that all the models used the same material properties for the timber elements. These values were selected from Eurocode 5 [47], which in turn are based on the ISO 834 fire [53]. 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 fire in fire. This study seeks to determine the difference in charring of historic hardwoods versus historic softwoods. The purpose of understanding if there is a difference in charring behaviour, and if so to what extent, is to aid designers in conserving historic timber structures. The char rate and depth is a common approach to determining the remaining strength of a timber member post-fire and is illustrated in standards such as CSA O86 Annex B [3].

Finally, there will be a discussion of a model which was developed to analyze these tests to further illustrate the need for a fundamental understanding of heritage wood. The model was developed by the co-authors of the original paper this manuscript is adapted from.

3.3 Experimental Fire Performance of Heritage Timber

In order to determine the charring behaviour between heritage softwood and hardwood, a Cone Calorimeter will be used. The Cone Calorimeter is a device which consists of a cone-shaped radiant heater which can be used to expose small samples (100 x 100 x 45 mm) of materials to specific heat exposures. It should be noted however that above the cone heater is active ventilation to exhaust the fumes from a fire. From the exhaust collected a cone calorimeter can determine the concentrations of O_2, CO_2, and CO [84]. Additionally, cone calorimeters are capable of analyzing heat release rates (HRR) from a sample during testing [84]. As a cone calorimeter provides a stable environment and can analyze products of a fire it is used for standardized pass/fail tests and used to collect data for fire models. It is also predicted that a cone calorimeter will be used often for studies of polymers (of which wood is) [84]. The experimental setup can be seen in Figure 3.3. While this does not simulate a realistic fire, since samples are exposed to a consistent heat exposure, different materials can be compared to each other with this same test procedure. Therefore, the Cone Calorimeter allows for small samples of heritage hardwood and softwood to be compared where only the intensity and duration of heat exposure are altered all other conditions are the same.

Figure 3.3: Cone calorimeter device with specimen circled in red (left) and zoomed-in image of specimen ignited during a test (right) (Author’s photos)

The softwood heritage samples were sourced from a joist whose dimensions were 350x70 mm, of Spruce species circa approximately 1830. The building was undergoing redevelopment and the timber members were removed by the developer and demolition crew. The hardwood samples were taken from a decommissioned farm structure beam circa 1880 and were of Oak species. Figure 3.4 illustrates the state of the spruce samples as they were acquired.

Figure 3.4: Samples of heritage timber before being prepared for the cone calorimeter (Courtesy of John Gales)

Once timber samples were located, they were inspected for signs of defects or deterioration such as rot, moisture damage, and pests. For use in the Cone Calorimeter tests, the heritage members were cut to 100 x 100 x 45 mm. Samples were prepared so that a fresh-cut side was exposed to the heating element to prevent the surface oxidation of the timber members from affecting the test. The softwood samples were found to have an internal moisture content of 6.97% and the hardwood samples were 8.66% after being oven dry.

The Cone Calorimeter tests were performed following a modified ASTM E1354 procedure [85]. The main modification to test standard ASTM E1354 was that the test specimens were removed from the apparatus after specified exposure times and were immediately extinguished with water. The use of water was to halt the smouldering and combustion processes. This was to prevent continued charring of the wood specimen after the test had concluded. The water evaporated in contact with the wood, however, the specimens were kept in a temperature and humidity-controlled environment after the test. Additionally, no spark igniter was used for the tests. This is to follow the practices of previous tests in which the goal was to imitate a real fire where the wood would self-ignite without external ignition [81].

The test series consisted of wood samples being tested at different heat exposures and for different durations of exposure. Wood samples could be tested at either a low heat exposure of 30 kW/m^2 or a high heat exposure of 50 kW/m^2. At each level of heat exposure wood samples could be exposed for 3, 6, 10, 15, or 30 minutes. For both levels of heat exposure, there were two softwood and two hardwood samples tested at 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 were conducted by Chorlton et al. [81]. Additionally, one set of data for the hardwood samples was collected by Chorlton et al. (2019) [81]. Additional samples of softwood exposed for 30 minutes and a complete set of hardwood were tested for this study.

Measurements from the test series included the char depth and average char rate of the samples. Char measurements were recorded once the specimens had reached 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). 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. A level char front of a sample can be observed in Figure 3.5. 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 [3].

Figure 3.5: A hardwood sample after being tested (Author's photo)

3.3.1 Experimental Results

Once the samples were all tested there were a few qualitative observations made of the charring patterns. The first is the cupping of the samples and increased char depth on the edges of the samples. The cupping of the wood is to be expected and is a common behaviour of polymers exposed to fires [86]. Once the samples begin to cup, the outer edges have the potential to become directly exposed to the heating element which results in the deeper localized char depths. The second observation was the difference in charring between the hardwood and softwood samples. Figure 3.6 shows a side-by-side of both species after being exposed to 50 kW/m^2 for 30 minutes (i.e., the most extreme heat exposure of this study). The hardwood formed a tight, scaly char with a series of grid-like cracks. Whereas the softwood appears more "expanded" than the hardwood. Based on the drastically different appearances and textures of the char, it can be assumed that the char from each species may not provide the same level of thermal insulation. However, further testing should be performed to provide evidence for the validity of this assumption.

Figure 3.6: A hardwood (left) and softwood (right) sample exposed to 50 kW/m^2 for 30 minutes each (Author's photos)

From the Cone Calorimeter tests, data was collected to determine the char depth and average char rate of hardwood and softwood specimens when exposed to two different heat fluxes. Figure 3.7 and Figure 3.8 illustrate the average char rate of the hardwood and softwood at 3, 6, 10, 15, and 30 minutes at heat fluxes of 30 kW/m^2 and 50 kW/m^2 respectively. From Figure 3.7 and Figure 3.8, several observations can be made about the charring behaviour of the softwood and hardwood specimens. The first observation is that in the early stages of heat exposure (< 10 minutes), is when the average char rates will peak. This aligns with the fact that charred wood provides thermal insulation to the inner area of the cross-section. This is more apparent in the high heat exposure as the wood is able to quickly rise 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 heat exposure and length of exposure. The two exceptions are the average char rate 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 to each other. The fact that the char rates appear to be consistent after 30 minutes may point to a longer duration of high heat exposures will be similar between the species. However, additional tests would be required for durations longer than 15 minutes to confirm this.

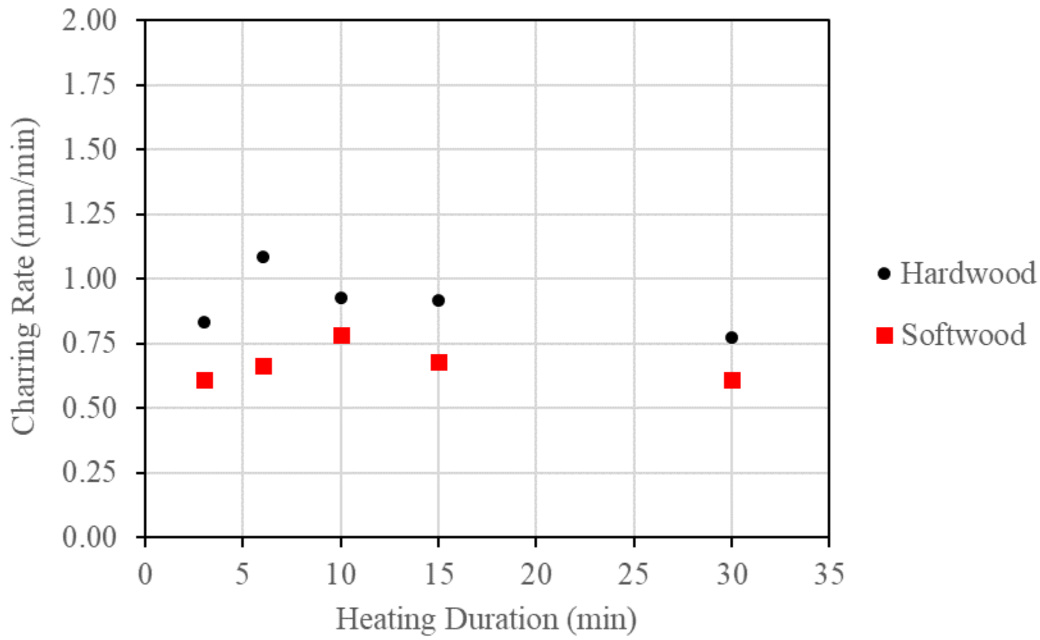


Figure 3.7: Average charring rate of wood samples at 30 kW/m^2

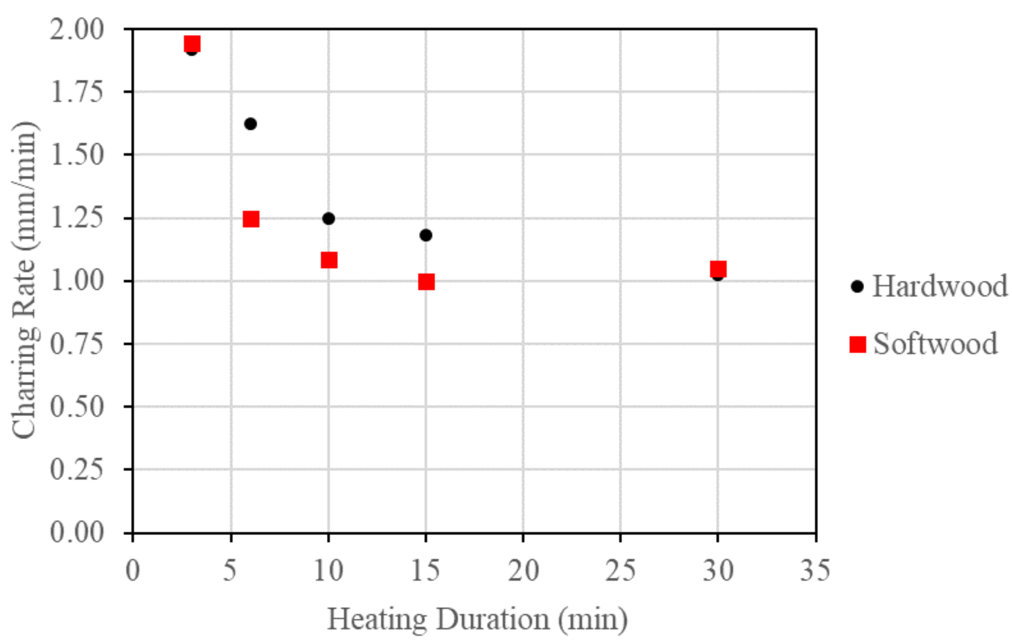


Figure 3.8: Average charring rate of wood samples at 50 kW/m^2

Figure 3.9 and Figure 3.10 illustrate the char depths of each specimen at 30 kW/m^2 and 50 kW/m^2 respectively. From Figure 3.9 and Figure 3.10, similar observations to the average char rate can be observed. Primarily that the hardwood specimens typically have a greater char depth than the softwood specimen. Visually it appears that the softwood chars more uniformly and the results are consistent. However, the hardwood samples have greater variability. As stated previously this may be due to wood being a natural material that may have greater uncertainty in performance. This is especially true for heritage wood which is not graded based on an established standard. However, to obtain useful statistics on the trends of the charring data more samples will need to be tested at all testing criteria. This is not feasible to do as heritage wood suitable for destructive testing is a limited resource.

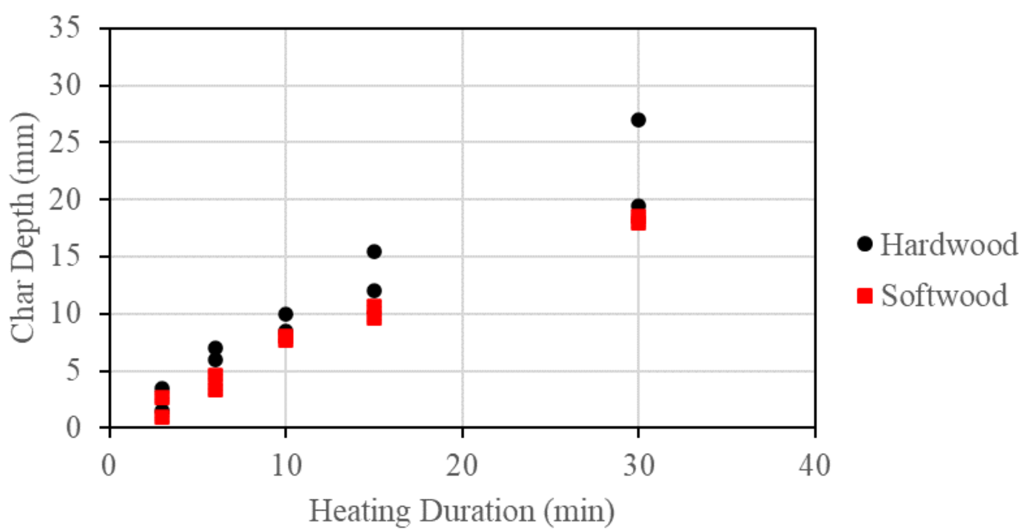


Figure 3.9: Char depth of samples exposed to 30 kW/m^2

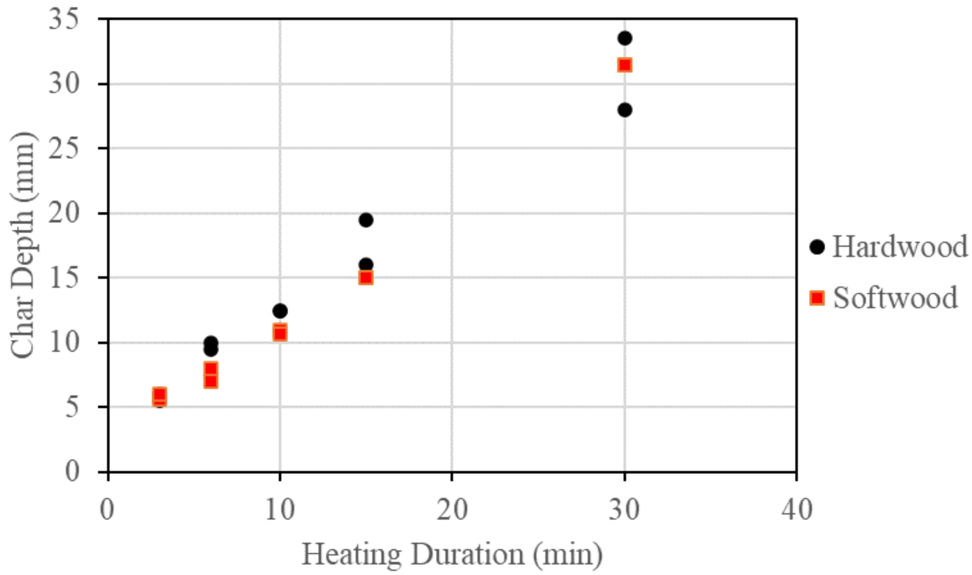


Figure 3.10: Char depth of samples exposed to 50 kW/m^2

Additionally, heat release rates (HRR) were collected during the tests. Figure 3.11 illustrates the HRR vs time 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 the samples exposed to 30 kW/m^2 did not ignite. This pattern was typical for all samples tested. The hardwood samples were able to reach 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 the HRR typically appears to stabilize without a second peak indicating that the samples were thermally thick. 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 3.11). The final observation is the capability of the heritage wood to generate additional heat. Once the HRR stabilized they typically plateaued at the heat exposure of the test (either 30 or 50 kW/m^2). However, the hardwood exposed to 50 kW/m^2 plateaued at approximately 55 – 60 kW/m^2 and one softwood exposed to 30 kW/m^2 began to climb to approximately 45 kW/m^2 before the test was terminated. This indicates that the structural wood could generate heat in addition to the incident heat flux which is critical to understand and account for in an analysis of structural timber in fire. From these tests, the wood itself may produce an additional 10% heat to the system from what the sample was originally exposed to.

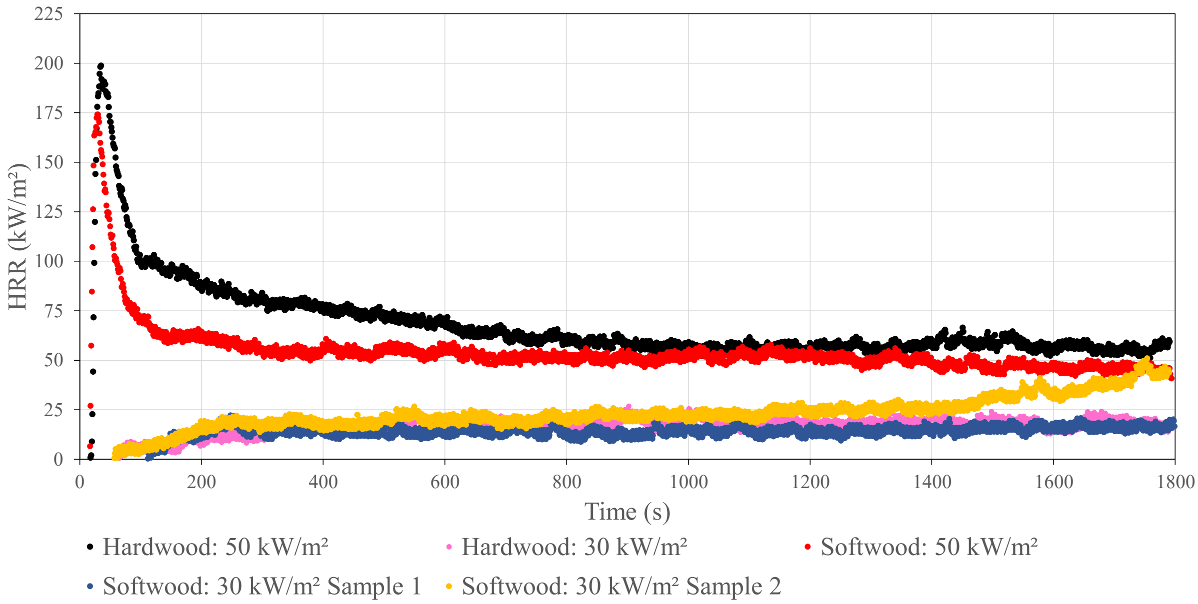


Figure 3.11: Heat Release Rates for Samples Exposed for 30 Minutes

Finally, fire chemistry data was collected for the samples. Below, Figures 3.12 to 3.14 illustrate the percent concentration of O_2, CO_2, and CO for the same samples shown in Figure 3.11. Figure 3.13 demonstrates the steady combustion via smouldering experienced by the samples exposed to 30 kW/m^2 due to the increased levels of CO_2 (over 0.1% vs typical ambient levels of 0.044%). The increased HRR of the softwood sample exposed to 30 kW/m^2 is also represented in the fire chemistry data. At approximately 1600 s there is a decrease in oxygen concentration and increase in carbon dioxide/monoxide concentrations. Final observations indicate that at the higher heat exposure samples appeared to be closer to a complete combustion than at the lower heat exposure (due to higher CO_2 concentrations and lower CO concentrations). If different concentrations of carbon are being produced as a gas, this indicates that the remaining char which is composed of carbon may have different compositions. Further studies should be performed to address if achieving a complete combustion affects the thermal properties of the char product.

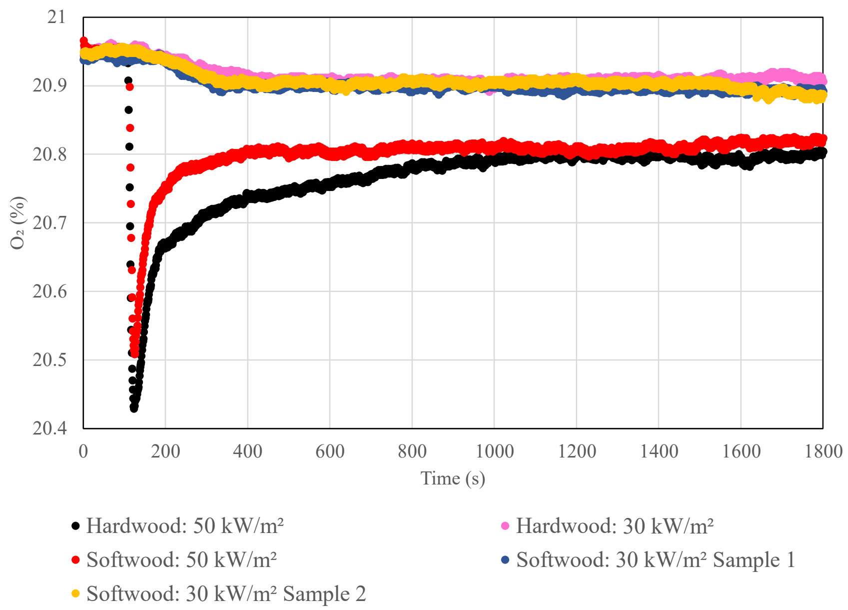


Figure 3.12: Oxygen concentrations in exhaust for samples exposed to 30 minutes

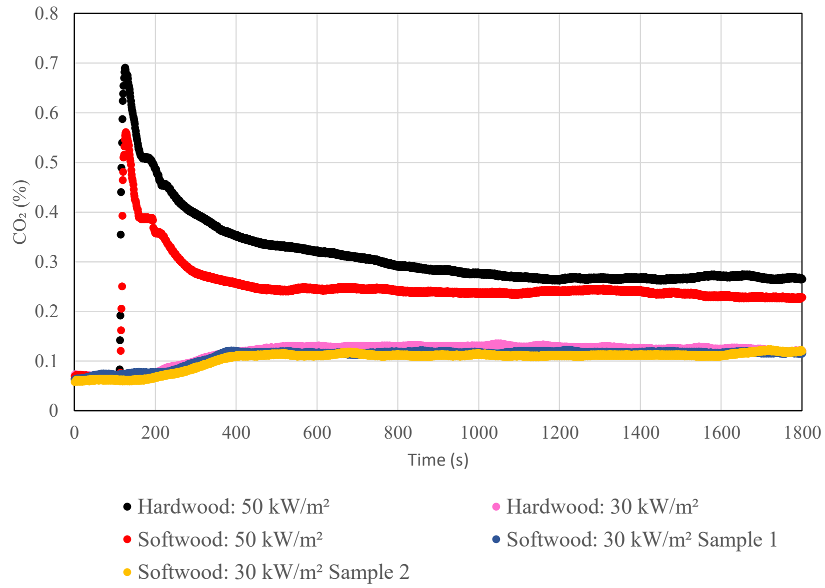


Figure 3.13: Carbon dioxide concentrations in exhaust for samples exposed for 30 minutes

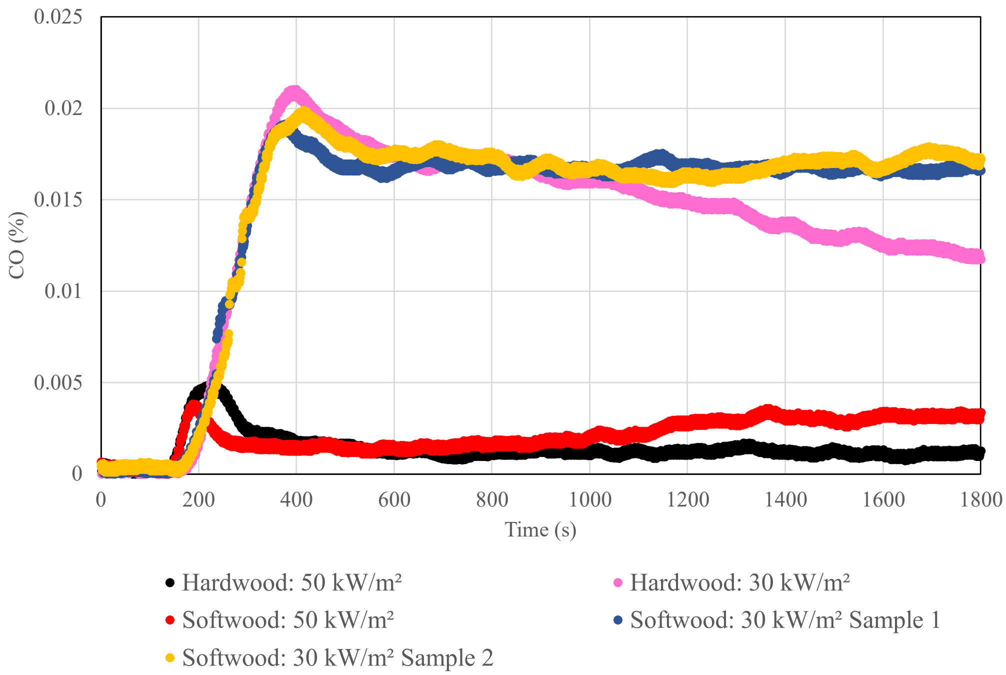


Figure 3.14: Carbon monoxide concentrations in exhaust for samples exposed for 30 minutes

3.3.2 Model Results

The work from which this chapter is adapted contained a numerical model to analyze the 1D charring of the hardwood samples. While the model was not the thesis author's own work, a discussion of the model results does align with the themes of this thesis. However, some key details of the model will be discussed here. The first is that this model was previously validated for heritage timber in fire (see Appendix A). The second is that moisture in the model was considered to account for the latent heat of the water as the moisture content of the samples was known. It is also important to note that LS DYNA was used as the analytical solver. This is important to note as the software does not allow material properties to change during a simulation. Therefore, as wood elements reached 300 ^{o}C the model could not account for the thermal insulating properties of char. Finally, the model was only applied to the hardwood tests. This was to examine the potential to use a numerical model to supplement the lack of heritage timber available for destructive testing.

Below, Figure 3.15 illustrates the difference between the experimental and model results. From Figure 3.15 it can be seen that the model overpredicted the char depth by approximately double that of the experimental results. While it is better to be over-conservative, an error of this magnitude indicates a fundamental error. Likely the error is a result of not being able to account for the thermal insulation of the char layer. This model still provided accurate results in Appendix A as the original validation study was performed on a much larger timber member. Therefore, the relative error due to not accounting for the char was significantly lower than for a cone calorimeter sample.

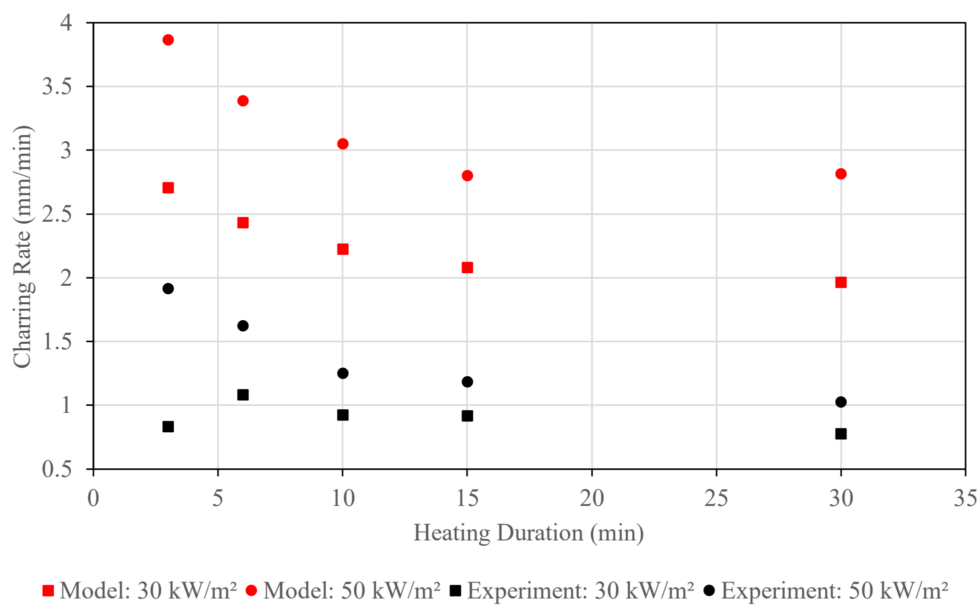


Figure 3.15: Experimental vs model results of hardwood char rate

3.4 Conclusion

As noted previously, one aspect of heritage wood structures which makes them unique is the use of hardwoods which is no longer 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 post-fire as a slower char rate would be used, resulting in a greater residual cross-section. 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 were capable of increasing heat to the system by an additional 10% of what the initial exposure was.

It was also observed that there is a variability of the hardwood specimens at lower heat exposures. While it may be simple to say that more tests can lead to greater confidence in the char behaviour of heritage timber, it is difficult to obtain suitable specimens. An opportunity exists to allow for numerical models to supplement a lack of experimental data. However, it has been seen through literature and work on this study that there is a lack of knowledge of material properties to have valid models. Current default practices were used to build the model and results showed overly conservative charring rates than what was seen in experiments though replicated trends well. This demonstrated the need for future research on how to implement changing material properties with temperature, such as density and adding a char layer which would insulate the sample and prevent such rapid charring within the software as is currently being investigated.

While previous chapters examined the technical aspects of mass timber in fire, this is only one aspect of engineering. The next chapter will study the industry itself and the people who would be undertaking this work.

Chapter 4: Gender Diversity within the Field of Timber Professional Engineering

4.1 Introduction

Chapters 2 and 3 addressed the technical side of fire safety while designing timber structures. This chapter will examine the industry itself. This will be performed by developing and analyzing a study issued to professional engineers in the field of timber engineering. The survey will outline the state of gender-based diversity within the industry and identify areas where future studies may have the greatest impact.

With the motivation towards more sustainable building infrastructures as identified in the Conference of the Parties 26, there has been a global influx of demand for timber structures, and this has been pronounced in Canada (as described in the oral presentation by Philion et al. [87]). In Canada alone, the number of engineered designed timber structures (see an example in Figure 4.1) increases annually with the advancement and creation of manufacturing technologies. Natural Resources Canada maintains statistical trends of timber-based construction in Canada, indicating annual increases in mass timber construction [5]. Large field-scale fire tests have increased confidence in building authorities [7], [88] which have led to novel code changes that are being rapidly developed and refined to provide greater guidance and more certainty in safety for mid- and high-rise construction (NBCC 2020). To complement educational initiatives towards this momentum, the Canadian Wood Council has hosted workshops with the goal of improving timber education in Canadian universities. From these workshops, Daneshvar et al. [89] conducted surveys to determine the state of timber education in Canadian Civil Engineering programs. Results of these surveys indicate that there is growing interest by students to participate in courses which incorporate timber design and relevant demand from the industry that they have these skillsets entering the workforce.

Figure 4.1: Selected Mass Timber building in the Greater Toronto Area (Courtesy of John Gales)

To support novel timber structures, increased efforts to retain and attract an engineering workforce are essential. A sound equity, diversity and inclusivity (EDI – also seen phrased as DEI) plan is typically part of this strategy. This begins from the educational sector and extends to practice. A collaborative and supportive environment which recognizes and mitigates protentional career barriers was found to ensure high retention as discussed in a previous industrial survey of engineers across Canada (see Mazur et al. [90]). The importance for understanding and mitigating barriers is essential. These typically involve those that may impact one's career beginning and progress. Some of these are related specifically to gender (among other EDI considerations), which is described below.

It should be acknowledged that while there are more genders than just man and woman, this study will focus primarily on men and women. This is because the study consists of a survey which examines the state of gender diversity and inclusion in the field of timber engineering. Within the survey, a multitude of genders were made available for selection (see Appendix B for full list) however only the man and woman choices were used by participants. For this reason, the literature review and discussion of data will only focus on the genders of man and woman. Any mention of the "two genders" or "all genders" is to be read in the context that only data for men and women was collected. Additionally, the use of terms regarding sex and gender which occur within this section are the ones which were used in the referenced material.

4.2 Background

When examining diversity in terms of gender in the workforce, it has been documented that 17.9% of newly licensed engineers were female and 25.2% of engineering students identified as female in Canada [91]. It should be noted that these statistics are taken from four years into a 15-year initiative, titled 30 by 30, in which the goal is to increase the percentage of newly licensed engineers who identify as females to 30% by 2030 [20]. For reference, prior to the start of this program (2014), only 17.0% of newly licensed engineers identified as females [92].

To benefit these movements, there are several groups which work to address this problem. One of which is a consortium named Engendering Success in STEM. Engendering Success is a collaboration of several universities and STEM-based associations and companies which seek to reduce barriers faced by girls and women from childhood through to university and early career [21]. Some focuses of Engendering Success is the effect of biases and a person's fit in an environment [93]. The idea of fitting in an environment such as STEM can be seen to have three main categories: self-concept, goals, and social. Self-concept fitting relates to one being able to be their authentic self in an environment, a goal fit is about if a person's career goals align with an environment, and finally social fit is about one integrating with the environment [93]. Once these aspects of fit are affected, such as the default use of masculine phrasing or removing an emphasis on collaborative work, people may begin to self-segregate without there being explicit bias occurring [93].

The concept of fit in an environment is not a foreign idea. From a psychological viewpoint, it has long been understood that feeling a sense of belonging or accepted (self-concept and social fit) are important to a person's health [94]. Dasgupta and Stout [94] identified several barriers which women face in the STEM fields in their careers (from higher education to established careers). Many of these barriers are in some way related to a lack of fit experienced by women. Through higher education in STEM, common barriers for women include being outnumbered by men and a lack of same-sex role models.

Within the workforce, it is recognized that a mentor is beneficial. Saffie-Robertson [95] examined the state of mentorship for women in STEM-based careers through a series of interviews with women in the field. One key finding of the interviews was that when the interviewees were asked to think of any barriers to finding a mentor in their work, none stated issues with accessing a mentor. However, the interviewers did indicate barriers to developing the mentorship relationship. The primary barrier stated, by 75% of respondents, is that there needs to be a fit in the relationship [95]. In the context of the interviews, a need for fit related to sharing similar values with the mentor or a personal connection. Additionally, the example quote provided for when an interviewee explained the need for a personal connection is “And for me a mentor is even a step beyond that. You know it’s someone that you build that emotional connection with, that you can share a life view, you probably have similar points of view about things that are important to you.” [95] Another part of the interview was to ask the participants if they had a formal mentor at work and if so was it a positive, negative, or mixed experience. Of the 36 interviews, 15 had a formal mentor at work. Eight of these 15 had a negative experience and a further four had a mixed experience. These statistics are expected as a formal mentor in the context of Saffie-Robertson [95] is a sanctioned mentor based on matching the sharing of organizational knowledge and progressing a protégé's career. This method of developing a mentor relationship leaves the idea of fit to chance as opposed to naturally developing a mentor relationship.

In professional life, Dasgupta and Stout [94] indicate that a department climate and work-family balance are common barriers faced by women. Department climate is that sense of social fit and is often found to be lacking in STEM based departments [94], [96]. As stated in *Gender Inclusion & Fit in Stem* by Engendering Success in STEM [93], once the sense of fit is lacking, people may begin to self-segregate.

When examining the educational sector, a study performed at the University of California, Berkeley has acknowledged a low enrollment of females in engineering [97]. In 2008, they introduced an undergraduate course which addresses challenges in sustainability. One goal of this course was to introduce an inviting environment for minority students in terms of gender and ethnicity. At the beginning of this course, students were asked to fill out a survey to understand what STEM experiences they had during high school. From this survey, it was found that while more male students took a shop or design course than the female students, it was more female students who participated in extracurriculars related to engineering and participated in design competitions [97].

The phenomena described forms a practice trend titled the 'leaky pipeline'. In brief, the pipeline is the flow from a beginning (education in engineering) to an end (distinguished career in engineering) where some of those in the flow leak out and are left behind to no longer pursue engineering [98]. In the cases described above, it would be students making their way through engineering school and at key points, there are large drop-offs in female enrollment and/or continuation into the field or further studies. While this model can be used to aid in identifying what issues exist throughout a person's career, this model has been criticized as even if all the "leaks are patched" nothing has addressed that the students are not treated equally and is more than one distinct "flow" in the pipeline [99]. A model that has been developed to address the different environments faced by females and males is the "Chilly Climate". This model came to be when it was noticed that female engineering students would describe the learning environment as "chilly and inhospitable to women" [98], [100]. Consequences of this range from mentor figures who push female students away from continuing education, but even family members may push female students away from engineering [101]. A more recent study by Mazur et al. [102] identified numerous barriers in the form of colleague-to-colleague discouragement at various universities which affects the retention of female students.

A factor which has been shown to aid students in completing their education and remaining in the field of engineering is for them to self-identify as an engineer. Meyers et al. [103] surveyed the undergraduate engineering students at an American Midwestern school about what they feel defines engineering. Within the survey, the participants were asked if they identified as engineers. At all class levels, it was found that male students were more likely than female students to identify as engineers. Meyers et al. [103] did conclude that more studies are required as the cultures and experiences of students can vary and one survey may not represent the norm. In contrast to Meyers et al. [103], Hamlet et al. [104] found that in upper years, female engineering students were more likely to self-identify as an engineer as opposed to a male student. It should be noted that Hamlet et al. [104] believe that the language used in the survey may influence these results. However, it was also noted that Chachra et al. [105] used the same framework but surveyed lower-year students and found that there was no statistical difference between the amount of male and female students who identified as engineers. This potentially indicates that upper-year female students are more likely to have formed an engineering identity.

These issues noted are not unique to education and academia, the workforce has also seen an imbalance of genders taking STEM roles. In 2018, a report was published by the National Sciences and Engineering Research Council of Canada (NSERC), authored by the then Chairs of Women in Science and Engineering, and detailed a summary of the distribution of males and females in various STEM fields in Canada [106]. In this report, it was found that from 2006–2016 there was never more than 30% of the workforce being women, with the peak of 20.05% occurring in 2015 [106]. In this report, STEM fields were composed of Agriculture, Biology, Engineering, General Science, and Math/Computer Science. Examining each of these fields on their own, Engineering had the lowest distribution of women. In 2006, Engineering had 12.47% of its workforce be women and only increased to 17.07% by 2016 [106]. Part of the reason for this low distribution is the "chilly" environment of STEM. The chilly environment is a combination of several factors such as sexist beliefs such as women being less capable of success in STEM and that women are not welcome in the field [107]. The workplace and academic settings share these inhospitable environments that lead women to feel a lack of fit in said environment.

This study herein aims to understand the current state of gender-based diversity within the field of timber professional engineering. Data collected in this study consists of age, race, gender, and motivators for working in the industry. This baseline data of the field will allow for the creation for future studies which can target research needs in EDI with quantitative evidence for its need. Additionally, this data may be used for developing diversity strategies that focus on gender retention and recruitment within the timber (and even general) engineering practice. It is one of many engineering educational projects underway. Canada has rapidly mobilized research and attention into this area. The topic of engineering education in general has grown in Canada the last decade. The previous focus has paid attention to curriculum enhancements [108], [109], graduate attribute enhancement [110], university-industry development [111] or now more specifically EDI. As of 2020, nearly 16% of Canadian engineering education studies, seen at the annual Canadian Engineering Education Association conference series, were on the topic of EDI in engineering education [112].

Herein, a comprehensive survey performed in 2022 is discussed. The survey was generated and analyzed by York University researchers and distributed through Canadian Wood Council's membership directory. The membership directory consisted of engineering companies across Canada that are currently working on timber design projects. This survey examines how individuals in these organizations were motivated to perform timber design, and whether certain factors can be used to attract and retain future timber engineers. The survey inquires into the respondents' past experiences in timber, both through their education and their career, as well as whether they see themselves remaining in timber design. The survey explores the existing state of EDI training within the workspace and areas where it may be improved upon.

Participants in the survey numbered over 132 with most identifying themselves as practicing engineers in Canada and nearly all having at least an engineering undergraduate degree. Findings are analyzed based on self-identified gender by the respondents (man/woman ex.). Gender non-specific and specific findings are analyzed based on populations representing small to large engineering firms currently involved in the engineering design of timber structures. A list of recommendations and future research follows. This discussion is to provide how certain educational strategies can be used to attract future timber engineers and retain those currently practicing in timber engineering to continue the momentum of its growth and demand in the Canadian building sector. Additionally, the results of this study may be able to suggest that including timber education within engineering programs will encourage females and marginalized populations to pursue engineering.

4.3 Methodology

The survey was generated with thirty questions to meet the research aims of the study. Before beginning the survey, participants are presented with an informed consent form. Both the informed consent form and survey are found in Appendix B. In general, the questions follow the language used by NSERC when asking for demographic or company-specific information. Deviations in language are also adopted from the internal ethics process or databases of information being held by the Canadian Wood Council. The first three questions examine the population demographic undertaking the survey. Questions 4 and 5 consider the licensure status and highest educational degree. Question 6 regards family background. Questions 7 to 10 categorize previous timber education and related motivations. Questions 11 to 16 gauge the experience level the individual has with timber design in general. Questions 17 to 21 investigate the motivation to continue practicing in the timber design domain. Questions 22 and on were considered optional to the survey though they largely had the same degree of participation. These were optional as there was potential that the respondents could be identified with the information they may provide. These questions investigated the region and company information. Here, more pointed questions pertaining to EDI are presented which consider the degree of training received (i.e., did the training address barriers which we describe in Section 1 for example). Questions were tailored to allow the study of linkages and correlations between the industry and EDI and to allow follow-up analyses of the work. In the event that respondents classify 'other' in their answers, detailed feedback was requested for clarification. It is acknowledged that not all data would or could be used immediately, however, the data is useful for future survey planning and associated non-gender-specific EDI studies.

Once the survey was completed, it underwent an ethics review. As the survey would rely on the membership database of the Canadian Wood Council, it required internal clearance first and a subsequent letter affirming the organization's role in the dissemination of the survey. Canadian Wood Council reviewed the survey and provided feedback to include the addition of project-specific information not directly related to EDI but to gauge the practice in general in Canada. This information would be for future studies and was beyond this paper’s scope. The informed consent form, survey and release protocol were submitted and then approved by the York University ethics board under certificate e2022-219 (See Appendix C for certificate). The ethics protocol specified the timing of the survey could be considered open and the alteration of some of the language being used in the questions being asked. It should be acknowledged that ethical procedures at universities (and industry) are becoming more and more specific in protocol and language in passing years, and more specifically acknowledged that they are traditionally grounded in fields outside of engineering and may not fully have the requisite expertise to ensure that the surveys are of the most stringent consideration for the safety of the responder. Subsequently, there is caution that this survey herein may have been further altered had it been processed at a different institution with the similar procedural conditions.

The survey was hosted on Microsoft Forms platform and participants were able to complete the survey through a device which can connect to any web browser and internet (i.e. personal computer and smartphone). Participants were not required to answer all questions. Several questions allowed them to expand upon their selected answers from the previous questions. Once participants accessed the link sent or shared with them from the Canadian Wood Council, they would be shown the informed consent form. If they consented to partake in the survey, they would then be allowed to access the survey questions. If the participant declined to consent to their participation, the survey would close. At any time, a participant could change their consent and opt-out of the survey. Responses were not logged until the participant submitted at the end of the survey. Therefore, surveys that people did not complete were not part of the final data. The survey length and this aspect may have affected to overall data obtained however it was felt complete datasets were essential as opposed to partial ones where linkages between questions may not have been possible or practical.

Participants were recruited by email and social media invitation via LinkedIn from the Canadian Wood Council. Participants were given 35 days to complete the survey from the first email. Reminder emails were sent out twice (evenly distributed) throughout the 35 days. The survey itself had no time limit for questions. All participants received identical surveys. Figure 4.2 illustrates the social media and subsequent interaction as of the time of writing.

The survey was distributed among those who classified themselves as members of the Canadian Wood Council. The membership extends beyond only engineers including architects, trades etc. hence the high number is not exclusive to engineers and the others would not fill out the survey anyway. This approach also allowed the survey to be distributed outside the membership list. There is no definitive total number of people who may have been contacted available. However, there appeared no strong evidence that this was happening through social media engagement nor the responses themselves as those identified their affiliations with Canadian Wood Council membership. The survey was open for a month. In total, 132 respondents completed the survey with one indicating that they did not wish to partake. An average time of 12 minutes 46 seconds

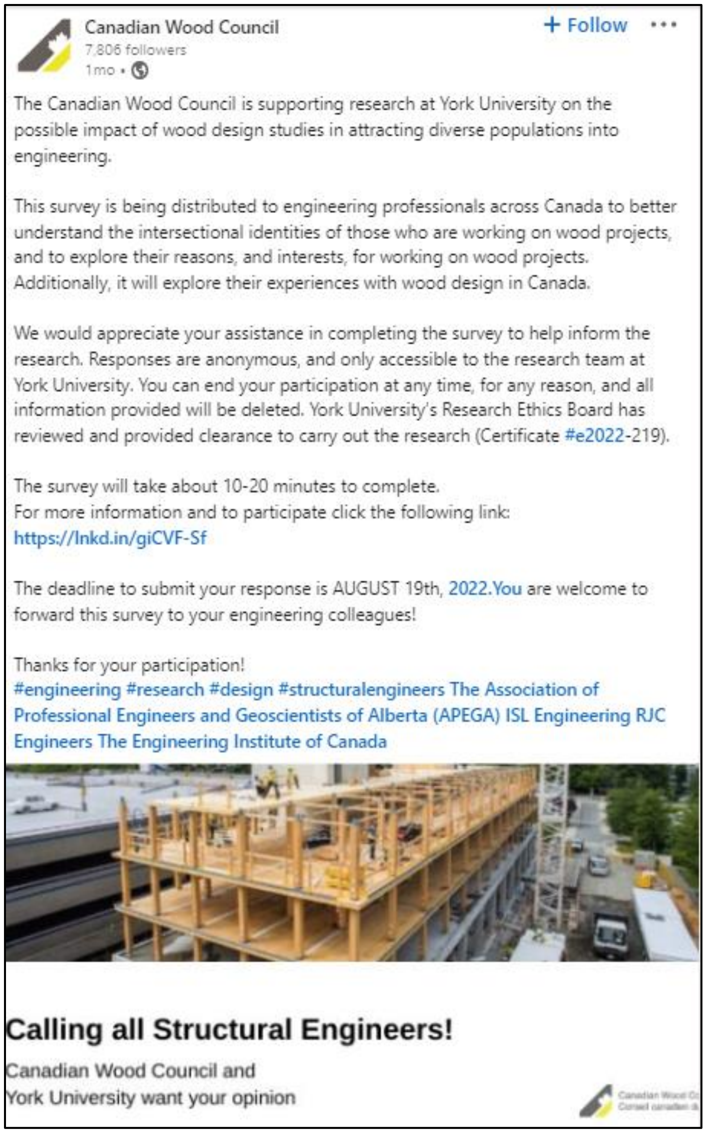


Figure 4.2: Survey Recruitment

was taken to complete the 30-question survey. No respondents were removed from the data which was ultimately extracted as a spreadsheet in the sequence of respondents answering the survey (unsorted) for the manual analysis. While it is acknowledged that there is an appearance of a low participation rate, those participating fully completed the survey giving nearly 4000 pieces of data to analyze. It is acknowledged that the length of the survey may have impacted the participation number. Future studies can be more refined to focus on specific themes with fewer questions and a higher participation rate. However, the approach used herein allows the author to expand their research beyond just the diversity of gender, which is the focus of this chapter, in future work.

4.4 Survey Results and Discussion

The analysis is split into two themes, first a generalized overview of the survey results which are gender non-specific and then followed by gender-specific information pertaining to both men and women. There were no other groups who identified themselves specifically by other genders, and therefore the study of gender other than men and women is beyond the scope of this paper. The gender non-specific results will provide a baseline of the diversity landscape of the industry. From this gender-specific findings can be presented in the context of the industry as a whole.

4.4.1 Gender Non-Specific Results

The following results describe the general landscape (age, gender, race distributions) of the field of timber professional engineering. Additionally, results will describe the level of education and experience of all those who responded to the survey. By outlining the results without a focus on results based on gender provide a baseline to which the gender-specific results can be compared.

4.4.1.1 Demographic of Respondents

Of the 132 persons who participated, most selected were White, with 67% (n=92) fully or partially identifying with this group. Figure 4.3 illustrates the identified population background responding to the survey. While beyond the scope to study different barriers of racialized groups, it is acknowledged that future research should consider this topic. Further discussion of the importance of addressing racial barriers can be found in Kalev et al. [113]. Specific classifications of racialized groups follow the NSERC classification.

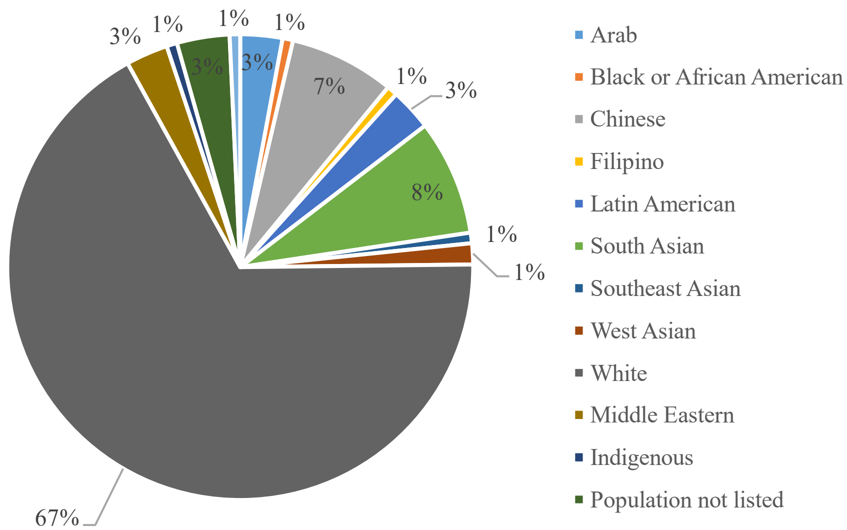


Figure 4.3: Population Identification of Respondents

16% identified themselves as a woman, 2.3% chose not to identify themselves, and the remainder identified themselves as a man. Most respondents fall within the middle (30 to 49 years old, n=67) to late (50 to 65+ years old, n=51) age groups. Only one participant was aged under 24 years old. Figure 4.4 provides a breakdown of the ages and genders selected by the respondents. The age distribution was reflected in the engineering license status, with the majority (84%, n=110) being fully licensed, and only 11.5% being Engineers in Training (n=6) or not licensed (n=9). The remainder have Limited Licenses (n=4) or Provisional Licenses (n=2).

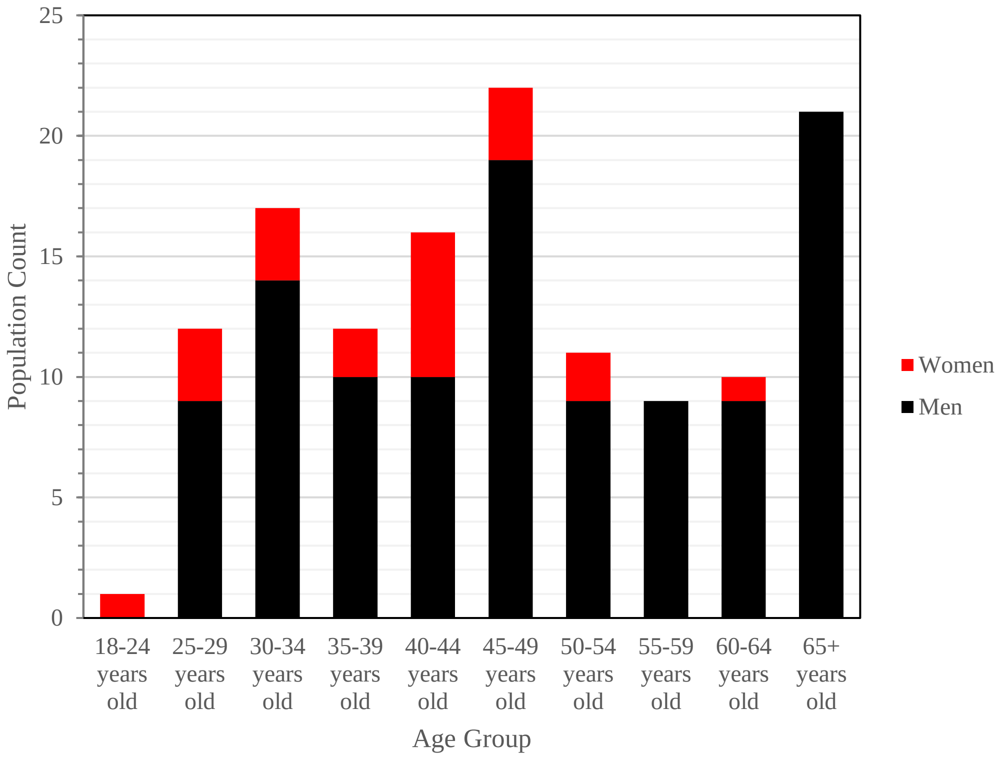


Figure 4.4: Age of Respondents

4.4.1.2 Experience and Education of Respondents

The type of experience the respondents have, as seen in Figure 4.5, could indicate the availability of timber education. This may identify deficiencies in the university education system which could assist in recruiting people entering the field as opposed to converting people once they are in the field. Where one finds the motivation to study timber gives information regarding recruitment into the field, as seen in Figure 4.6. In this case, there is a correlation that most practitioners are learning by performing work projects and extracting motivation to continue from that. While many do indicate university experiences, this is not the principal motivation noted in the survey for continuing work in this area; work projects begin to dominate this as was indicated in the survey.

It was observed that most engineering designs being performed by those surveyed identified the most commonly designed elements that they encountered to be light-frame, trusses and glulam, with over 100 respondents indicating experience with those materials (Figure 4.7). 128 respondents identified as working on low rise (< 6 storeys) construction, 33 mid rise (6-10 storeys), and 12 on high rise (10+ storeys). The majority of the current projects rely on the existing design skillsets being identified. As code provisions change however, more high-rise design opportunities may exist which consequently may increase the need for engineered floor designs either of Cross Laminated Timber (CLT) or of a proprietary configuration requiring greater understanding of the mechanics involved as seen in many proposed hybrid systems. Current designs are commonly accessible and practical to communicate within a design module for training. Correlating to the lack of education, it is observed that only 52 people indicated that they designed with Cross Laminated Timber. CLT is becoming more common place but does contain more complexity in design which makes it less effective in training all factors (Figure 4.7). Curriculum developments need to place focus on these emerging systems.

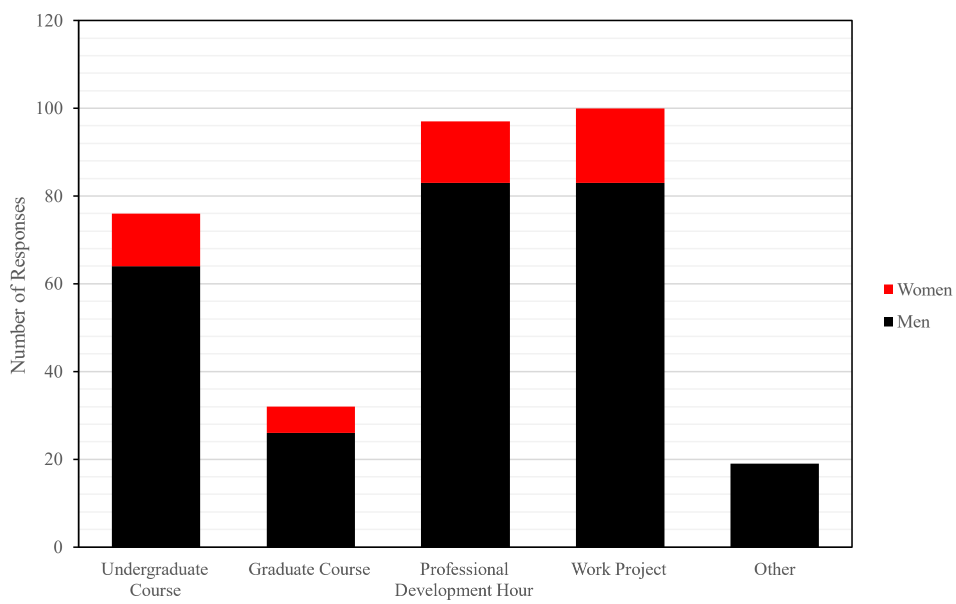


Figure 4.5: Timber Educational Experience of Respondents

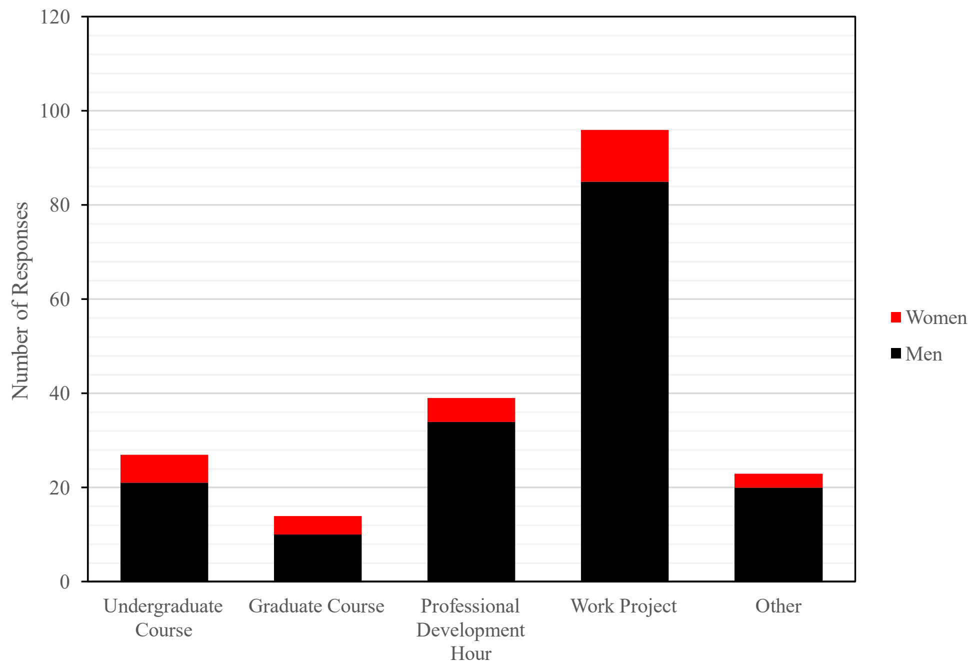


Figure 4.6: Source of Experiential Motivation to pursue Timber-based design

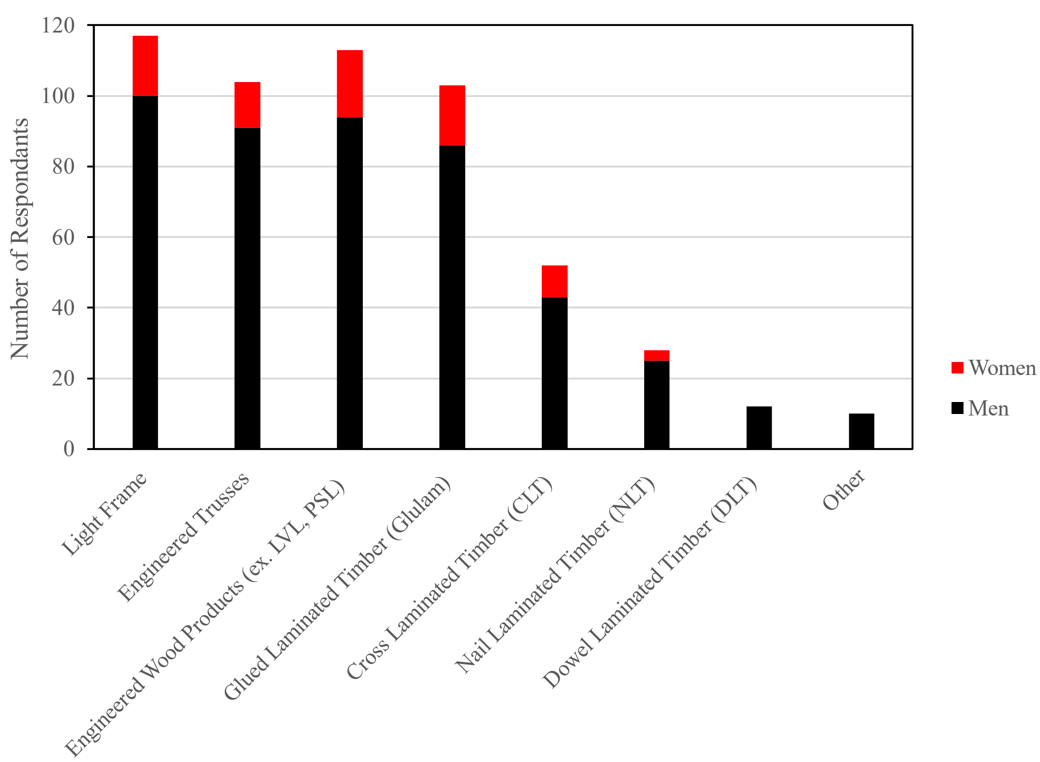


Figure 4.7: Type of Experience of Respondents

In all genders represented in this study, there was only one individual who indicated that they would not continue working in the timber design field which gives a positive indication to retention not currently being an issue in timber engineering based on the data. Of the respondents' personal motivations (see Figure 4.8), it is observed that sustainability is a high driver for the practitioner in undertaking timber. This may set a very important precedent that timber-based design work has the potential for high retention in engineering practice. Additionally, by understanding the motivators and goals that are present in people pursuing timber professional engineering, the industry can push these motivators and promote a fit for peoples' goals.

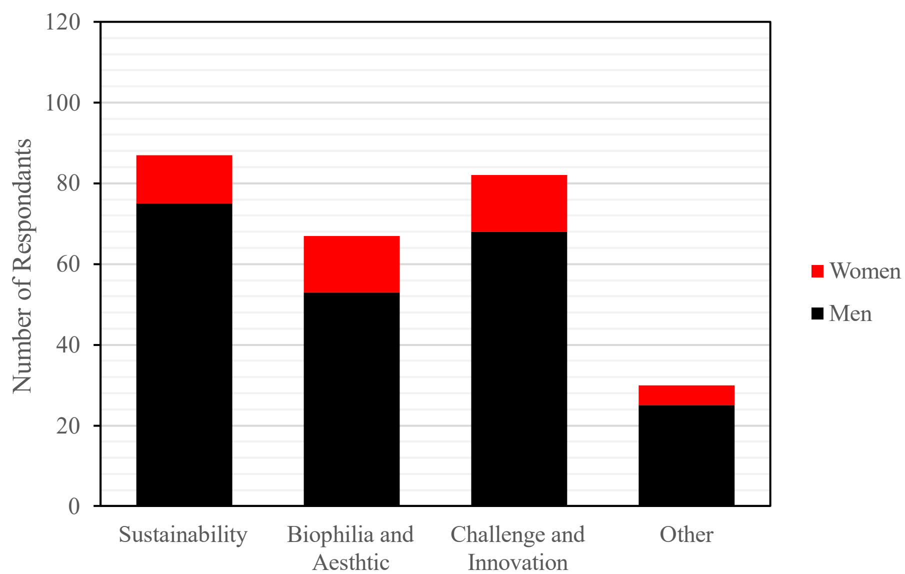


Figure 4.8: Personal Motivation to undertake Timber by Respondents

While not all participants responded to the optional questions, a majority did choose to respond to these questions in some capacity. The majority of companies/organizations were considered small, with less than 20 employees (46.9%, n=60). Medium (20-99 employees) and large (100-500+ employees) companies represented almost equal shares (with 21.9%, n = 28 and 25%, n = 32 respectively). Company size differentiation was determined following Canadian

Wood Council's classification. It is acknowledged that these may differ in other organization classifications. It should be noted that there is the possibility that multiple individuals work within the same companies/organizations.

Experience with EDI training was similar between men and women, though training did correlate to the size of the company. Of the women who responded, 38% indicated that they received EDI training with the majority indicating that it covered discussion on barriers in practice. 75% of those who received training indicated that they worked in a medium to large firm. For men, 36% indicated that they received EDI training with the majority indicating that it covered barriers in practice. 67% of those who received training indicated that they worked in a medium to large firm. Of those working for small firms, only 19% received training. The types of training received were detailed by 17 respondents. Seven responses detailed EDI training pertaining to the removal of barriers and unconscious bias training. Other responses detailed training which involved disabilities, empowering staff, and how to be an effective leader. About half of the responses detailed that training was sourced from exterior programs to their companies. Because only the topic of training was revealed in this question, it is difficult to gauge the effectiveness of the program's companies were offering to the respondents though one individual responded that they did not remember the training type. Additional questions which examined the effectiveness of the training were not asked. At this stage, the purpose of the study was to gain insight into where additional research should be allocated. Furthermore, the survey was already lengthy and additional questions would have potentially deterred participants from responding.

Of the respondents, 27 provided written detail to the question "Do you have any additional feedback you would like to add regarding wood in the design and construction industry?". Feedback primarily focused on improving education and material knowledge. Specific focus considering the creation of timber courses with an emphasis on making these mandatory as part of a program's accreditation (n=5). Related to these comments, it was remarked (n=5) that there is a need for the creation of materials for practitioners to learn how to design engineered timber for their projects.

4.4.2 Gender-Specific

With a baseline of the education and experience of the industry as a whole, there is now data to compare the gender-specific results to. Educational and work experience showed differences which suggest women working in timber design have not pursued graduate degrees in their education. Of the 21 respondents who identified as a woman, 61% (n = 13) indicated that they had only a bachelor's education, 28% (n = 6) had a master's and 10% (n = 2) had a Ph.D. 19% (n = 2) indicated that they did not have licensure at the moment. With respect to the same data sets by those identifying as a man, 52% (n = 57) indicated that they had a bachelor's education, 41% (n = 44) had a master's and 3% (n = 3) had a Ph.D. 13% (n = 7) indicated that they did not have licensure at the moment. Figure 4.9 displays the highest level of education of participants. Of those practicing, men had on average 16 years of experience with wood design and women 11 years.

Proportionally, the women answering the survey were younger than the men as shown in Figure 4.4. As noted by Engendering Success in STEM [93] it is important for mentors in which junior employees can relate to exist for retention. Therefore, to help encourage junior engineers who identify as a woman to stay in the industry, attention should be paid to why there are not many mid to late-career women engineers in the field. This is not to say that people only relate to those of the same gender, however, the choice should exist. It is unlikely that women engineers are leaving the field of timber professional engineering by mid-career as both men and women indicated similar levels of enjoyment of their career, Both the men and the women indicated similar satisfaction averaging scores out of five as 4.14+/-0.79 for the women, to 4.22 +/- 0.89 for the men. Enjoyment of wood design scored nearly identical. In combination with the fact that only one participant of the survey indicated not remaining in the field, these values are strong indications of the timber engineering field having a high retention aspect of engineers.

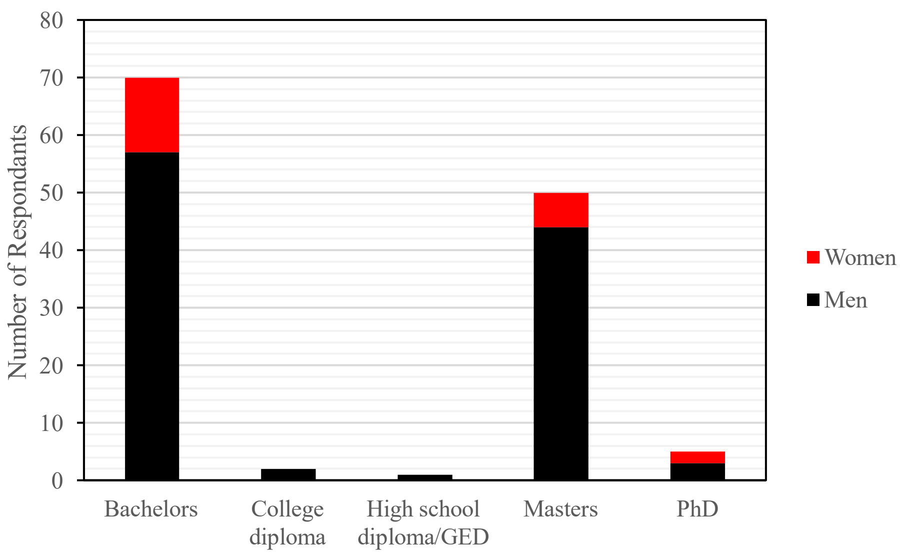


Figure 4.9: Highest level of education of participants

Forty percent of the women indicated that they had a previous family member who worked in engineering who influenced their career. Only 20% of the men indicated the same. This correlation stands as significant and requires further study. It is known (see Mazur et al. [90]) that exemplars influence career paths, and the large percentage in the responses from women may be suggestive that these are coming from family, and men find these elsewhere though no definitive explanation for the difference exists in the data collected.

In reference to Figure 4.5, men and women were consistent in terms of their education type despite the women having an overall lower sample size. However, there was evidence in Figure 4.6 that the women would draw more motivation from undergraduate and graduate courses than the men by nearly 10% in both categories, in addition, the women were proportionally less than the men to draw motivation to pursue timber design from work projects at 76% (men) opposed to 52% (women). In reference to Figure 4.7, there was no large difference between the work experience type by proportion. In reference to Figure 4.8, 66% of the women who responded cited biophilia as personal motivation as opposed to the 47% of men who responded. In sustainability, the men were found to have personal motivation towards this at 67% as opposed to 57% of the women. There was a large portion of choosing 'other' which predominately focused on responses indicating economic and profit making as motivation. Both men and women were proportionally close to this selection. The women were also found to be more motivated by the challenge of design than the men at 67% as opposed to 61% respectively. These differences have usefulness in drawing recruitment and retention strategies in both the industry and academic sectors where plans are created.

4.5 Future Research and Limitations

The following is a list of future research areas and limitations the research experienced. The presentation of these areas is not sequenced in priority.

The research herein did not consider demographic analysis in detail particularly the cultural background of the respondents. Due in part to ethical considerations relating to confidentiality and the approval process, this was not studied beyond a category of respondents but is certainly worthy of consideration in an EDI perspective particularly that the majority of those working identified as white. An intersectional approach was not taken in considering results as the majority of the respondents came from the same categories. There would be difficulties to maintain anonymity and confidentiality. In addition, as the majority of participants identified as male and white, an analysis of the intersection of gender and race would result in categories with too few participants to make legitimate conclusions. An example is only one participant identified as a woman and Arab. From the participants of this survey, there was not enough data to perform an in-depth analysis of the intersection of what people identify as. Further studies should consider intersectionality.

The survey should be expanded to include other engineering disciplines (others in civil, mechanical, electrical, chemical, software etc.) beyond the subject matter of only timber to assess if observations are timber specific or generalized across the Canadian engineering community (and for that matter, internationally).

Opening the survey longer, while not permissible for this study, would allow more data to be collected. Though observations could be found meaningful with the data obtained, the shortened time the survey was open prevented more robust statistical analysis due to the lack of data.

The survey release and content were determined through its ethics protocol. As mentioned previously, this study was to identify the diversity landscape of the field of timber professional engineering. This would then identify needs for future studies/surveys which could have more direct questions that help identify barriers in the field which are preventing equality in the field. While care would still need to be taken to ensure surveys to not pose a significant risk to participants, this study justifies future studies requiring such questions.

Overall, the survey did not have a high number of participants who identified as a woman. However, what was seen was more a representative aspect of the population in conformance with Engineers Canada statistics on licensure therefore representative of the population of engineers. A parallel survey which was released only to networks supporting engineers who identify as a woman should be necessary to allow a deeper study into barriers that they may face.

Future work is also required to address the competency of the industry. Figures 4.6 and 4.7 illustrate that a majority of the participants primarily learn on the job and have little experience with more complex timber products such as CLT. As noted in previous chapters, proper mass timber engineering requires competency in several different fields such heritage conservation and fire safety engineering. If the industry does not have general experience with the products available then they cannot be expected to be competent in these specialized fields.

4.6 Recommendations and Conclusions

The following is a list of recommendations and conclusions based on the survey observations that the industry can consider in enhancing recruitment and retention strategies in timber engineering design.

A meaningful conclusion to the survey is that while it appears EDI training related to barrier removals, specifically impacts on gender, is being provided at medium to large-sized Canadian firms, it is lacking in small firms. Even small firms should consider training in EDI consideration, especially with respect to barriers that populations may experience. This will only help with retention practices as employees may transition in their careers to other companies.

There exists the potential for timber engineering to instill retention aspects to those undertaking work in the field. This is correlated to respondents' preferences to the challenging nature of design, biophilia and sustainability impacts which pertain closely to engineering design today these should be considered when developing EDI strategies.

There is no correlation that the focus of an engineering degree at this point leads one to the undertaking of timber-specific engineering. This is impacted by the lack of timber-specific engineering programs as indicated in the survey's freeform section responses. While effort has been made to create free and off-the-shelf timber-focused courses that any university may freely use by the Canadian Wood Council, there are accreditation barriers which impact the adoption of these courses also exemplified in the survey responses. It is necessary that university systems align with trends in structural and environmental engineering. Growing sustainability objectives are very clear that the industry is about to enter a further renaissance in construction with timber buildings (mid-rise and high-rise buildings, bridges, stations, etc.). Major metropolitan centers in Canada have already laid the foundation necessary for timber production. It is therefore essential that the next generation of students undertaking university studies be educated in this subject in the same manner they have in steel and concrete structures decades before them. The need for this is further made evident that current practitioners are not as experienced with engineered products such as CLT and NLT.

Any university program should adopt a capstone-based project or competition-based design as is seen in concrete and steel. It is clear from the survey motivation to work in timber is fostered by workplace design. These large project-styled aspects can be introduced into an undergrad program and promote interest in timber engineering before entering the workforce.

Timber design requires a more concentrated effort to promote exemplary women in engineering. It is suggested that women engineers may be drawing upon family as opposed to practitioners. There are ample timber projects in the industry where men are being featured as the experts and designers. Attention should be given to women designers to instill exemplars and improve recruitment. Again this can also tie into the sense of fit. If women (or anyone) do not feel a sense of belonging, whether intentional or not, they will not remain.

The findings have laid a groundwork for future research and provided a baseline for understanding how specific studies, such as wood engineering, can affect the recruitment and retention of diverse people. Of note, future studies regarding support needs for those in their mid-career are needed. As seen through the data collected in this study there are few women in their late career. Providing support to those in their mid-career can help develop a sense of fit and belonging, encouraging those to remain in the field. This can then lead to the future generations entering their early career having the opportunity to have role models and mentors they can relate to.

This chapter highlights the need for improvements in the field of timber professional engineering itself. It was shown that there is a lack of women engineers in the field and the potential exists for this to remain the same or worsen. However, the field is in a position to address this need and ensure there are engineers who want to design with wood.

Chapter 5: Conclusions and Recommendations

5.1 Summary

Engineered mass timber is emerging as a popular structural material as made evident by the increase in completed mass timber building on the database [5]. As engineered mass timber is new as a structural material it is important to understand how its use fits into current best practices of design. This is especially true due to the combustible nature of wood and that current design practices use non-combustible structural materials. Therefore, there is a need to understand how the use of a combustible structural material affects our understanding of compartment fire dynamics as well as how the material itself performs in a fire. Poor understanding of these can result in loss of property and life. Alternatively, structures may be overdesigned to account for the uncertainties of the use of a combustible structural material. This thesis examined mass timber design from a holistic approach and addressed modern mass timber, heritage mass timber, and the industry itself. The research performed is able to further our understanding of these fields as well as identify areas for future research.

A review of compartment fire design and the effects of the use of mass timber was provided in Chapter 2 to provide the required knowledge for this thesis. Key points summarized in Chapter 2 were the effects of smouldering, moisture, and lack of testing at the scale of actual compartments. Smouldering is significant, as with traditional non-combustible materials there is less concern about the performance of a material during the decay or cool-down phase of a fire. This can even be seen in the time-temperature curve of standard fires in which no decay phase exists. However, timber may continue to combust, produce heat, and lose strength while smouldering when the rest of a compartment is in a decay phase. Chapter 2 also examined the current state of fire modelling of timber. This was done to provide a summary of considerations for researchers and practitioners who seek to model timber in a fire. From this review, it was found that there is little research investing in the modelling of the pyrolysis of timber, the smouldering stage, or the creation of thermos-mechanical models.

To address the performance of heritage timber Chapter 3 examined the difference in the performance of heritage softwood and heritage hardwood. By being exposed to steady and constant heat exposures in a cone calorimeter, the charring of the heritage samples was able to be compared. Data collected from the experimental testing included char depths, average char rates, and heat release rates of the samples during heat exposure. The different species of wood each had a visually different char potentially indicating the char formed differently and may provide different insulating properties. Additionally, Chapter 3 provided a summary of considerations for heritage design that makes it unique to design contemporary structures. Overall, Chapter 3 demonstrated that while there is some knowledge transfer from conventional design to heritage design, additional knowledge and skill sets are required.

For proper timber design to occur, an industry needs competent people to do the design work. Chapter 4 addresses the current state of diversity within the field of timber professional engineering. The data collection consisted of a survey which was distributed to current practitioners and was a part of the Canadian Wood Council's mailing list. The survey collected information on the field's demographic stats, highest level of education, education/experience with timber design, and motivators for timber design. The survey also collected information about companies performing timber design as well as EDI related training. This study was a preliminary study which identified where future work is required to promote sound EDI studies within the field so that a community that is supportive of it people performing this design work can exist and improve.

5.2 Limitations

Within the studies of this thesis there were limitations discussed. In summary they are:

- Heritage wood is a limited resource. It is difficult to acquire heritage wood for destructive testing as you must acquire it from a structure which is representative of what is being conserved. Due to this a limited number of samples were tested in Chapter 3 as there was a limited amount of heritage wood available to use.
- Higher heat exposures to the heritage wood samples were not feasible with the equipment. While the heritage samples were not exposed to heat exposures they may experience in a fire, self-ignition of the samples was still observed.
- For the study in Chapter 4, the survey could not remain open for a longer period of time. Overall, this limited the amount of respondents which participated.

5.3 Conclusions

The following key conclusions were drawn based on the review and experimental testing regimes described in the thesis:

- The decay phase of a fire is important to account for when using mass timber. Mass timber may continue to combust via smouldering where it will produce heat and lose strength while the rest of the compartment no longer has flaming combustion;
- Moisture has a notable impact on the heat transfer through wood as it will delay the temperature increase of the wood. Furthermore, wet wood will have different thermal properties than dry wood. However, there is not yet a standardized approach to accounting for moisture in wood during fire tests;

- A lack of fundamental knowledge of the material properties of wood adds uncertainty to the fire modelling of timber. Additionally, a lack of compartment size experiments creates difficulties for the validation of fire dynamic modelling involving wood;
- Once the heat release rates of the heritage timber samples in the cone calorimeter plateaued, they were capable of increasing heat in the system by 10% of what the initial thermal exposure was;
- The peak heat release rate of the ignited heritage hardwoods and softwoods were approximately 200 kW/m^2 and 185 kW/m^2 respectively;
- Typically, the heritage hardwoods charred at a higher rate than the heritage softwoods. At a heat exposure of 30 $kW/m^{2,}$ the average char rate of the hardwoods and softwood were 0.78 mm/min and 0.61 mm/min respectively. At a heat exposure of 50 kW/m^2 both species of wood charred at a rate of approximately 1.05 mm/min;
- A majority of the survey participants identified as white (n=92, 67%) and a majority identified as a man (n= 107, 81.7%). 16% of participants identified as a woman, this falls in line with current distributions of newly licensed engineers (17.9% female) [92]. This indicates the survey is representative of the industry;
- Regardless of gender, participants primarily gained timber experience from work projects and not undergraduate and graduate courses. Additionally, it was found that there was a lack of experience with complex engineered wood products such as cross-laminated timber and nail-laminated timber;
- 71.4% of women participating were ages 44 and under vs 39.1% of that for men. Having more experienced employees which junior employees can relate to and see as a mentor figure.

Several additional conclusions can be drawn from the research presented herein, including that:

- When creating fire models for timber, researchers have used published values such as those in Eurocode 5 [47]. These values were determined based on exposures to standard fires. Therefore, attempts to model timber in natural fire exposures have large levels of uncertainty due to using thermal properties calibrated to different fire exposures;
- Attempts at modelling the heritage hardwood samples with a previously validated model produced char rates which were notably more conservative. A primary reason assumed for the conservative char values was that the model was not capable of accounting for the insulating properties of the char layer;
- Satisfaction of career in the field of timber professional engineering was similar between men and women with scores out of five of 4.22 +/- 0.89 and 4.14 +/- 0.79 respectively.

5.4 Design Recommendations

From this thesis several recommendations can be made for the design and engineering of mass timber in fire:

- As more complex timber designs are proposed, the use of fire models needs to be complemented with a thorough understanding of the fundamentals of timber in a fire. From this thesis, it was shown that typical values for thermal properties are calibrated to standard fires and not natural fires. Additionally, some modelling packages are not able to properly account for changing material properties during pyrolysis and charring which are fundamental factors in how wood performs in fire;
- Understand that heritage and contemporary design are not 1-to-1. While the principles of how the materials behave and perform are similar, heritage wood was grown, milled, and

constructed differently than conventional wood. Such considerations include the fact that hardwoods were used, and which based on the data in this thesis, chars at a higher rate than softwoods. Additionally, any design work on heritage structures should consider the cultural significance of the historic structure whether or not it is protected;

- Acknowledge the EDI issues in the industry and work towards addressing them. One way which was highlighted in this thesis, is to have people of various demographics in positions where they can provide mentorship. While it is encouraging to see women beginning their careers in the field of timber professional engineering, having a mentor they can relate to will help them feel a sense of belonging and fit.

5.5 Research Recommendations

From this thesis, several recommendations can be made for further research on mass timber in a fire.

Recommendations for future research from Chapter 2 include:

- Further understanding of the thermal properties of wood. This includes thermal properties between species of wood, how thermal properties change as wood raises in temperature and chars, and thermal properties based on different fire exposures. Having this thorough understanding of how the thermal properties change will contribute to the creation of fire models with higher levels of confidence;
- There is a need for experiments on the scale of compartments. Testing at the scale of compartments will allow for data and observations to be made of the way timber affects the fire dynamics of a compartment. This knowledge will allow for timber designs to be

made with a higher level of confidence for fire safety. Having compartment test data will allow for fire dynamic models to be validated against realistic fires.

Recommendations for future research from Chapter 3 include:

- Additional studies are needed for the development of the char layer. While conclusions were made within Chapter 3 on the charring of heritage hardwood vs heritage softwood it was all made on the condition that additional studies were required to validate the findings.
- Development of thermal models that are capable of accounting for wood changing as a material as it turns to char. By incorporating temperature dependant thermal properties, fire models would increase in confidence. Once fire models become capable of accurately modelling heritage timber in a fire it can be used to supplement the fact that experimental testing of heritage is difficult due to a lack of suitable materials.

Recommendations for future research from Chapter 4 include:

- Further studies which target women. The results within Chapter 4 were not able to have a complete statistical analysis as there were not enough participants who identified as a woman. By gaining more woman participants and performing an in-depth statistical analysis would greatly strengthen the findings;
- Similar studies should be performed where the focus is on race-specific findings. There has been research and goals such as the 30 by 30 movement which focus on the unbalanced gender ratio in STEM. However, not much attention is given towards similar EDI issues related to race in STEM.

Overall, this thesis investigated several aspects of mass timber design. The thesis investigated contemporary mass timber, the state of fire modelling of mass timber, heritage timber, as well as the industry itself. From this, further understanding of heritage timber in fire and the industry was presented based on the studies performed. Finally, based on the findings recommendations for designers and future research was provided which can strengthen the design of mass timber.

References

[1] Architecture 2030, “Why the Building Sector,” *Architecture 2030*, 2023. https://architecture2030.org/why-the-building-sector/ (accessed May 18, 2023).

[2] P. D. Evans, H. Matsunaga, A. F. Preston, and C. M. Kewish, “Wood Protection for Carbon Sequestration — a Review of Existing Approaches and Future Directions,” *Curr Forestry Rep*, vol. 8, no. 2, pp. 181–198, Apr. 2022, doi: 10.1007/s40725-022-00166-x.

[3] CSA Group, *CSA O86-19: Engineering Design in Wood*. Mississauga, Canada, 2019.

[4] *Standards and guidelines for the conservation of historic places in Canada*, 2nd ed. Ottawa: Parks Canada, 2010.

[5] National Resources Canada, “The State of Mass Timber in Canada,” 2022. https://nrcan-rncan.maps.arcgis.com/apps/dashboards/041e338d2a4d4b3a82ff2c238a9f0f93

[6] A. H. Buchanan, *Structural Design for Fire Safety*, 1st ed. John Wiley & Sons, 2001.

[7] P. Kotsovinos *et al.*, “Fire dynamics inside a large and open-plan compartment with exposed timber ceiling and columns: CodeRed #01,” *Fire and Materials*, pp. 1–27, 2022, doi: https://doi.org/10.1002/fam.3049.

[8] P. Kotsovinos *et al.*, “Impact of Ventilation on the Fire Dynamics of an Open-Plan Compartment with Exposed Timber Ceiling and Columns: CodeRed #02,” *Fire and Materials*, no. May, pp. 1–28, 2022, doi: 10.1002/fam.3049.

[9] P. Kotsovinos *et al.*, “Impact of Partial Encapsulation on the Fire Dynamics of an Open-plan Compartment with Exposed Timber Ceiling and Columns: CodeRed #04,” *Fire and Materials*, vol. 47, no. 4, pp. 597–626, Jan. 2023, doi: https://doi.org/10.1002/fam.3112.

[10] E. Lalonde, “Mass Timber Research Fire Test Performed as Expected : Fire Performance Similar to Non-Combustible.” Ottawa, 2022.

[11] Canadian Wood Council, “Mass Timber Fire Tests Program,” 2022. https://firetests.cwc.ca (accessed Aug. 11, 2022).

[12] A. I. Bartlett *et al.*, “Auto-extinction of engineered timber: Application to compartment fires with exposed timber surfaces,” *Fire Safety Journal*, vol. 91, no. February, pp. 407–413, 2017, doi: 10.1016/j.firesaf.2017.03.050.

[13] R. M. Hadden *et al.*, “Effects of exposed cross laminated timber on compartment fire dynamics,” *Fire Safety Journal*, vol. 91, no. February, pp. 480–489, 2017, doi: 10.1016/j.firesaf.2017.03.074.

[14] R. Emberley *et al.*, “Description of small and large-scale cross laminated timber fire tests,” *Fire Safety Journal*, vol. 91, pp. 327–335, 2017, doi: 10.1016/j.firesaf.2017.03.024.

[15] “O. Reg. 451/22.” Ontario Gazette, May 14, 2022.

[16] K. Koo, M. Mohammad, and E. Karacabeyli, “A Study on Historic Tall-Wood Buildings in Toronto and Vancouver,” FP Innovations, 301006152, May 13.

[17] The Colliery Engineer Co., *A Treatise on Architecture and Building Construction*, vol. 3. Scranton, 1899.

[18] E. Garcia-Castillo, I. Paya-Zaforteza, and A. Hospitaler, “Analysis of the fire resistance of timber jack arch flooring systems used in historical buildings,” *Engineering Structures*, vol. 243, p. 112679, Sep. 2021, doi: 10.1016/j.engstruct.2021.112679.

[19] G. Harun, B. Chorlton, F. Richter, and J. Gales, “The Effects of Radial Cracks on the Fire Performance of Heritage Timber,” *Fire and Materials*, vol. 47, no. 3, pp. 386–399, Sep. 2022, doi: 10.1002/fam.3104.

[20] Engineers Canada, “30 by 30.” https://engineerscanada.ca/diversity/women-in-engineering/30-by-30 (accessed Jul. 07, 2022).
[21] Engendering Success in STEM, “Engendering Success in STEM,” 2023. https://successinstem.ca (accessed Apr. 02, 2023).
[22] Perkins&Will, “Canada’s Earth Tower.” https://perkinswill.com/project/canadas-earth-tower/
[23] H. Ikei, C. Song, and Y. Miyazaki, “Physiological effects of wood on humans: a review,” *Journal of Wood Science*, vol. 63, no. 1, pp. 1–23, 2017, doi: 10.1007/s10086-016-1597-9.
[24] C. D. Oliver, N. T. Nassar, B. R. Lippke, and J. B. McCarter, “Carbon, Fossil Fuel, and Biodiversity Mitigation With Wood and Forests,” *Journal of Sustainable Forestry*, vol. 33, no. 3, pp. 248–275, 2014, doi: 10.1080/10549811.2013.839386.
[25] E. Rackauskaite, P. Kotsovinos, and D. Barber, “Letter to the Editor: Design Fires for Open-Plan Buildings with Exposed Mass-Timber Ceiling,” *Fire Technology*, vol. 57, no. 2, pp. 487–495, 2021, doi: 10.1007/s10694-020-01047-0.
[26] A. Law and R. Hadden, “We need to talk about timber: fire safety design in tall buildings,” *The Structural Engineer*, no. 3, pp. 12–18, 2020.
[27] A. Cowlard, A. Bittern, C. Abecassis-Empis, and J. Torero, “Fire safety design for tall buildings,” in *Procedia Engineering*, Amsterdam: Elsevier Ltd, 2013, pp. 169–181. doi: 10.1016/j.proeng.2013.08.053.
[28] Think Wood, “Brock Commons Tallwood House.” https://www.thinkwood.com/projects/brock-commons-tallwood-house (accessed Dec. 16, 2021).
[29] D. Hagan, “The best of all worlds: a hybrid approach to mass timber,” 2021. https://www.wsp.com/en-GB/insights/a-hybrid-approach-to-mass-timber (accessed Dec. 16, 2021).
[30] D. Hopkin, M. Spearpoint, C. Gorska, H. Krenn, T. Sleik, and M. Milner, “Compliance Road-map for the Structural Fire Safety Design of Mass Timber Buildings in England,” *SFPE Europe*, no. 20, pp. 27–34, 2020.
[31] D. Lange, J. Sjöström, J. Schmid, D. Brandon, and J. Hidalgo, “A Comparison of the Conditions in a Fire Resistance Furnace When Testing Combustible and Non-combustible Construction,” *Fire Technology*, vol. 56, no. 4, pp. 1621–1654, 2020, doi: 10.1007/s10694-020-00946-6.
[32] W. Węgrzyński, P. Turkowski, and P. Roszkowski, “The discrepancies in energy balance in furnace testing, a bug or a feature?,” *Fire and Materials*, vol. 44, no. 3, pp. 311–322, 2020, doi: 10.1002/fam.2735.
[33] B. Karlsson and J. Quintiere, *Enclosure Fire Dynamics*. Boca Raton: CRC Press, 1999. doi: 10.1201/9781420050219.
[34] D. Drysdale, *An Introduction to Fire Dynamics*. West Sussex, UK: John Wiley & Sons, 2011.
[35] G. Rein, “Smouldering Combustion Phenomena in Science and Technology,” *International Review of Chemical Engineering*, vol. 1, pp. 3–18, 2009.
[36] R. Emberley, A. Inghelbrecht, Z. Yu, and J. Torero, “Self-Extinction of Timber,” *Proceedings of the Combustion Institute*, vol. 36, no. 2, pp. 3055–3062, 2017.
[37] A. Bartlett *et al.*, “Needs for total fire engineering of mass timber buildings,” in *WCTE 2016 - World Conference on Timber Engineering*, Vienna, Austria: TU Verlag Wien, 2016.

[38] R. Crielaard, J. Van De Kuilen, K. Terwel, G. Ravenshorst, and P. Steenbakkers, “Self-extinguishment of cross-laminated timber,” *Fire Safety Journal*, vol. 105, no. l, pp. 244–260, 2019, doi: https://doi.org/10.1016/j.firesaf.2019.01.008.
[39] F. Wiesner *et al.*, “Structural capacity in fire of laminated timber elements in compartments with exposed timber surfaces,” *Engineering Structures*, vol. 179, no. October 2018, pp. 284–295, 2019, doi: 10.1016/j.engstruct.2018.10.084.
[40] J. Gales, B. Chorlton, and C. Jeanneret, “The Historical Narrative of the Standard Temperature–Time Heating Curve for Structures,” *Fire Technology*, vol. 57, no. 2, pp. 529–558, 2021, doi: 10.1007/s10694-020-01040-7.
[41] C. Zhang, G. Q. Li, and A. Usmani, “Simulating the behavior of restrained steel beams to flame impingement from localized-fires,” *Journal of Constructional Steel Research*, vol. 83, pp. 156–165, 2013, doi: 10.1016/j.jcsr.2013.02.001.
[42] E. Rackauskaite, C. Hamel, A. Law, and G. Rein, “Improved Formulation of Travelling Fires and Application to Concrete and Steel Structures,” *Structures*, vol. 3, pp. 250–260, 2015, doi: 10.1016/j.istruc.2015.06.001.
[43] S. Craft, “An Overview of the Ottawa Mass Timber Demonstration Fire Tests.” Toronto, 2022.
[44] European Committee for Standardization, “CEN, Eurocode1: Actions on Structures - Part 1-2: General Actions - Actins on Structures Exposed to Fire.” Brussels, Belgium, 2002.
[45] T. Gernay, “Fire resistance and burnout resistance of timber columns,” *Fire Safety Journal*, vol. 122, no. April, p. 103350, 2021, doi: 10.1016/j.firesaf.2021.103350.
[46] N. Werther *et al.*, “Parametric Study of Modelling Structural Timber in Fire With Different Software Packages,” in *7th International Conference on Structures in Fire*, Bingley, England: Emerald Group Publishing Ltd, 2012.
[47] European Committee for Standardization, *EN 1995-1-2: Eurocode 5: Design of Timber Structures - Part 1-2: General - Structural Fire Design*. Brussels, Belgium, 2004.
[48] A. R. Medina, “Fire Resistance of Partially Protected Cross-Laminated Timber Rooms,” Carleton University, 2014.
[49] J. Su, P.-S. Lafrance, M. S. Hoehler, and M. F. Bundy, “Fire safety challenges of tall wood buildings – phase 2: task 2 & 3 – cross laminated timber compartment fire tests,” *National Research Council of Canada*, no. February, p. 396, 2018.
[50] B. Chorlton, B. Forrest, J. Gales, and B. Weckman, “Performance of type X gypsum board on timber to non-standard fire exposure,” *Fire and Materials*, vol. 45, no. 7, pp. 885–900, 2021, doi: 10.1002/fam.2822.
[51] V. D. Thi, M. Khelifa, M. Oudjene, M. E. Ganaoui, and Y. Rogaume, “Finite element analysis of heat transfer through timber elements exposed to fire,” *Engineering Structures*, vol. 143, pp. 11–21, 2017, doi: 10.1016/j.engstruct.2017.04.014.
[52] Z. Xing, Y. Wang, J. Zhang, and H. Ma, “Comparative study on fire resistance and zero strength layer thickness of CLT floor under natural fire and standard fire,” *Construction and Building Materials*, vol. 302, no. July, 2021, doi: 10.1016/j.conbuildmat.2021.124368.
[53] International Organization for Standardization, “ISO 834-11: Fire resistance tests - Elements of building construction - Part 11: Specific requirements for the assessment of fire protection to structural steel elements.” 2014.
[54] Y. Wang, “Theoretical and Experimental Research on the Structural Behaviour of Cross-Laminated Timber Structures on Compartment Fire,” Southeast University, 2019. doi: 10.27014/d.cnki.gdnau.

[55] H. Quiquero, J. Gales, A. Abu, and R. Al Hamd, *Finite Element Modelling of Post-tensioned Timber Beams at Ambient and Fire Conditions*, vol. 56, no. 2. 2020. doi: 10.1007/s10694-019-00901-0.
[56] M. Kleinhenz, A. Just, and A. Frangi, "Temperature-dependent thermal properties for cross-laminated timber exposed to standard fire," in *INTER, International Network on Timber Engineering Research*, Karlshruhe, Germany: KIT Holzbau und Baukonstruktionen, 2021.
[57] C. Bedon, C. Chifliganec, I. Džolev, R. Pečenko, and T. Hozjan, "Numerical Modelling of Timber Concrete Composite Structures in Fire - Guidance Document," *COST Action FP 1404 "Fire Safe Use of Bio-Based Building Products."* ETH Zurich, Zurich, Switzerland, 2018. doi: 10.3929/ethz.
[58] European Committee for Standardization, *EN 1992-1-2: Eurocode 2: Design of Concrete Structures - Part 1-2 General - Structural Fire Design*. Brussels, Belgium, 2004.
[59] P. Palma and A. Frangi, "Modelling the fire resistance of steel-to-timber dowelled connections loaded perpendicularly to the grain," *Fire Safety Journal*, vol. 107, no. November 2017, pp. 54–74, 2019, doi: 10.1016/j.firesaf.2017.12.001.
[60] K. W. Johansen, "Theory of Timber Connections," *IABSE Publications*, vol. 9, pp. 249–262, 1949, doi: https://doi.org/10.5169/seals-9703.
[61] M. Létourneau-Gagnon, C. Dagenais, and P. Blanchet, "Fire performance of self-tapping screws in tall mass-timber buildings," *Applied Sciences (Switzerland)*, vol. 11, no. 8, 2021, doi: 10.3390/app11083579.
[62] European Committee for Standardization, "CEN Eurocode 3: Design of Steel Structures - Part 1-2: General - Structural Fire Design." 2005.
[63] J. König and L. Walleij, *One-dimensional charring of timber exposed to standard and parametric fires in initially unprotected and postprotection situations*. 1999.
[64] C. Dagenais, "Assessing the Fire Integrity Performance of Cross-Laminated Timber Floor Panel-to-Panel Joints," Carleton University, 2016.
[65] Z. Chen, C. Ni, C. Dagenais, and S. Kuan, "Wood ST : A Temperature-Dependent Plastic-Damage Constitutive Model Used for Numerical Simulation of Wood-Based Materials and Connections," *Journal of Structural Engineering*, vol. 146, no. 3, p. 04019225, 2020, doi: 10.1061/(asce)st.1943-541x.0002524.
[66] C. Chen, L. Jiang, J. Qiu, M. A. Orabi, W. S. Chan, and A. Usmani, "OpenSees Development for Modelling Timber Strucutral Members Subjected to Realistic Fire Impact," *Fire and Materials*, vol. 47, pp. 461–478, 2023, doi: 10.1002/fam.3115.
[67] F. Wiesner *et al.*, "Structural Capacity of One-Way Spanning Large-Scale Cross-Laminated Timber Slabs in Standard and Natural Fires," *Fire Technology*, vol. 57, no. 1, pp. 291–311, 2021, doi: 10.1007/s10694-020-01003-y.
[68] Commonwealth Standards Network, "CSN EN 338 Structural Timber - Strength Class." 2016.
[69] Joint Committee on Structural Safety, "Probabilistic model code." 2001.
[70] APA, "PRG 320 standard for performance-rated cross-laminated timber." APA-The Engineered Wood Association, Tacoma, 2018.
[71] E. Garcia-Castillo, T. Gernay, and I. Paya-Zaforteza, "Probabilistic Models for Temperature-Dependent Compressive and Tensile Strengths of Timber," *J. Struct. Eng.*, vol. 149, no. 2, p. 04022239, Feb. 2023, doi: 10.1061/JSENDH.STENG-11369.

[72] F. Richter, A. Atreya, P. Kotsovinos, and G. Rein, “The effect of chemical composition on the charring of wood across scales,” *Proceedings of the Combustion Institute*, vol. 37, no. 3, pp. 4053–4061, 2019, doi: 10.1016/j.proci.2018.06.080.
[73] F. Richter, P. Kotsovinos, E. Rackauskaite, and G. Rein, “Thermal Response of Timber Slabs Exposed to Travelling Fires and Traditional Design Fires,” *Fire Technology*, vol. 57, no. 1, pp. 393–414, 2021, doi: 10.1007/s10694-020-01000-1.
[74] F. Richter and G. Rein, “A multiscale model of wood pyrolysis in fire to study the roles of chemistry and heat transfer at the mesoscale,” *Combustion and Flame*, vol. 216, pp. 316–325, 2020, doi: 10.1016/j.combustflame.2020.02.029.
[75] B. R. Kirby, D. E. Wainman, L. N. Tomlinson, T. R. Kay, and B. N. Peacock, “Natural Fires in Large Scale Compartments,” *International Journal on Engineering Performance-Based Fire Codes*, vol. 1, no. 2, pp. 43–58, 1999.
[76] E. Rackauskaite *et al.*, “Fire Experiment Inside a Very Large and Open-Plan Compartment: x-ONE,” *Fire Technology*, 2021, doi: 10.1007/s10694-021-01162-6.
[77] Wood for Good, “COP26.” 2021. [Online]. Available: https://woodforgood.com/cop26/
[78] Acton Ostry Architects, “Brock Commons Phase 1”.
[79] E. Garcia-Castillo, I. Paya-Zaforteza, and A. Hospitaler, “Fire in heritage and historic buildings, a major challenge for the 21st century,” *Developments in the Built Environment*, vol. 13, p. 100102, Mar. 2023, doi: 10.1016/j.dibe.2022.100102.
[80] NFPA, *NFPA 914: Code for Fire Protection of Historic Structures*. 2019.
[81] B. Chorlton and J. Gales, “Fire performance of cultural heritage and contemporary timbers,” *Engineering Structures*, vol. 201, p. 109739, Dec. 2019, doi: 10.1016/j.engstruct.2019.109739.
[82] L. Karlman, T. Mörling, and O. Martinsson, “Wood Density, Annual Ring Width and Latewood Content in Larch and Scots Pine,” *Eurasian Journal of Forest Research*, vol. 8, no. 2, pp. 91–96, 2005.
[83] A. I. Bartlett, R. M. Hadden, and L. A. Bisby, “A Review of Factors Affecting the Burning Behaviour of Wood for Application to Tall Timber Construction,” *Fire Technology*, vol. 55, no. 1, pp. 1–49, Jan. 2019, doi: 10.1007/s10694-018-0787-y.
[84] V. Babrauskas, “The Cone Calorimeter,” *doctorfire*. https://doctorfire.com/the-cone-calorimeter/ (accessed Jun. 12, 2023).
[85] ASTM International, *ASTM E1354 - 17 Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*. West Conshohocken, PA, 2017. [Online]. Available: https://doi.org/10.1520/E1354-17
[86] T. Belt, L. Rautkari, K. Laine, and C. A. S. Hill, “Cupping behaviour of surface densified Scots pine wood: the effect of process parameters and correlation with density profile characteristics,” *J Mater Sci*, vol. 48, no. 18, pp. 6426–6430, Sep. 2013, doi: 10.1007/s10853-013-7443-1.
[87] E. Philion, C. Jeanneret, J. Gales, and R. Kelterborn, “Enhancing Timber Engineering Education with Development and Analysis of an Off-Shelf Course,” in *NHICE*, Victoria, 2022.
[88] P. Kotsovinos, “The CodeRed Experiments - Evidence Based Fire Safety Solutions for Timber Buildings.” 2022.
[89] H. Daneshvar, T. Goni, S. Zhang, R. Kelterborn, and Y. H. Chui, “Structural Timber Design in Curricula of Canadian Universities: Current Status and Future Needs,” *Education Sciences*, vol. 11, no. 12, 2021, doi: 10.3390/educsci11120765.

[90] N. Mazur, B. Chorlton, J. Ellingham, and J. Gales, “Canadian Women in Engineering Academia and Industry,” *Canadian Consulting Engineer*, pp. 26–28, 2019.
[91] Engineers Canada, “2020 National Membership Information,” 2020. [Online]. Available: https://engineerscanada.ca/2020-national-membership-information#-summary
[92] Engineers Canada, “National Membership Report 2015,” 2015. [Online]. Available: https://engineerscanada.ca/national-membership-report-2015
[93] Engendering Success in STEM, “Gender Inclusion & Fit in STEM.” 2022. Accessed: Mar. 28, 2023. [Online]. Available: https://successinstem.ca/wp-content/uploads/2022/12/Gender-Inclusion-and-Fit-in-STEM-Final.pdf
[94] N. Dasgupta and J. G. Stout, “Girls and Women in Science, Technology, Engineering, and Mathematics: STEMing the Tide and Broadening Participation in STEM Careers,” *Policy Insights from the Behavioral and Brain Sciences*, vol. 1, no. 1, pp. 21–29, Oct. 2014, doi: 10.1177/2372732214549471.
[95] Ma. C. Saffie-Robertson, “It’s Not You, It’s Me: An Exploration of Mentoring Experiences for Women in STEM,” *Sex Roles*, vol. 83, no. 9–10, pp. 566–579, Nov. 2020, doi: 10.1007/s11199-020-01129-x.
[96] National Research Council, *Gender differences at critical transitions in the careers of science, engineering, and mathematics faculty*. Washington, DC: National Academies Press, 2009.
[97] L. Oehlberg, R. Shelby, and A. Agogino, “Sustainable product design: Designing for diversity in engineering education,” *International Journal of Engineering Education*, vol. 26, no. 2, pp. 489–498, 2010.
[98] J. Clark Blickenstaff, “Women and science careers: leaky pipeline or gender filter?,” *Gender and Education*, vol. 17, no. 4, pp. 369–386, Oct. 2005, doi: 10.1080/09540250500145072.
[99] S. J. Aiston, “Whose academy? Gender and higher education,” in *Researching Higher Education*, Routledge, 2016, pp. 80–96.
[100] B. R. Sandler, S. A. Silverberg, and R. M. Hall, “The Chilly Classroom Climate: A Guide to Improve the Education of Women,” 1996.
[101] E. de Pillis and L. de Pillis, “Are Engineering Schools Masculine and Authoritarian? The Mission Statements Say Yes,” *Journal of Diversity in Higher Education*, vol. 1, no. 1, pp. 33–44, 2008, doi: 10.1037/1938-8926.1.1.33.
[102] N. Mazur, B. Chorlton, and J. Gales, “Comparing the Experiences of Women in Undergraduate Engineering Across Different Schools,” in *10th Canadian Engineering Education Association’s Annual Conference*, Ottawa, 2019.
[103] K. L. Meyers, M. W. Ohland, A. L. Pawley, S. E. Silliman, and K. A. Smith, “Factors Relating to Engineering Identity,” *Global Journal of Engineering Education*, vol. 14, no. 1, pp. 119–131, 2012.
[104] L. C. Hamlet, A. Roy, G. Scalone, R. Lee, C. Poleacovschi, and J. Kaminsky, “Gender and Engineering Identity among Upper-Division Undergraduate Students,” *Journal of Management in Engineering*, vol. 37, no. 2, 2021, doi: 10.1061/(asce)me.1943-5479.0000876.
[105] D. Chachra, D. Kilgore, H. Loshbaugh, J. Mccain, and H. Chen, “Being and Becoming: Gender and identity Formation of Engineering Students,” in *ASEE Annual Conference and Exposition, Conference Proceedings*, 2008. doi: 10.18260/1-2--3597.

[106] A. Perreault, T. Franz-Odendaal, E. Langelier, A. Farenhorst, C. Mavriplis, and L. Shannon, “Analysis of the distribution of females and males in STEM fields in Canada,” NSERC Chairs for Women in Science and Engineering, 2018.
[107] S. L. Clark, C. Dyar, E. M. Inman, N. Maung, and B. London, “Women’s career confidence in a fixed, sexist STEM environment,” *IJ STEM Ed*, vol. 8, no. 1, p. 56, Dec. 2021, doi: 10.1186/s40594-021-00313-z.
[108] C. Boton, “A Framework for Building Information Modeling Implementation in Engineering Education,” *Canadian Journal of Civil Engineering*, vol. 45, no. 10, pp. 866–877, 2018, doi: https://doi.org/10.1139/cjce-2018-0047.
[109] H. Quiquero, M. Smith, and J. Gales, “Developing Fire Safety Engineering as a Practice in Canada,” *Canadian Journal of Civil Engineering*, vol. 45, no. 7, pp. 527–536, 2018, doi: https://doi.org/10.1139/cjce-2016-0552.
[110] S. M. Easa, “Framework and Guidelines for Graduate Attribute Assessment in Engineering Education,” *Canadian Journal of Civil Engineering*, vol. 40, no. 6, pp. 547–556, 2013, doi: https://doi.org/10.1139/cjce-2012-0485.
[111] A. Daoud, A. Tsehayae, and A. Fayek, “A Guided Evaluation of the Impact of Research and Development Partnerships on University, Industry, and Government,” *Canadian Journal of Civil Engineering*, vol. 44, no. 4, pp. 253–263, 2017, doi: https://doi.org/10.1139/cjce-2016-0381.
[112] A. Martins-Robalino, A. Wang, B. Chorlton, and J. Gales, “A Thematic Review of Canadian Engineering Education Research between 2017-2021,” in *13th Canadian Engineering Education Association’s Annual Conference*, Toronto, 2022.
[113] A. Kalev, F. Dobbin, and E. Kelly, “Best Practices or Best Guesses? Assessing the Efficacy of Corporate Affirmative Action and Diversity Policies,” *Am Sociol Rev*, vol. 71, no. 4, pp. 589–617, Aug. 2006, doi: 10.1177/000312240607100404.

Appendix A: Structural Fire Modelling Strategies for Exposed Mass Timber Compartments and Experimental Gaps for Model Validation

From:

Philion, E., Chorlton, B., Gales, J, and Kotsovinos, P. (2022) Fire Modelling Strategies for Exposed Mass Timber Compartments and Experimental Gaps for Model Validation. Journal of Performance of Constructed Facilities (ASCE), 36(6), DOI: 10.1061/(ASCE)CF.1943-5509.0001761.

Abstract

Exposed mass timber is being increasingly used for tall hybrid structures due to its sustainability features, rapid construction time, and the aesthetic desire to see exposed timber. However, there are currently many knowledge gaps in timber's performance in fire. Current prescriptive methods can be limiting, and designers are therefore required to develop alternative solutions to design tall and/or exposed timber structures. One approach which can be used to better evaluate timber's performance in fire is numerical modelling, which is often used in synergy with some form of fire testing. The authors have reviewed literature primarily published over the past five years to determine the state of the art of modelling timber at elevated temperatures. Following this review, an a priori model of a cross-laminated timber (CLT) ceiling subjected to a localized fire was developed in LS-DYNA to determine what datasets are currently required to better calibrate a thermal model of timber at elevated temperatures. Datasets include the flame spread rate of CLT, the heat flux produced by CLT, charring rates at high heat fluxes, and criteria for the extinction of timber.

1.0 Introduction

While timber itself is not a new structural material, mass timber structural systems are being used in increasingly taller and complex building designs (Perkins&Will n.d.). Building with timber has several advantages, such as its biophilia effects (Ikei et al. 2017), environmental benefits (Oliver et al. 2014), as well as architectural appeal. These contemporary designs are often concentrated on either the residential (small compartments) or commercial (large open-plan spaces) sectors. In large open compartments, it has been observed in non-combustible structures that non simultaneous fire propagation across the floorplate is possible which is in disagreement with traditional approaches to fire dynamics for small enclosures (Rackauskaite et al. 2021a). Timber is a combustible material, and the presence of exposed timber will add a fuel source and allow flame spread through the compartment further complicating fire dynamics in exposed timber compartments. Therefore, it is important to have suitable design methods for exposed mass timber compartments.

A prescriptive approach to ensure safety in design is to completely encapsulate all mass timber members. However, often there is a desire in design for the timber to be left exposed. In some cases, the timber can be overdesigned using the Reduced Cross-Section Method. This method accounts for the reduction of the cross-section of a timber member due to charring based on the time exposed to fire. The method assumes that the charred region (plus an additional allowance) will lose all strength while the remaining portion of the cross-section retains its full strength (CSA Group 2014). It should be noted, however, that the reduced cross-section method only accounts for the lower capacity of a timber member after being exposed to a fire. This method does not address elements such as the fire dynamics of having an exposed, combustible surface in a compartment. Therefore, additional criteria, other than only the remaining capacity, should be examined to determine if the timber member should be exposed.

Encapsulation of a timber member with a fire-rated material typically takes the form of a Type X gypsum (CSA Group 2014). Adequate fire testing and correct implementation on-site are necessary to avoid premature failure of the material (Law and Hadden 2020). In the event of encapsulation failure, the combustible structure would become exposed to the fire which can impact the stability of the building. Building designs that have both encapsulated and exposed timber structure in the same compartment would need to consider the impact of the exposed timber on fire dynamics and the fire resistance requirements of both the structure and the encapsulation.

Additionally, current design proposals consider high-rise mass timber buildings. Questions have been posed by researchers and designers that current building and fire codes may not be designed with such structures in their scope (Cowlard et al. 2013). Several of these tall timber buildings are designed to be a hybrid of several structural materials, using each material to its advantage. For example, Brock Commons is an 18-storey timber-concrete hybrid structure. The timber components make up the floor slab and columns, whereas the concrete is used to construct the core of the structure (Think Wood n.d.). Other hybrid designs such as a CLT slab with steel beams are also being used due to the environmental and speed of construction advantages (Hagan 2021).

For the design of buildings which may not fall within the parameters of current prescriptive methods, alternative solutions are required. A common approach to verifying the performance of an alternative solution is to perform a comparative risk-based analysis to a non-combustible building (Ministry of Natural Resources and Forestry 2017). Other approaches include a semi-qualitative method in which either the consequence of an unwanted event or the frequency of these events is quantified. Finally, quantitative approaches also exist. These approaches often require computational tools and can consider both the consequence and frequency of unwanted events and are more robust. If the risk of an alternative solution can be shown to have a risk no greater than a current acceptable solution, then the proposed alternative solution may be considered acceptable (Craft 2018).

A typical approach that, when properly validated, can be used to analyze an alternative solution is numerical modelling and more specifically finite element modelling. Finite element modelling can allow practitioners to analyze proposed alternative solutions for designs that include irregular geometries and unusual boundary conditions. Furthermore, after a model has been validated against experimental data, the model can be used to analyze the effects of minor changes to determine what criteria govern the design. Once the behaviour and governing criteria of the systems and materials are better understood, generalized solutions can be developed for these complex designs. Numerical modelling can also be used to guide the development of an experimental program.

The purpose of this study is 1) to perform an in-depth review of the current state of modelling of the fire performance of mass timber structures and 2) present an a priori finite element model that helps to identify knowledge gaps that are required to be addressed to develop numerical models capable of being used in the design of modern mass timber designs. As engineered timber is being used with newer design constraints, such as leaving it exposed, additional knowledge about the performance and behaviour of timber in these designs is required to ensure safety in the event of a fire. As these applications of timber are new, there have not yet been many research programs to address the performance of timber. While the use of a validated model can be a method of addressing these knowledge gaps, due to the lack of research programs there are not many data sets to validate the model against. Therefore, these knowledge gaps must be addressed through experimental study, at least until models will be able to be validated with confidence. The results of this review will highlight current gaps in the knowledge base which are preventing more accurate models from being validated so that can be extensively used by practitioners as another tool to analyze the performance of an alternative solution when prescriptive routes are not desirable.

2.0 Current Methodologies of Timber Design

Regarding modelling timber in fire, two knowledge areas need to be understood that are interlinked due to the combustible nature of the timber. The first is compartment fire dynamics and the thermal exposure to the structure. Secondly, the thermal and mechanical response of the structure.

2.1 Compartment Fire Dynamics

As opposed to other contemporary structural materials, timber is combustible. Therefore, when timber is exposed to a fire, it will contribute fuel to its own burning as well as allow the flames to propagate and overall increase the severity of a fire (Hopkin et al. 2020; Lange et al. 2020; Węgrzyński et al. 2020).

For a conventional compartment fire, there are three main phases the fire can experience, the growth phase, fully developed phase, and decay phase. All fires begin with a growth phase. During this phase, the fire first begins and starts to spread throughout a compartment. If the flames are not extinguished (by means of either suppression or auto-extinction due to lack of sustained burning), the fire may reach flashover. A definition of flashover describes it as being the point when all temperatures within the compartment achieve at least 600 ^{o}C, or the radiation to the floor of the compartment reaches 15 – 20 kW/m^2 (Karlsson and Quintiere 1999). Regarding the auto-extinction of a fire involving timber, researchers have several opinions on the exact definition. This is because timber will continue to combust, in the form of smouldering, after the end of flaming. Smouldering is a phenomenon that can occur post-burnout of a compartment and is a slow and low-temperature form of flameless combustion that involves surface oxidation of the char layer (Drysdale 2011; Rein 2009). Due to the presence of multiple forms of combustion, some researchers consider auto-extinction to mean when the flames have been extinguished (Bartlett et al. 2016; Emberley et al. 2017), whereas others consider it to be the termination of any combustion process including smouldering (Crielaard et al. 2019). Wiesner et al. (2019) have noted that once in the decay phase of a conventional compartment fire, exposed timber members will continue to deteriorate due to a "… continued propagation of a thermal wave beneath the char layer (Wiesner et al. 2019)." Furthermore, Wiesner et al. (2019) recommend that designs for tall timber buildings should consider the decay phase of fire when sizing members, even though local prescriptive design methods may not explicitly state to do so (Wiesner et al. 2019).

For a typical compartment when flashover is reached, the fire will have moved into the fully developed phase in which the highest temperatures will be met. Afterwards, the fire will enter the decay phase in which the temperatures and energy release rates will decrease (Karlsson and Quintiere 1999). Although this method alongside a standardized time-temperature curve has been commonplace, designers have recently been utilizing newer, time-temperature curves to better capture the behaviour of fires being observed in compartments which the standard time-temperature heating curve was not necessarily intended to represent (Gales et al. 2021).

The use of alternative time-temperature curves acknowledges that the standard curve does not represent real fire. Particularly, the standard time-temperature curve does not account for the lowering temperatures of the decay phase of a fire. This impacts contemporary building designs, which are incorporating large open spaces. It has been observed that in large compartments of steel and concrete structures, a fire behaves differently than what is proposed by conventional flashover fire dynamics and the standard time-temperature curve (Zhang et al. 2013). Rather than an instance where the entirety of the compartment is involved in the fire simultaneously, the fire will grow non-uniformly across the floor plate and/or stories (Rackauskaite et al. 2015). For longer duration fires, if a model uses uniform gas temperatures there could be significant errors in the thermal and structural analysis (Rackauskaite et al. 2015). Figure 1 illustrates an arbitrary comparison of the standard time-temperature curve, calculated parametric curves, and travelling fires. The parametric curves are meant to include the heating and cooling phases of different compartment fires. The travelling fire time-temperature curves are meant to represent a localized fire travelling through a compartment. In this scenario, different locations in a compartment will be heating and cooling at different times during the fire.

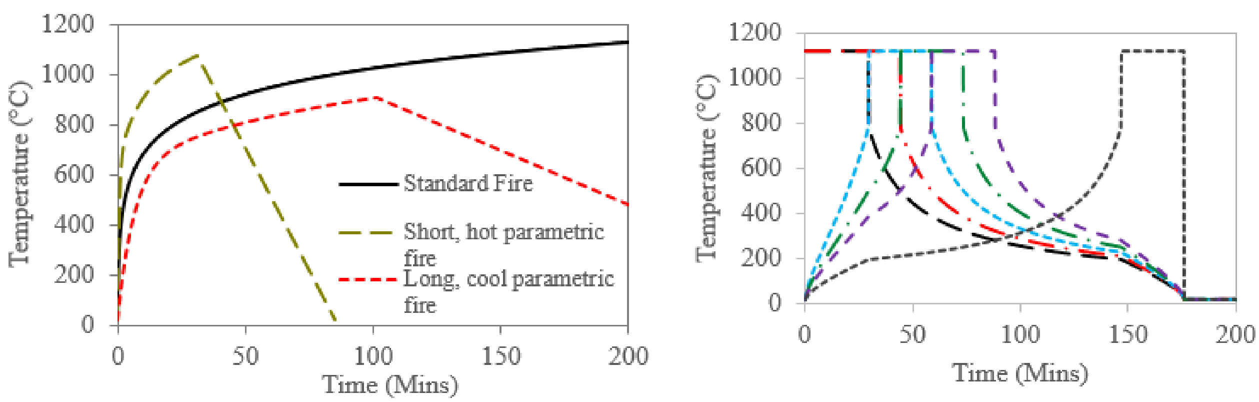


Figure 1: Different design fire examples including (Left) the standard fire, two-sample parametric fires and (Right) a sample travelling fire as it progresses through a fixed dimensioned compartment of 20 x 20m (Adapted from Gales et al. (2021))

For non-combustible materials such as steel and concrete, simplified methods have been developed to assess the effects of these non-uniform (travelling) fires (Dai et al. 2020; Heidari et al. 2019; Rackauskaite et al. 2015). Through past experimental and computational research, there has been evidence that during a localized fire the peak temperatures in materials can exceed that of a post-flashover fire (Rackauskaite et al. 2017). Furthermore, the localized fires can create non-uniform temperature distributions in which simultaneous heating and cooling is occurring (Zhang et al. 2013).

While research is currently being conducted on non-uniform fires, very little has focused on the use of combustible materials. The use of exposed timber in large compartments creates several complications in a design. As outlined in Rackauskaite et al. (2021) these challenges involve a lack of data for combustible materials including fire sizes, fuel load, heat release rate, near field heat flux, and far field thermal exposure (Rackauskaite et al. 2021b). In the context of this study, near field represents flames directly impinging on the ceiling from an external source, whereas far field represents the cooler temperatures away from the direct impingement.

Convection effects in compartment fires are associated with the transfer of heat by the motion of a fluid, which often arises naturally, or is forced when external factors are present, and is the primary mode of heat transfer in the early stages of a fire. The heat transfer convection heat transfer coefficient is related to the heat flux and the difference in temperature between a solid and the surrounding fluid. Most of the available literature regarding timber fire modelling has considered a convection coefficient of 25 W/m^2K, aligning with the standard temperature time curves which are being modelled. Eurocode 1 Part 1-2 recommends a convection heat transfer coefficient of 25-50 W/m^2K depending on the temperature time curve considered (European Committee for Standardization 2002).

Additionally, another approach used in fire design is compartmentation, which is to contain a fire in its room of origin. This approach intends to ensure the fire will decay even if not suppressed. This will allow for safe egress, firefighting access, and resilience to the structure. However, due to smouldering induced by the combustible nature of timber, during what would be the traditional decay phase of a compartment fire, the structure may continue to lose strength and resilience.

2.2 Performance of Timber in Elevated Temperatures

When designing timber structures, additional considerations are required to account for timber's combustible nature. Currently, there are a limited number of prescriptive methods to design for timber in elevated temperatures. These methods such as calculating a char depth (CSA Group 2014) have the potential to be overly or under-conservative, depending on the impact of timber on fire dynamics. Within the method of calculating a char depth, typically an additional layer referred to as a zero-strength layer is added to the char depth to account for the possible reduction in strength of cross-section which may have been exposed to high temperatures (CSA Group 2014). While the zero-strength layer does acknowledge that timber will lose strength before reaching 300^oC and charring, it does not account for the fact during cooling, heat will penetrate further into the cross-section and potentially reduce the strength of the entire cross-section (Gernay 2021). Until further research is performed to deepen the understanding of the performance of timber, current prescriptive design methods may not be adequate to account for these uncertainties for exposed timber structures, particularly large compartments where a long decay period is likely.

One important characteristic of timber is that it retains moisture (Werther et al. 2012). Once temperatures of a timber member reach 100^oC the moisture will begin to evaporate which consumes thermal energy and delays the heating of the timber. Difficulties arise to account for this as once the timber member heats up some of the moisture will migrate making it difficult to identify the amount of moisture evaporation occurring in a given moment. One approach is to increase the specific heat of timber within the range of 99^oC to 120^oC as described in the Eurocode 5 (European Committee for Standardization 2004). The increase in specific heat accounts for a greater amount of energy required to increase the temperature of the timber member. After 120°C it is assumed that all moisture has evaporated and the artificial increase in specific heat is taken away. Alternatively, designers can follow a latent heat/enthalpy approach (Werther et al. 2012). For this, a user-defined moisture content is modelled as latent heat. This allows for a model of the timber element to non-explicitly account for moisture within a member and does not require a peak in specific heat values. Some commercial software can automatically follow this latent heat method while most other packages can have this method be implemented.

Due to the smouldering of timber, additional design considerations are required. Design procedures do not typically account for the performance of timber while it smoulders during the decay phase. When timber burns, it creates its own heat, which in turn has the potential to heat material found deeper in the member. This in turn can cause more material to be included in the combustion process even after flaming combustion has been extinguished. Therefore, timber can continue to combust and potentially fail long after a fire has been considered extinguished in a compartment (Gernay 2021). While smouldering, the effective cross-section will continue to decrease as the material degrades during combustion until it finally has an assumed zero strength when charred. Additionally, during or after a fire, sections of char can fall off or delaminate from the timber member. Without this protective layer, portions of the cross-section which may have previously not been involved in the fire may now combust due to either a continuing fire or smouldering depending on the current state of the compartment fire (Medina 2014; Su et al. 2018). Current prescriptive methods, such as the Reduced Cross-Section Approach from Annex B of the CSA O-86 (CSA Group 2014), do not explicitly consider the decay phase of a fire. It has been shown that timber members can fail post-burnout due to the continued combustion via smouldering (Gernay 2021).

Designers have utilized various fire safety strategies which either reduce the risk of a fire growing to the point where it poses a threat to the structure or prevent timber and other combustible materials from becoming involved in the fire. A common approach is to use a fire-rated Type X gypsum to encapsulate any combustible surface (Law and Hadden 2020). While these methods can prevent the underlying material from becoming involved in a fire, the encapsulation could still fail in a fire if its performance is not adequately tested, or if it is not implemented properly during construction (Chorlton et al. 2021). The drawbacks of encapsulation are its larger environmental footprints due to the use of redundant layers of protection, covering the timber, as well as increasing the time of construction. These drawbacks are opposing the benefits of timber which are its environmental strength, the desire for exposed timber, and its rapid rate of construction. By having a deeper understanding of timber's behaviour and performance in fire, solutions can be developed which allow for complete or partial exposure of the timber surfaces.

3.0 Current State of Timber Modelling

The use of numerical models to assess the performance of timber in fire is a topic of current interest and several studies have been performed to validate this ability of current software packages. In one of the earliest studies, Werther et al. (2012) found that finite element software such as ANSYS, SAFIR, and ABAQUS are capable of modelling timber, however, some accounted for the moisture content of wood more intuitively than others. Where some software could automatically account for moisture as a latent heat, others would have to be manually set to account for moisture in this method. Otherwise, when accounting for moisture with a discontinuity in the specific heat of wood as prescribed by Eurocode 5 it was found that smaller timesteps (greater computational time) were required to avoid divergence (Werther et al. 2012). While accounting for latent heat may produce a less conservative design, it may be more representative of the actual performance of the timber assuming the moisture content used is realistic. From a designer's perspective, accounting for latent heat can lead to more efficient use of the material as there will not be a need to overdesign to account for the unknown heat flowing through the members. From a modeller's viewpoint, accounting for latent heat can reduce discrepancies from the model results to experimental data (i.e., model producing overly conservative results.

The capabilities of modelling the rate of pyrolysis and charring when a timber member is exposed to high temperatures have also been researched. Thi et al. (2017) utilized a user-defined subroutine, UMATHT, in ABAQUS to model heat transfer through structural timber members. The model developed by the researchers was capable of identifying the locations of the char layer, pyrolyzed wood, dried wood, and wood at ambient temperatures (Thi et al. 2017). Geometric configurations included a small-scale laminated veneer lumber (LVL) sample and a large-scale cross-laminated timber (CLT) beam.

Xing et al. (2021) developed a model to determine the char depth and zero strength layer of a CLT panel for both when the char layer remains intact and when there is char fall off under the ISO 834 standard fire (International Organization for Standardization 2014) or natural fire. The natural fire is based on previous experimental data collected by Wang (2019). Xing et al. (2021) found that in most cases the results of the model were in good agreement with charring rates stated from Eurocode 5 (European Committee for Standardization 2004). Overall, the model was considered to adequately capture the performance of the CLT panels.

Quiquero et al. (2020) used ABAQUS to develop a finite element model of post-tensioned timber beams under both ambient and fire conditions. In terms of thermal analysis, the temperature gradients and char depths aligned with the results of other experimental studies. A main challenge encountered in the thermal modelling was to adequately capture the effects of moisture evaporation (Quiquero et al. 2020). It was noted that discrepancies at the end of the trials may be due to the model not accounting for the continued combustion due to smouldering of the timber member. Additional studies into complex timber members have been performed by Kleinhenz et al. (2021). This study investigated temperature-dependent thermal properties of "CLT rib panels". The rib panels are composed of glulam columns (the rib) which are evenly spaced out and sandwiched by two CLT panels. Additionally, work has been performed to develop models capable of analyzing timber-concrete composites (TCC). Bedon et al. (2018) tested the capabilities of analyzing a TCC beam-type slab with in-house finite-element software, COMP-WOOD.

Chen et al. (2020) developed a constitutive model which was able to simulate the temperature gradient, deformation, and failure mode of an LVL beam and a glulam bolted connection which were loaded and subjected to elevated temperatures. This model accounts for the post-peak softening of timber in tension and shear, the plastic flow and hardening of timber in compression, as well as a second hardening in compression. Gernay (2021) developed a numerical model within SAFIR to assess the response of timber columns that experience a “standardized natural fire”. This standardized natural fire follows the Eurocode parametric fire model (European Committee for Standardization 2002), where the heating phase is similar to that of the standard ISO 834 curve (International Organization for Standardization 2014).

There have also been researchers who have approached thermal modelling of timber with different methods other than finite element analysis. Examples of such attempts include modelling the chemical kinetics of timber combustion. Recent studies of kinetic modelling can be found in (Richter et al. 2019, 2021; Richter and Rein 2020). In addition to the finite element and chemical kinetic models previously described, studies have been performed using a fundamental mechanics approach such as by Wiesner et al. (2021), in which they analyzed the capacity of one-way CLT panels in standard and natural fires.

Table 1 provides a brief summary of the literature discussed. As illustrated in Table 1, most studies discussed are not applying their models to natural fire exposures. Additionally, it can be seen that there is little done to account for the smouldering of timber within a timber model.

While there have been several research studies to investigate the capabilities of modelling timber, they typically follow conventional compartment fire dynamic theories. With the current demand to construct timber buildings with open plan, well-ventilated spaces, these models and their results may not be robust enough in considering all possible fires. However, at this time further data and research are needed to understand the fire dynamics for these types of compartments. The current lack of experimental data should be noted when comparing the current state of timber modelling when compared to that of other materials. Materials such as concrete and steel have had large experimental studies such as the fire experiments performed at Cardington (Kirby et al. 1999; Rackauskaite et al. 2021a, b), whereas exposed timber construction is only currently receiving attention with regard to large-scale compartment experiments such as those performed recently as part of the CodeRed series of experiments (Kotsovinos et al. 2022). This lack of experimental data for timber is likely because steel and concrete are being used in complex applications for a very long period of time, allowing researchers to undertake experiments and develop and validate numerical models.

Table 1: Literature Review Summary

Year	Author	Primary Focus	Thermal Exposure	Thermal Model	Mechanical Model	Pyrolysis	Moisture (Specific Heat)	Moisture (Latent Heat)	Smouldering
2012	Werther et al.	Modelling Heat Transfer	Standard Fire	X			X	X	
2017	Thi et al.	Modelling Heat Transfer	Standard Fire	X		X	X		
2018	Bedon et al.	Timber-Concrete Composite	Standard Fire	X	X		X		
2019	Richter et al.	Chemical Kinetic Model of Timber Charing	Constant Heating Rate	X		X			
2020	Richter and Rein	Chemical Kinetic Model of Timber Pyrolysis	Steady Heat Flux	X		X	X		
2020	Quiquero et al.	Numerical Model of Complex Timber Elements	Standard Fire	X	X			X	
2020	Chen et al.	Constitutive Model	Standard Fire	X	X		X		
2021	Gernay	Fire and Burnout Resistance	Standard and Natural Fires with Cooling Phases	X			X		X

2021	Xing et al.	Modelling CLT in natural and standard fires	Standard and Natural Fires	X	X	X			
2021	Kleihenz et al.	Temperature dependant thermal properties	Standard Fires	X		X	X		
2021	Wiesner et al.	Semi-Probabilistic Model of CLT	Standard and Natural Fires		X				X

4.0 Development of an A Priori Model

From the previous sections, it is clear that there is an absence of models regarding the performance of timber in open-plan, well-ventilated spaces and the lack of experimental data that would help validate such models. In order to determine which data gaps have the greatest impact on a numerical model being able to provide an accurate representation of timber's performance in these spaces, a finite element model was developed, by the authors, with such purpose in mind. The purpose of the model considered herein is to identify datasets that should be collected experimentally that will allow for model calibration. The intent is not to precisely calibrate a thermo-mechanical model, but rather to understand which data sets are needed for calibration and recommend instrumentation for future experimental studies. Future research (not included within the scope of this paper) could then perform the appropriate experiments and develop a calibrated model and simplified analytical methodologies for understanding the fire performance of open plan, well-ventilated timber structures.

4.1 Methodology of Model

The a priori model was created using LS DYNA, a general-purpose nonlinear finite element program that accommodates changing boundary conditions, large deformations, nonlinear materials, and transient dynamic events (LS-DYNA 2020). The mathematical theory of the heat transfer equations used in the LS-DYNA solver is based on the assumption that the change in internal energy is equal to the change in conduction in and out of the system, plus any heat sources/sinks present (Shapiro 2012). LS DYNA is capable of modelling both the thermal and structural response and therefore this model could be expanded in the future to include structural aspects, after relevant validation against experimental data.

Solidworks was used to create the geometry whereas Altair Hypermesh generated the mesh. Oasys Primer was for the preprocessing which involved defining the boundary conditions, initial conditions, material properties, solution control, and output parameters. Finally, Oasys D3Plot was used for the postprocessing which involved plotting the results of the parameters with respect to time.

4.1.1 Material Properties Used for Model

The CLT panel modelled as a ceiling will be designed under the assumption of future experiments that will be undertaken following the results of this analysis for model validation. Therefore, the moisture content of the CLT is assumed to be 8% which is a typical value if the panel were to be stored in a laboratory setting (Williams 1999). The emissivity of the timber was taken as 0.8 as per Eurocode 5 (European Committee for Standardization 2004), and the coefficient of heat transfer by convection was taken as 25 W/m^2K as per Eurocode 1 part 1-2 (European Committee for Standardization 2002). It should be noted herein that the convective heat transfer coefficient of 25 W/m^2K is specified for standard temperature time curves (e.g. as defined by EC 1 1-2 (European Committee for Standardization 2002)), and has been widely used for the purposes of modelling timber subject to standard temperature time curves. However, in this case, a nonstandard fire is considered, and there is little available information regarding the most appropriate parameters and inputs for nonstandard fires. The objective of this model, however, was to create a starting point using readily available parameters that can be used to identify data sets needed for collection. The convection coefficient of 25 W/m^2K is therefore adequate for this purpose. This value is also in line with previous research that has shown the convection coefficient to be between 10-40 W/m^2K for compartment fires (Tanaka and Yamada 1999). Additionally, values for thermal conductivity were taken from Eurocode 5 Annex B (European Committee for Standardization 2004) and are summarized in the paper's supplemental data (Table S1). Within LS DYNA the timber was modelled as thermal material type 10; characterized as being thermally isotropic, with properties that are temperature dependent and can be defined by load curves. These features allow for properties such as specific heat capacity and thermal conductivity to be defined as a function of temperature.

The specific heat capacity was also determined from Eurocode 5 Annex B (European Committee for Standardization 2004), however, the discontinuity between 99^oC and 120^oC (372 K and 393 K) were omitted. This was done to account for the moisture via a latent heat approach rather than through the discontinuity as described by Werther et al. (2012). Taking the heat of evaporation of water to be 2260 kJ/kg and with the moisture content being 8%, the latent energy of the moisture in the CLT panels can be calculated to be 180 kJ/kg_{wood} following Equation S1 in the paper's supplemental materials.

4.1.2 Determination of Suitable Mesh Size

A sensitivity study was completed to determine an appropriate mesh size. This mesh sensitivity analysis considered mesh sizes of 3 mm, 5 mm, and 10 mm as these sizes align with previous studies while also aligning with the dimensions of the CLT panels. Additionally, a mesh size of 1 mm was examined to verify that the larger meshes converge. The dimensioning for this verification analysis is based on the heat transfer model outlined by Thi et al. (2017) and the tests performed by Menis (2012), which involve a 150 mm thick CLT panel, with a moisture content of 12%, a density of 460 kg/m^3, and subjected to ISO 834 (International Organization for Standardization 2014) thermal exposure. The test performed by Menis (2012) was used as a reference as this test series is similar to the purpose of this model (i.e. CLT panels exposed to fire from their soffit). This test series was also selected as it clearly reported the temperatures throughout the test duration at several depths of the CLT panel. While the data collected was able to provide a temperature gradient through the CLT panels, there are some limitations. Primarily the experiment was not instrumented to capture the heat fluxes at the soffits of the panels, or flame spread along the panels. Experimental data relating to the heat fluxes along the soffit of the panels and the flame spread along the panels would be useful in calibrating a model to better estimate the impact of a burning CLT panel on a compartment. Secondly, due to safety concerns, some tests concluded early and the resulting data do not reflect the entire test.

Figure 2 illustrates the results of the mesh analysis. The results are compared to the modelling results of both Thi et al. (2017) and Menis (2012), as well as the data from two experimental tests performed by Menis (2012). From the mesh sensitivity analysis, it was determined that a 3 mm mesh size would be adequate for this modelling endeavour of identifying data sets needed for future model calibrations. Through the analysis, it was found that the 3 mm mesh size produced nearly identical results to that of the 1 mm mesh size while only requiring 4% of the computational time. For comparison, the final temperature difference at 60 minutes between the 3 mm and 1 mm mesh size was 1% at 21 mm depth, and 2% at 52 mm. Thus, the increased computational time to continue using the 1 mm mesh size is not justified for such a small discrepancy in results. Although the 5 mm and 10 mm mesh sizes had faster computational times, they did not readily converge with the 1 mm and 3 mm meshes and were discarded.

As stated earlier, the soffit of the CLT panels will be exposed to the fire in this model. As a baseline, the thermal boundary conditions of the area of CLT directly above the localized fire were characterized as radiation and convective contributions from the pool fire. The pool fire will consist of 14.3 L of methanol in a pan which measures 0.48 m x 0.6 m. This boundary condition does not account for the contribution of the timber, and therefore experimental results could expect to see different temperatures or heat fluxes.

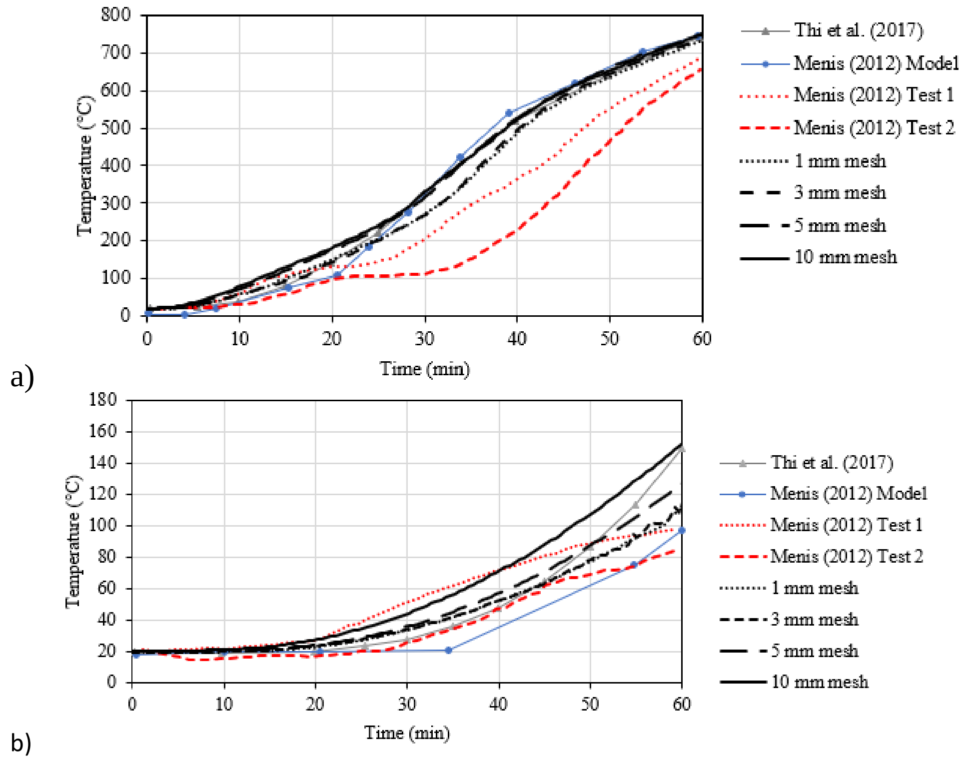


Figure 2: Comparison between predicted temperatures of different mesh sizes, with measured temperatures and previous studies by other authors at a) a depth of 21 mm and b) a depth of 52 mm.

4.1.3 Studies Used for Verification Study

To verify that the model works as intended, two previous experimental studies (Chorlton 2021; Quiquero et al. 2018) were also modelled. In this context, verification indicates testing that the model meets the requirements at this stage of development, whereas validation would ensure a final model meets the needs and expectations of the model. The first experimental study (Quiquero et al. 2018) considers five Glulam beams with cross-sectional dimensions of 45 mm x 195 mm. These beams were exposed to a kerosene pool fire for 10 minutes on each of the longer sides of the beams (i.e., one of the 195 mm sides was exposed to the pool fire, then the member was flipped to allow the opposite side to be exposed to the pool fire). The char depth was found to be 5 mm +/- 1 mm (Quiquero et al. 2018). The second experimental study involves two heritage timber members (Chorlton 2021). These members had an average density of 657 kg/m^3 and a moisture content of 10%. The heritage members were exposed to a 30-minute methanol pool fire. The maximum char depths on the soffit of 25 mm and 21 mm for the first and second trials.

For the model verification, the heat flux was calculated from the fuel, based on the burning rate and the heat of combustion of the fuel (Drysdale 2011). The mass burning rate was taken as 0.039 kg/m^{2}s for kerosene and 0.017 kg/m^{2}s for methanol, while the heat of combustion for the fuels was taken as 43,200 kJ/kg and 20,000 kJ/kg respectfully (Society of Fire Protection Engineers 2016). The empirical constant was further used for heat release rate calculations of the fuel representing the product of the extinction absorption coefficient and the beam-length corrector was taken as 3.5 m^{-1} for kerosene (Babrauskas 2015). Heat release rates were calculated following Equation S2 (Babrauskas 2015) in the paper's supplemental materials.

The incident heat flux on the members was taken as the heat release rate of the fuel due to the proximity of the fuel. The incident heat flux on the soffit of the members was therefore taken as 52.6 kW/m^2 for the glulam members (kerosine pool fire) and 24.2 kW/m^2 for the heritage members (methanol pool fire).

4.1.4 Determining Uncertain Fire Parameters

Current methodologies for non-combustible compartments consider several parameters for the design of non-uniform fires. These include flame length (as a function of ceiling height and heat release rate), incident heat flux on the ceiling relative to the location of localized fire flames, fire spread rate, time for fuel to auto-extinguish, and ambient room temperature, among other parameters (Heidari et al. 2019). As previously mentioned, adapting existing methods for timber structures becomes challenging due to the contribution of the timber to the fire, as well as the lack of existing data regarding the thermal performance of CLT ceilings. There is limited experimental evidence available regarding the fire spread and extinction rates of CLT ceilings, as well as expected heat fluxes or temperatures in the near and far field regions.

In terms of available information regarding fire spread and extinction rates, there has been some investigation regarding non-combustible structures, as well as flame spread/extinction along the top of wood cribs. Gupta et al. (2021) looked at the flame spread characteristics of wood cribs, considering the experimental setup and results of the Malveira Fire Test, from which the location and velocity of the flame front were determined (Gupta et al. 2021; Hidalgo et al. 2019). Additionally, there are recent fire tests with the purpose of examining natural fires in open-plan compartments. An example of which are the x-ONE and x-TWO experiments also considered full-scale experimental tests of large-scale, open plan non-combustible structures, in which it was found that the fire was observed to travel with clear leading and trailing edges (Heidari 2021; Heidari et al. 2020).

From a review of the literature, it was found that the parameters of incident heat flux, flame spread rate, and extinction rate are lacking detail as to what might be expected when considering CLT ceilings. Additionally, there is a lack of knowledge of the impact a burning CLT ceiling has on the rest of a compartment such as the vertical temperature gradient or heat flux experienced at the floor level. There is a need to understand likely heat fluxes and flame temperatures of CLT ceilings in the near-field region. For this, a localized fire underneath the ceiling will be considered, with two incident heat fluxes. These heat fluxes will be taken as 23.9 kW/m^2 (Tewarson and Pion 1976) and 77.5 kW/m^2 (Petrella 1979), meant to represent the high and low end of heat fluxes provided by timber flames as observed in literature. In the studies by Tewarson and Pion (1976), as well as by Petrella (1979), the researchers examined the ideal burning rate in which small samples of various combustible materials, including several timber species, were exposed to radiant heat. The heat flux provided by the materials' flames was then calculated. It should be noted that the heat fluxes considered are meant to represent a range of values, more than accurate values that would be expected, as expected heat fluxes and flame temperatures specific to the soffit of CLT ceilings have yet to be experimentally collected. It should also be noted that these heat fluxes consider only contributions from the timber ceiling and not from external fuel sources. From this analysis, parameters needed for calibration will be explored.

Dimensions of the ceiling strip were selected as 0.5 m x 0.1 m x 2.4 m, chosen as large enough to observe heat transfer through the depth of the ceiling and along the length, but not so large as to cause unnecessary computational expense. The thickness of 0.1 m is aligned with available CLT thicknesses, and the length of 2.4 m is a scaled-down version of what could potentially be considered in experimental tests.

In terms of relevant information to use as a starting point for horizontal flame spread and extinction rates of CLT ceilings, to the authors' awareness, there is no readily available data. Data in general regarding fire spread rate in realistic fires is limited, though some data has been reviewed by Rackauskaite et al. (2015) based on a review of available experimental data and by Grimwood (2018) based on fire-fighter collective experience. Collected fire spread rates include the reconstruction of the World Trade Centre Fired, tests on natural fires in large scale (non-combustible) compartments, the St. Lawrence burn tests from 1958, and the First Interstate Bank fire from 1988. Of these, fire spread rates ranged from 1.5 mm/s to 19.3 mm/s (Rackauskaite et al. 2015), however, all of the experiments examined considered non-combustible structures. Both the maximum and minimum flame spread rates are derived from tests by Kirby et al. (1999) which considered nine compartment fire tests at the Cardington lab. The structure was primarily concrete with insulated lining (ceramic fibre or plasterboard) with fuel provided by wooden cribs. Given the lack of data related to flame spread rates of combustible compartments, these data will be considered as a starting point for the a priori model considered in this study however, these setups are notably different from solid CLT members for several reasons, including that the flame is propagating along the porous crib, where in a CLT compartment it could be propagating along a solid ceiling. This again reinforces the need for experimentally collected data to understand the potential rates of fire spread and extinction of CLT ceilings.

Regarding appropriate extinction rates, to the authors' awareness, even less data has been collected than for flame spread. Of those that have considered the rate of the trailing edge are the aforementioned x-ONE and x-TWO experiments, in which a concrete building was fitted with wood cribs throughout the length of the building, and flame spread and the rate of the trailing edge were observed (Heidari et al. 2020). Two trials were performed with varying fuel load densities, the first with a higher fuel load density that had a non-constant rate of the trailing edge, and the second that had a lower fuel load density that did reach a steady-state rate of travel. For the purposes of this model, the steady-state rate of the trailing edge will be considered, which was evaluated to be 0.02 m/min (0.33 mm/s) less than the flame spread rate of the leading edge. This value again stems from experiments in non-combustible structures, highlighting the need for this data to be collected in combustible structures. Nevertheless, the values selected should be reasonable in achieving the objective of this study, recommending data sets for experimental collection using an a priori model. A summary of parameter values used within the a priori model is provided in Table 2.

Table 2: Summary of parameters used for the a priori model

Parameter	Value	Source
Moisture content of CLT	8%	Williams (1999)
Emissivity of timber	0.8	Eurocode 5
Coefficient of heat transfer	25 W/m^2K	Eurocode 1 Part 1-2
Mesh size of elements	3 mm	Through a sensitivity analysis with comparison to Menis (2012) and Thi et al. (2017)
Incident heat flux	Lower: 23.9 kW/m^2 Upper: 77.5 kW/m^2	Tewarson and Pion (1976) Petrella (1979)
CLT dimensions	0.5 m x 0.1 m x 2.4 m	Selected as it can be replicated in future experiments
Fire spread rates	Lower: 1.5 mm/s Upper: 19.3 mm/s	Rackauskaite et al. (2015) and Kirby et al. (1999)
Trailing edge rate	Lower: 1.17 mm/s Upper: 19 mm/s	Heidari et al (2020)

Important assumptions made in the creation of this model are assumptions related to delamination and char fall off, as well as assumptions related to auto-extinction. This model assumes that the adhesives do not allow for delamination, and char fall off is insignificant. Otherwise, additional fresh timber would be exposed to the thermal exposure following the delamination or char fall off, providing additional fuel to the fire impacting the severity of the thermal exposure. If the timber being modelled were to delaminate, several aspects of its fire performance would be altered, including its char depth. However, the current practice in many countries is to avoid char-fall off by adopting a CLT ceiling that their adhesive has been appropriately tested. Further, the current model assumes timber will auto-extinguish in that the timber will not experience continued flaming or smouldering combustion. These considerations need to be addressed by designers in addition to any numerical models.

4.2 Results of Model

4.2.1 Results of Verification Study

The temperature distributions of the Glulam as well as the heritage members used for verification are seen in Figure 3. In Figure 3, the red line at 300°C is used to visualize when a certain depth of timber might char. It can be seen in Figure 3 (left) which considers the Glulam beams, that the beam chars to a depth of 3 mm at approximately 7 minutes and 9 seconds, and the peak temperature at a depth of 6 mm is 262°C after 10 minutes. From the experiments, it was recorded that the beams charred to a depth of 5 mm +/- 1 mm. Through interpolation, it is expected that after 10 minutes, the timber would be at a temperature of 308°C at 5 mm from the soffit (and would be considered charred). The percent difference between the modelled char depth and the experimental char depth is 3.5%. The charring rate observed in the model is on average 0.52 mm/min over the 10-minute period. Figure 4 shows a comparison of the cross-section of the Glulam members post-fire, as well as the results of the numerical model. The cracking shown in the photograph was induced by the mechanical loading during post-heating experimental testing, and the projected initial areas as outlined in red are adjusted to account for these cracks.

Similarly, in Figure 3 (right), the heritage members are considered. The experimental tests of these members showed a char depth of 21 mm and 25 mm in the two trials. From the figure, it can be seen that the depth of 24 mm reaches a peak temperature of 292°C after 30 minutes. Interpolation between 24 mm and 21 mm shows that the depth which would reach 300°C after 30 minutes and would therefore be considered charred is found at 23.85 mm, well within the range observed in the experimental trials. The percent difference between the modelled char depth and the experimental char depth is 3.7%. The charring rate observed in the model is on average 0.80 mm/min over the 30-minute period. Figure 4 shows a visual comparison of the char depths at the end of the heat exposure of the experimental trial that showed a maximum char depth of 25 mm, and the numerical model. Note that in Figure 4, a heritage member is shown rather than an engineered member – the initial surface of the member was not perfectly even prior to fire exposure.

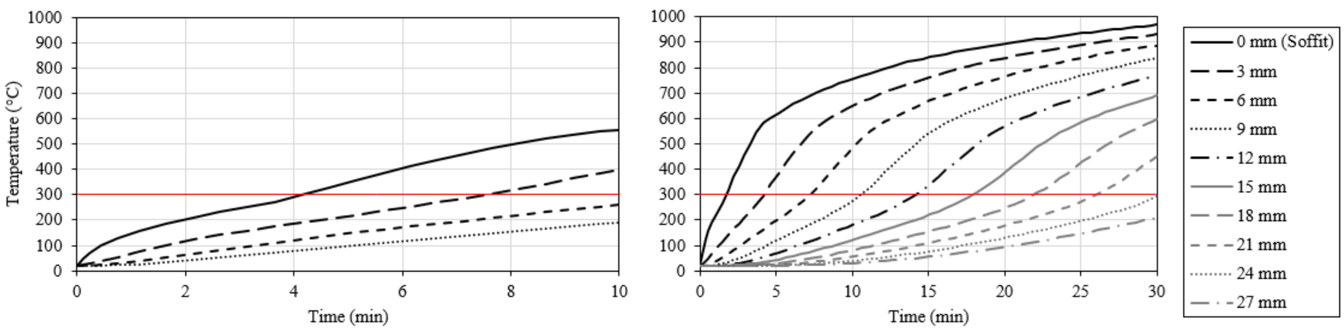


Figure 3: Temperature distributions of the Glulam members (left) and the heritage members (right). Depths in the legend represent the distance from the soffit of the member, red horizontal line indicates the anticipated charring temperature

a)

b)

Figure 4: Comparison of the charred member and numerical model of a) the Glulam members and b) the heritage members

Though the results of verification models showed good alignment with the experimental studies, it should be noted that in these models the thermal properties of timber were input as being reversible i.e. they will return to their original strength when the member is cooled down to ambient. This was done following the material properties outlined in Annex B of Eurocode 5 (European Committee for Standardization 2004) even though nonstandard fires were considered in this model, in an attempt to develop a modelling procedure that was accessible and straightforward. The Eurocode properties do not inherently consider cooling as they were developed with a standard fire in mind. However, the models considered for verification were short in duration, and cooling and auto-extinction were not considered. Had other heat exposures been considered, including those that have a cooling phase, the models may not have aligned as well with the experimental results. The choice of convection coefficient is one parameter that will impact the results. Though radiation may be the dominant mode of heat flux in compartment fires (Drysdale 2011), altering the convection coefficient (along with other parameters as outlined in Section 4.1.4) will impact the results as more experimental information becomes available, and the results will change (e.g., the temperature profiles and temperature distributions may be hotter as the parameters are changed). However, much of the discussion herein relates to identifying knowledge gaps and research needs required for model calibration, the current parameters including the convection coefficient are sufficient for this purpose.

4.2.2 Results of the CLT Flame Spread Model

Once the model was validated it was used to simulate the CLT panels being exposed to the two heat fluxes. The results of the heat transfer of the two heat flux models are shown in Figure 5, where the legend shows the distance from the soffit (the application of the heat flux). Figure 6 also shows the temperature distributions within the CLT ceiling at 15, 30 and 60 minutes. Further, the flame spread models were used to highlight the needs for data collection. The temperature distribution of the flame spread models is seen in Figure 7. It is seen that the temperatures, as expected, are highly dependant on the rate of flame spread and the rate of extinction. Figure 5 and Figure 6 highlight the importance of having a clear understanding of incident heat flux of the soffit of the CLT ceiling and its effect on temperature distribution throughout the depth of the ceiling. It was found that the maximum char depth of the models was 2.32 mm for the model with a flame spread rate of 19.3 mm/s, and 11.88 mm for the model with the flame spread rate of 1.5 mm/s (assuming that there is no residual smouldering on the member). The slower flame spread rate, therefore, had a maximum char depth of over 5 times the quicker flame spread rate, emphasizing the importance of flame spread rate in determining the damaged area of a timber member, and resultantly, the residual strength. Figure 7 further demonstrates the uncertainty related to flame spread rate, extinction rate, and the impact of these metrics on the temperature distribution of the ceiling, and as a result, the structural capacity of the ceiling.

In order to calibrate these models precisely, several datasets are recommended for experimental collection. The first being the heat flux distribution on the soffit of the ceiling, in relation to the position of the ignition source below the ceiling. Understanding the incident heat flux on the ceiling will allow for a better determination of the expected temperature profiles. The next required dataset is an assessment of flame spread rates, along the ceiling, if any. With an exposed timber ceiling, there is the potential for the ceiling to ignite and for the flame to propagate along the ceiling at a different rate of any fuel at the floor level. This flame spread rate may be non-constant throughout the fire. Following this, an assessment of burn-out rates/speed of the trailing edge of the fire, if any, is required. An understanding of the burn-out rate of the timber (if burn-out occurs) will give a better idea as to the overall projected size of the fire. The final dataset is the flame extension of the fire below the ceiling and its impact of flame spread across the ceiling and the fuel bed.

One aspect that was not considered within the model was the iterative nature of the timber's contributions to the thermal exposure. When timber burns, it creates its own heat, which in turn has the potential to induce additional charring. The primary reason that the iterative contributions of the timber to the thermal exposure were not considered was due to the limited information available for inputs. These missing inputs can be used to identify datasets that should be collected experimentally, along with the datasets needed for model calibration.

To gather the required datasets, some instrumentation is recommended for future experimental studies of flame spread along CLT ceilings. The first is an array of cameras positioned along the length of the ceiling. Cameras could help to determine flame spread rates, and potentially extinction rates of the ceiling. These can be used as model inputs. Further, cameras could further allow for qualitative observation. Next, thermocouples along the length of the CLT ceiling are recommended. At a minimum, these should include thermocouples on the top and soffit of the CLT at regularly spaced intervals. Intervals could be dependent on the length of the ceiling in the experiment in consideration. Recording temperatures along the top and soffit of the CLT will allow for an assessment regarding if the model is working as intended. Further, assessing the ceilings after the experiments for the undamaged depth of timber will give an idea of the depth of timber that reached 300 °C which could be further compared to the model. Measuring the temperature of the ceiling will be vital for model calibration. Finally, in order to measure the heat flux incident on the soffit of the CLT ceiling, plate thermometers are recommended. The incident heat flux should be measured directly above a potential ignition source (e.g., radiant heater or pool fire), and at periodic intervals along the length of the ceiling (e.g., every 300 mm or as is deemed appropriate).

In terms of data sets needed to incorporate the contribution of timber into the thermal exposure, several data sets should be collected experimentally. The first data set is the charring rates of timber at extreme heat fluxes. While charring data of timber is available, many tests accommodate lower heat fluxes as available through traditional apparatuses. Charring rates may be greater under larger heat fluxes, as might be expected in large fires. An accurate assessment of the charring rate will help to determine the amount of char formed during a given thermal exposure, and better estimate the contributions of the timber to the overall thermal exposure. Additionally, data about the heat flux generated by the timber itself should also be collected. While again there is some data available to this extent, the data is limited. It would also be useful to understand expected heat flux when flaming is present, and when smouldering is present. These datasets would also help to better determine the contributions of the timber to the overall thermal exposure. Furthermore, the criteria for extinction, if extinction is to be considered within the model, should be determined. This includes both flaming extinction and smouldering extinction. This will help to better understand the thermal environment predicted at a given heating or cooling state. Finally, data about the heat flux experienced at the floor level along with the thermal gradient along the height of a compartment should be collected. These datasets would help determine the impact of a burning timber ceiling on the rest of the compartment.

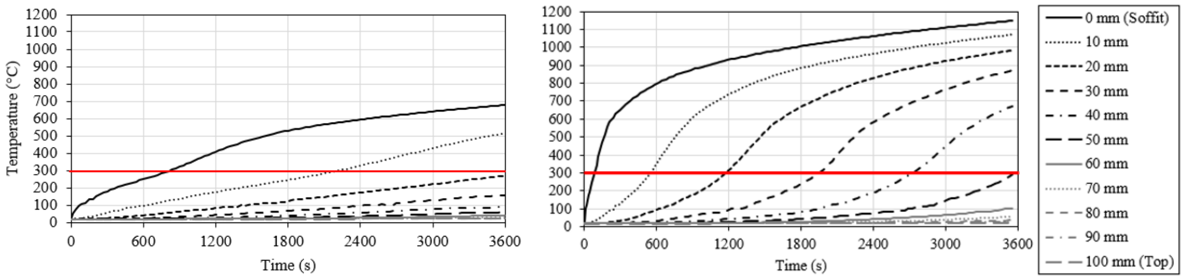
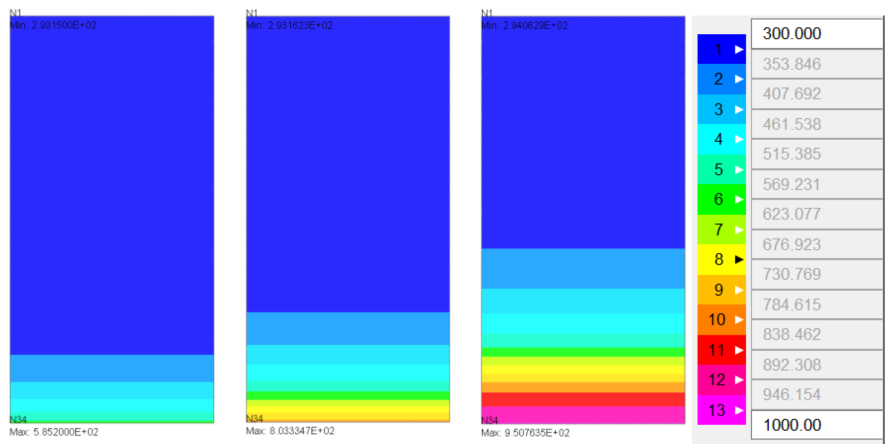


Figure 5: Distribution of temperatures based on heat fluxes applied at the soffit of a) 23.9 kW/m2 (left), and b) 77.5 kW/m2 (right). Depths in the legend represent the distance from the soffit of the member, red horizontal line indicates the anticipated charring temperature

a)



b)

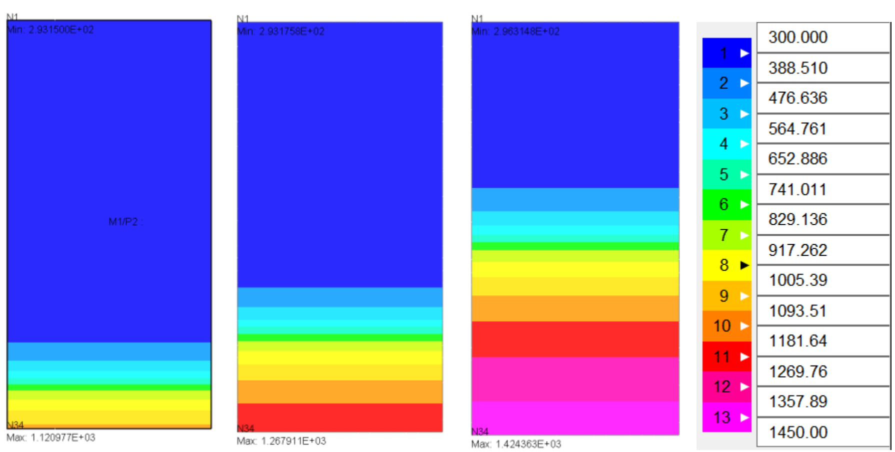
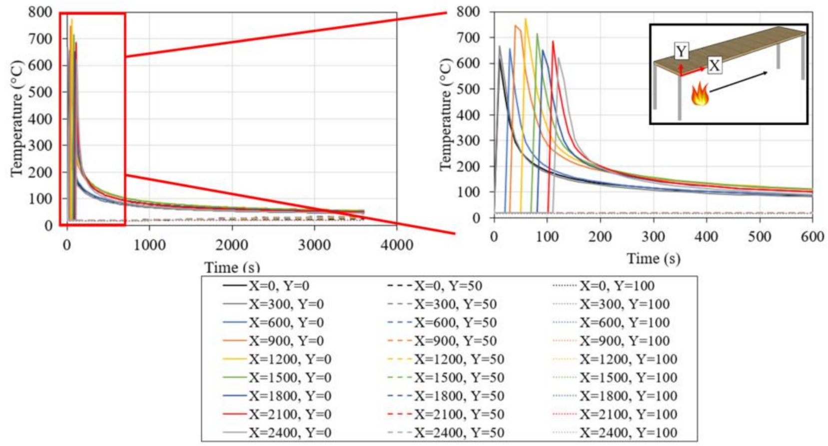


Figure 6: Temperature distributions throughout the CLT (from left to right) at 15, 30 and 60 minutes of a) an applied heat flux of 23.9 kW/m², and b) and applied heat flux of 77.5 kW/m² (units of temperature are K)

a)



b)

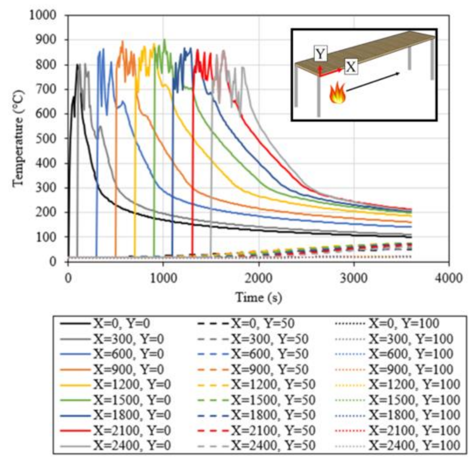


Figure 7: Temperatures at varying points along the ceiling considering flame spread rates of a) 19.3 mm/s and b) 1.5 mm/s

5.0 Conclusions

With the desire to construct mass timber structures with open plan, well-ventilated floor plans there is a need to gain a deeper understanding of the performance of timber in fire as well as the fire dynamics of these designs. Finite element modelling offers several advantages in the design and analysis of these types of spaces allowing a better understanding of the resilience of the structure under a range of realistic fire scenarios.

The purpose of this study was to identify current understanding with regards to modelling timber in fire as well as data sets recommended for experimental collection, to support the creation of future design methodologies which address open plan, well-ventilated timber structures. This was done by examining which data would be required for model input and calibration, using an a priori finite element model.

Reviewing the state of the art, it is observed that future research needs for the modelling of timber include the further development of thermal-structural models. These have begun to be addressed by other researchers (Quiquero et al. 2020; Gernay 2021; Chen et al. 2020), but additional modelling endeavours considering loaded thermal models could examine different thermal exposures (including nonstandard fires) and structural loading scenarios. This would help to make thermal-structural modelling of timber more established, contributing to the development of these models being used for design. Other properties unique to timber could be investigated through modelling. These include the effect of moisture content, including the effect of having varied localized moisture contents throughout the timber caused by moisture migration during heating. Current methods of accounting for moisture only account for the energy required to evaporate the moisture rather than simulate its movement throughout the timber member (Werther et al. 2012; European Committee for Standardization 2004b). Smouldering is also a phenomenon not seen in all structural materials, but that can affect the temperature profile of the section and in turn weaken the member after the flames are extinguished. The development of a model which considers smouldering through software currently used by industry members would contribute towards more accurately modelling the fire performance of timber structures.

LS DYNA was used to create the a priori finite element model. The results of the model, which considered a range of heat fluxes, flame spread rates, and extinction rates from literature highlighted the importance of future experiments related to the fire performance of CLT ceilings. Each of these areas greatly impacts the expected temperature distribution throughout the ceiling, and therefore the area of timber of which the structural capacity would be reduced. The results of this model indicate that more data is needed for charring rates of timber at extreme heat fluxes, the heat flux generated from the timber when both flaming is present and when smouldering, criteria for when to consider the extinction of timber, and data of the heat flux experienced along the floor level during a fire.

From the creation of this model, recommendations were made regarding the instrumentation of future experiments to gather these data sets. These recommendations include an array of cameras positioned along the length of the ceiling. The cameras can be used to determine flame spread rates as well as aid in determining an extinction rate of the fire. CLT samples should also be instrumented with thermocouples along their lengths. Each interval should at minimum have a thermocouple on the top and the soffit so that the temperature gradient of a model can be validated to that of the real temperature gradient. Finally, plate thermometers are recommended to be used to measure the heat flux experienced by the CLT from the source fire as well as the heat flux experienced by the floor from the ceiling. The collection of these data sets will help with providing model inputs, and data sets for model calibration.

As values for the applied heat flux and flame spread rate were taken at the far ends of accepted values (23.9 and 77.5 kW/m^2 for heat flux and 19.3 and 1.5 m/s for flame spread rate) the simulated results in turn have a large variability, demonstrating the need for further collection of experimental data for timber. It was observed that the char depth varied by approximately 20 mm (66% increase) when exposed to a higher heat flux. It was also observed that assuming a faster flame spread the fire was shorter in duration and reached lower temperatures.

Although several steps need to be taken before simplified design methodologies for open plan, well-ventilated timber structures can be created, the fire research community is beginning to mobilize and address some of these research gaps. Currently, in-progress experiments and analyses are anticipated to help better understand the expected fire dynamics of these types of spaces. By understanding how fires in well-ventilated, open plan spaces differ from compartment fires recently considered in experimental research, analysis of these types of fires becomes possible, and the creation of methodologies for the design of these spaces becomes more accessible.

Acknowledgements

The authors would like to acknowledge the contributions of ARUP in providing technical and financial support of this research. The Natural Science and Engineering Research Council of Canada is acknowledged through its Alliance program

Supplemental Materials

Table S1 and Equations S1 -S2 are available online in the ASCE Library (ascelibrary.org).

Data Availability

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

References

Babrauskas, V. (2015). "Chapter 26: Heat Release Rates." *SFPE Handbook of Fire Protection Engineering*, Springer, 799–904. New York: Springer.

Bartlett, A., Wiesner, F., Hadden, R., Bisby, L., Lane, B., Lawrence, A., Palma, P., and Frangi, A. (2016). "Needs for total fire engineering of mass timber buildings." *WCTE 2016 - World Conference on Timber Engineering*. Vienna, Austria: TU Verlag Wien.

Bedon, C., Chifliganec, C., Džolev, I., Pečenko, R., and Hozjan, T. (2018). "Numerical Modelling of Timber Concrete Composite Structures in Fire - Guidance Document." *COST Action FP 1404 "Fire Safe Use of Bio-Based Building Products."* Zurich, Switzerland: ETH Zurich.

CEN (European Committee for Standardization). 2002. CEN, eurocode1: Actions on structures—Part1-2: Generalactions—Actions on structures exposed to fire. Brussels, Belgium: CEN.

CEN (European Committee for Standardization). 2004. Eurocode 5: Design of timber structures—Part1-2:General—Structuralfiredesign. EN 1995-1-2. Brussels, Belgium: CEN.

Chen, Z., Ni, C., Dagenais, C., and Kuan, S. (2020). " Wood ST : A Temperature-Dependent Plastic-Damage Constitutive Model Used for Numerical Simulation of Wood-Based Materials and Connections ." *Journal of Structural Engineering*, 146(3), 04019225. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002524.

Chorlton, B. (2021). "The Thermo-Mechanical Response of Timber to Real Fire Exposures." York University.

Chorlton, B., Forrest, B., Gales, J., and Weckman, B. (2021). “Performance of type X gypsum board on timber to non-standard fire exposure.” *Fire and Materials*, 45(7), 885–900.

Cowlard, A., Bittern, A., Abecassis-Empis, C., and Torero, J. (2013). “Fire safety design for tall buildings.” *Procedia Engineering*, 62, 169–181.

Craft, S. (2018). “Fire Risk Assessment for Tall Wood Buildings.” <https://www.canadianconsultingengineer.com/features/fire-risk-assessment-for-tall-wood-buildings/> (Sep. 24, 2021).

Crielaard, R., Kuilen, J. Van De, Terwel, K., Ravenshorst, G., and Steenbakkers, P. (2019). “Self-extinguishment of cross-laminated timber.” *Fire Safety Journal*, 105(April), 244–260.

CSA Group. (2014). *CSA O86-14: Engineering Design in Wood*. Mississauga, Canada: CSA.

Dai, X., Welch, S., Vassart, O., Cabova, K., Jiang, L., Maclean, J., Clifton, G. C., and Usman, A. (2020). “An extended travelling fire method framework for performance- based structural design.” *Fire and Materials*, 44(3), 437–457.

Drysdale, D. (2011). *An Introduction to Fire Dynamics*. John Wiley & Sons, West Sussex, UK.

Emberley, R., Inghelbrecht, A., Yu, Z., and Torero, J. (2017). “Self-Extinction of Timber.” *Proceedings of the Combustion Institute*, 36(2), 3055–3062.

European Committee for Standardization. (2002). “CEN, Eurocode1: Actions on Structures - Part 1-2: General Actions - Actins on Structures Exposed to Fire.” Brussels, Belgium.

European Committee for Standardization. (2004). *EN 1995-1-2: Eurocode 5: Design of Timber Structures - Part 1-2: General - Structural Fire Design*. Brussels, Belgium.

Gales, J., Chorlton, B., and Jeanneret, C. (2021). “The Historical Narrative of the Standard Temperature–Time Heating Curve for Structures.” *Fire Technology*, 57(2), 529–558. https://doi.org/10.1007/s10694-020-01040-7.

Gernay, T. (2021). “Fire resistance and burnout resistance of timber columns.” *Fire Safety Journal*, Elsevier Ltd, 122(April), 103350. https://doi.org/10.1016/j.firesaf.2021.103350.

Grimwood, P. (2018). “Strucutral fire engineering: realistic ‘traveling fires’’ in large office compartments.’”

Gupta, V., Torero, J. L., and Hidalgo, J. P. (2021). “Burning dynamics and in-depth flame spread of wood cribs in large compartment fires.” *Combustion and Flame*, Elsevier Inc., 228, 42–56. https://doi.org/10.1016/j.combustflame.2021.01.031.

Hagan, D. (2021). “The best of all worlds: a hybrid approach to mass timber.” <https://www.wsp.com/en-GB/insights/a-hybrid-approach-to-mass-timber> (Dec. 16, 2021).

Heidari, M. (2021). “Travelling Fires Methodology and Probabilistic Design of Structures.” Imperial College London.

Heidari, M., Kotsovinos, P., and Rein, G. (2019). “Flame Extension and the Near Field under the Ceiling for Travelling Fires Inside Large Compartments.” *Fire and Materials*, (Special Issue), 1–14. https://doi.org/10.1002/fam.2773.

Heidari, M., Rackauskaite, E., Bonner, M., Christensen, E., Morat, S., Mitchell, H., Kotsovinos, P., Turkowski, P., Wegrzynski, W., Tofilo, P., and Rein, G. (2020). “Fire experiments inside a very large and open-plan compartment: x-TWO.” *11th International Conference on Structures in Fire*, Brisbane, Australia.

Hidalgo, J. P., Goode, T., Gupta, V., Cowlard, A., Abecassis-Empis, C., Maclean, J., Bartlett, A. I., Maluk, C., Montalvá, J. M., Osorio, A. F., and Torero, J. L. (2019). “The Malveira fire test: Full-scale demonstration of fire modes in open-plan compartments.” *Fire Safety Journal*, Elsevier Ltd, 108(May). https://doi.org/10.1016/j.firesaf.2019.102827.

Hopkin, D., Spearpoint, M., Gorska, C., Krenn, H., Sleik, T., and Milner, M. (2020). “Compliance Road-map for the Structural Fire Safety Design of Mass Timber Buildings in England.” *SFPE Europe*, (20).

Ikei, H., Song, C., and Miyazaki, Y. (2017). “Physiological effects of wood on humans: a review.” *Journal of Wood Science*, Springer Japan, 63(1), 1–23. https://doi.org/10.1007/s10086-016-1597-9.

International Organization for Standardization. (2014). “ISO 834-11: Fire resistance tests - Elements fo building construction - Part 11: Specific requirements for the assessment of fire protection to structural steel elements.”

Karlsson, B., and Quintiere, J. (1999). *Enclosure Fire Dynamics*. Boca Raton, FL: CRC Press.

Kirby, B. R., Wainman, D. E., Tomlinson, L. N., Kay, T. R., and Peacock, B. N. (1999). “Natural Fires in Large Scale Compartments.” *International Journal on Engineering Performance-Based Fire Codes*, 1(2), 43–58.

Kleinhenz, M., Just, A., and Frangi, A. (2021). “Temperature-dependent thermal properties for cross-laminated timber exposed to standard fire.” *In Proc., INTER Int. Network on Timber Engineering Research, 54.Karlshruhe, Germany: KIT Holzbau und Baukonstruktionen.*

Kotsovinos, P., Rackauskaite, E., Christensen, E., Glew, A., O’Loughlin, E., Mitchell, H., Amin, R., Robert, F., Heidari, M., Barber, D., Rein, G., and Schulz, J. (2022a). “Fire dynamics inside a large and open-plan compartment with exposed timber ceiling and columns: CodeRed #01.” *Fire and Materials*. https://doi.org/10.1002/fam.3049.

Kotsovinos, P.,et al. (2022b). “Impact of ventilation on the fire dynamics of an open-plan compartment with exposed CLT ceiling and glulam columns: CodeRed #02." *Fire and Materials*. https://doi.org/10.1002/fam.3082.

Lange, D., Sjöström, J., Schmid, J., Brandon, D., and Hidalgo, J. (2020). “A Comparison of the Conditions in a Fire Resistance Furnace When Testing Combustible and Non-combustible Construction.” *Fire Technology*, 56(4), 1621–1654. https://doi.org/10.1007/s10694-020-00946-6.

Law, A., and Hadden, R. (2020). “We need to talk about timber: fire safety design in tall buildings.” *The Instituiton of Structural Engineers*, 6.

LS-DYNA. (2020). “Technology LS.” Livermore, CA: Livermore Software Technology.

Medina, A. R. (2014). “Fire Resistance of Partially Protected Cross-Laminated Timber Rooms.” Carleton University.

Menis, A. (2012). “Fire resistance of Laminated Veneer Lumber (LVL) and Cross-Laminated Timber (XLAM) elements.” Ph.D. thesis, Doctoral School of Civil and Architecture, Univ. of Cagliari.

Ministry of Natural Resources and Forestry. (2017). *Ontario’s Tall Wood Building Reference*. Toronto: Queen’s Printer for Ontario.

Oliver, C. D., Nassar, N. T., Lippke, B. R., and McCarter, J. B. (2014). “Carbon, Fossil Fuel, and Biodiversity Mitigation With Wood and Forests.” *Journal of Sustainable Forestry*, Taylor & Francis, 33(3), 248–275. https://doi.org/10.1080/10549811.2013.839386.

Perkins&Will. (n.d.). “Canada’s Earth Tower.” <https://perkinswill.com/project/canadas-earth-tower/>.

Petrella, R. V. (1979). “The mass burning rate and mass transfer number of selected polymers, wood, and organic liquids.” *Polymer-Plastics Technology and Engineering*, 13(1), 83–103. https://doi.org/10.1080/03602557908067676.

Quiquero, H., Chorlton, B., and Gales, J. (2018). “Performance of adhesives in Glulam after short term fire exposure.” *International Journal of High-Rise Buildings*, 7(4), 299–311.

Quiquero, H., Gales, J., Abu, A., and Al Hamd, R. (2020). *Finite Element Modelling of Post-tensioned Timber Beams at Ambient and Fire Conditions*. *Fire Technology*, 56 (2): 737–767. https://doi.org/10.1007/s10694-019-00901-0.

Rackauskaite, E., Bonner, M., Restuccia, F., Fernandez Anez, N., Christensen, E. G., Roenner, N., Wegrzynski, W., Turkowski, P., Tofilo, P., Heidari, M., Kotsovinos, P., Vermesi, I., Richter, F., Hu, Y., Jeanneret, C., Wadhwani, R., and Rein, G. (2021a). “Fire Experiment Inside a Very Large and Open-Plan Compartment: x-ONE.” *Fire Technology*, https://doi.org/10.1007/s10694-021-01162-6. Springer US.

Rackauskaite, E., Hamel, C., Law, A., and Rein, G. (2015). “Improved Formulation of Travelling Fires and Application to Concrete and Steel Structures.” *Structures*, Elsevier B.V., 3, 250–260. Amsterdam, Netherlands: Elsevier. https://doi.org/10.1016/j.istruc.2015.06.001.

Rackauskaite, E., Kotsovinos, P., and Barber, D. (2021b). “Letter to the Editor: Design Fires for Open-Plan Buildings with Exposed Mass-Timber Ceiling.” *Fire Technology*, Springer US, 57(2), 487–495. https://doi.org/10.1007/s10694-020-01047-0.

Rackauskaite, E., Kotsovinos, P., and Rein, G. (2017). “Structural response of a steel-frame building to horizontal and vertical travelling fires in multiple floors.” *Fire Safety Journal* 91 (Jul): 542–552. https://doi.org/10.1016/j.firesaf.2017.04.018.

Rein, G. (2009). “Smouldering Combustion Phenomena in Science and Technology.” *International Review of Chemical Engineering*, 1, 3–18.

Richter, F., Atreya, A., Kotsovinos, P., and Rein, G. (2019). “The effect of chemical composition on the charring of wood across scales.” *Proceedings of the Combustion Institute*, Elsevier Inc., 37(3), 4053–4061. https://doi.org/10.1016/j.proci.2018.06.080.

Richter, F., Kotsovinos, P., Rackauskaite, E., and Rein, G. (2021). “Thermal Response of Timber Slabs Exposed to Travelling Fires and Traditional Design Fires.” *Fire Technology*, Springer US, 57(1), 393–414. https://doi.org/10.1007/s10694-020-01000-1.

Richter, F., and Rein, G. (2020). “A multiscale model of wood pyrolysis in fire to study the roles of chemistry and heat transfer at the mesoscale.” *Combustion and Flame*, Elsevier Inc., 216, 316–325. https://doi.org/10.1016/j.combustflame.2020.02.029.

Shapiro, A. (2012). “Using LS-Dyna for Heat Transfer Coupled Thermal-Stress Problems.” Livermore, CA: Livermore Software Technology.

Society of Fire Protection Engineers. (2016). *SFPE Handbook of Fire Protection Engineering*. New York: Springer.

Su, J., Lafrance, P.-S., Hoehler, M. S., and Bundy, M. F. (2018). “Fire safety challenges of tall wood buildings – phase 2: task 2 & 3 – cross laminated timber compartment fire tests.” *National Research Council of Canada*, (February), 396. Ottawa: National Research Council of Canada.

Tanaka, T., and Yamada, S. (1999). “Reduced Scale Experiments fo Convective Heat Transfer in the Early Stages of Fires.” *International Journal on Engineering Performance-Based Fire Codes*, (1), 196–203.

Tewarson, A., and Pion, R. F. (1976). “Flammability of plastics-I. Burning intensity.” *Combustion and Flame*, 26, 85–103. https://doi.org/10.1016/0010-2180(76)90059-6.

Thi, V. D., Khelifa, M., Oudjene, M., Ganaoui, M. El, and Rogaume, Y. (2017). “Finite element analysis of heat transfer through timber elements exposed to fire.” *Engineering Structures*, Elsevier Ltd, 143, 11–21. https://doi.org/10.1016/j.engstruct.2017.04.014.

Think Wood. (n.d.). “Brock Commons Tallwood House.” <https://www.thinkwood.com/projects/brock-commons-tallwood-house> (Dec. 16, 2021).

Wang, Y. (2019). “Theoretical and Experimental Research on the Structural Behaviour of Cross-Laminated Timber Structures on Compartment Fire.” Southeast University.

Węgrzyński, W., Turkowski, P., and Roszkowski, P. (2020). “The discrepancies in energy balance in furnace testing, a bug or a feature?” *Fire and Materials*, 44(3), 311–322. https://doi.org/10.1002/fam.2735.

Werther, N., Neill, J. W. O., Spellman, P. M., Abu, A., Moss, P. J., Buchanan, A. H., and Winter, S. (2012). “Parametric Study of Modelling Structural Timber in Fire With Different Software Packages.” *7th International Conference on Structures in Fire*. Bingley, UK: Emerald Group.

Wiesner, F., Bartlett, A., Mohaine, S., Robert, F., McNamee, R., Mindeguia, J. C., and Bisby, L. (2021). "Structural Capacity of One-Way Spanning Large-Scale Cross-Laminated Timber Slabs in Standard and Natural Fires." *Fire Technology*, Springer US, 57(1), 291–311. https://doi.org/10.1007/s10694-020-01003-y.

Wiesner, F., Bisby, L. A., Bartlett, A. I., Hidalgo, J. P., Santamaria, S., Deeny, S., and Hadden, R. M. (2019). "Structural capacity in fire of laminated timber elements in compartments with exposed timber surfaces." *Engineering Structures*, Elsevier, 179(October 2018), 284–295. https://doi.org/10.1016/j.engstruct.2018.10.084.

Williams, R. S. (1999). "Chapter 15: Finishing of Wood." *Wood Handbook: Wood as an Engineering Material*, Forest Products Laboratory.

Xing, Z., Wang, Y., Zhang, J., and Ma, H. (2021). "Comparative study on fire resistance and zero strength layer thickness of CLT floor under natural fire and standard fire." *Construction and Building Materials*, Elsevier Ltd, 302(July). https://doi.org/10.1016/j.conbuildmat.2021.124368.

Zhang, C., Li, G. Q., and Usmani, A. (2013). "Simulating the behavior of restrained steel beams to flame impingement from localized-fires." *Journal of Constructional Steel Research*, 83, 156–165. https://doi.org/10.1016/j.jcsr.2013.02.001.

Appendix B: Informed Consent and Survey used in Chapter 4

Ethics Statement and Informed Consent Form

Purpose of the Research: This study aims to determine the impact of timber design studies on attracting diverse populations into engineering. This survey is being distributed to engineering companies across Canada to identify the socio-economic background of those who are working on timber projects, and explore their reasons for working on timber-based projects. Additionally, it will explore their experiences with timber design in Canada.

What You Will Be Asked to Do in the Research: The following survey will take 15 to 20 minutes and the survey involves no more than 23 questions. Please fill out the survey based on your experiences with timber engineering design. Participation is strictly voluntary.

Benefits of the Research and Benefits to You: Your participation in this survey will help improve the knowledge regarding how timber engineering attracts different populations. This will help develop quantifiable evidence to say that timber education is a driving force for diversity in engineering, helping to expand the reach of education and research programs. This will help support the demand for timber structures, by increasing the workforce trained in timber engineering design.

<u>Online Informed Consent Form</u>

Risks and Discomforts: There is minimal risk associated with participating in this study. According to TCPS-2 from the Panel on Research Ethics, this means that the "probability and magnitude of possible harms implied by the participation in the research is no greater than those encountered by participants in those aspects of their everyday life that relate to the research." Participants may find it difficult, upsetting, or emotional to talk about their experiences in engineering. We foresee minimal risk, since the probability and magnitude of these possible harms is no greater than in the participants' everyday life as an engineer. You are not required to answer any questions that makes you uncomfortable or that you find too upsetting.

Voluntary Participation: Your participation in the study is completely voluntary and you may choose to stop participating at any time. Your decision not to volunteer will not influence your relationship with researchers, York University or other groups associated with this project either now, or in the future.

Withdrawal from the Study: You can stop participating in the study at any time, for any reason, if you so decide. Your decision to stop participating, or to refuse to answer particular questions, will not affect your relationship with the researchers, York University, or any other groups associated with this project. In the event you withdraw from the study, all associated data collected will be immediately destroyed wherever possible.

Confidentiality: All information you supply during the research will be anonymous and held in confidence. Your name will not appear in any report or publication of the research. Your data will be safely stored on an external hard drive at the end of survey completion and only research team members will have access to this information. The results will be deleted upon research completion. Data will be stored anonymously. Confidentiality will be provided to the fullest extent possible by law. The researcher acknowledge that the host of the online survey (Microsoft Forms) may automatically collect participant data without their knowledge (i.e., IP addresses.) Although this information may be provided or made accessible to the researchers, it will not be used or saved without participants' consent on the researchers' system. Further, because this project employs e-based collection techniques, data may be subject to access by third parties as a result of various security legislation now in place in many countries and thus the confidentiality and privacy of data cannot be guaranteed during web-based transmission.

Questions About the Research? If you have questions about the research in general or about your role in the study, please feel free to contact Chloe Jeanneret either by telephone at (416) 736-2100, extension 44221 or by e-mail (chloej96@yorku.ca). This research has received ethics review and approval by the Human Participants Review Sub-Committee, York University's Ethics Review Board and conforms to the standards of the Canadian

Tri-Council Research Ethics guidelines. If you have any questions about this process, or about your rights as a participant in the study, please contact the Sr. Manager & Policy Advisor for the Office of Research Ethics, 5th Floor, Kaneff Tower, York University (telephone 416-736-5914 or e-mail ore@yorku.ca).

1. Do you consent in taking part of this survey?
    - Yes
    - No

Survey

With the push towards a more sustainable building infrastructure identified in the COP26 there has been a global influx of demand for wood construction. To support this demand, increased efforts from universities and colleges in both teaching and research are needed. A thorough equity, diversity, and inclusivity (EDI) plan is typically important in the justification of expanding education and research programs. Currently, there is only an innate knowledge of whether wood design and construction attracts different social groups, with limited quantifiable evidence to say whether wood education, and subsequently design and construction, is a driving force for diversity.

This study aims to determine the impact of wood design studies on attracting diverse populations into engineering. This survey is being distributed to engineering professionals across Canada to better understand the intersectional identities of those who are working on timber projects, and explore their reasons, and interests, for working on timber projects. Additionally, it will explore their experiences with wood design in Canada.

1. Which option best describes your current gender identity?
    - Gender-fluid
    - Man
    - Non-binary
    - Trans man
    - Trans woman
    - Two-Spirit
    - Woman
    - I don’t identify with any option provided
    - I prefer not to answer
2. Which population group(s) do you identify with? (Please select all that apply)
    - Arab
    - Black or African American
    - Chinese
    - Filipino
    - Japanese
    - Korean
    - Latin American
    - South Asian (e.g., East Indian, Pakistani, Sri Lankan, etc.)
    - Southeast Asian (e.g., Vietnamese, Cambodian, Laotian, Thai)
    - West Asian (e.g., Iranian, Afghan)
    - White
    - Asian or Pacific Islander
    - Middle Eastern or North African
    - Indigenous (First Nation, Metis, Inuit, etc.)
    - Population group not listed above
    - I prefer not to answer
3. How old are you?
    - 18-24 years old
    - 25-29 years old
    - 30-34 years old
    - 35-39 years old
    - 40-44 years old
    - 45-49 years old
    - 50-54 years old
    - 55-59 years old
    - 60-64 years old
    - 65+ years old

4. What is your current education level?
    - High school diploma/GED
    - College diploma
    - Bachelors
    - Masters
    - PhD
5. What is your current engineering license status?
    - Fully licensed (P.Eng.)
    - Engineer In Training (EIT)
    - Limited License
    - Temporary License
    - Provisional License
    - None
6. Do you have an immediate family member who is a current or past practicing engineer?
    - Yes
    - No
7. What type of experiences have provided you with wood education? (Please select all apply)
    - Undergraduate course
    - Graduate course
    - Personal Development Hours (PDH) seminar/course
    - Work project
    - Other
8. If you selected ‘Other’ in Question 7, please list what experiences have provided you with timber education.
9. Which of the following experiences has most significantly motivated you to pursue timber engineering design? (Please select all that apply)
    - Undergraduate course
    - Graduate course
    - Personal Development Hours (PDH) seminar/course
    - Work project
    - Other
10. If you selected ‘Other’ or want to elaborate on your selection(s) for Question 9, please do so here.
11. How long have you been practicing structural engineering design (in years)?
12. Specifically, how long have you been practicing wood engineering design (in years)?
13. If you have worked on wood design projects, what range of projects were undertaken, even if only to conceptual design? (Please select all that apply)
    - Low rise (<6 storeys)
    - Mid rise (6-10 storeys)
    - High rise (10+ storeys)
14. If you have worked on wood design projects, what type of occupancies were considered for the projects undertaken, even if only to conceptual design? (Please select all that apply)
    - Assembly occupancies
    - Care treatment or detention occupancies
    - Residential (single family) occupancies
    - Residential (multi-family) occupancies
    - Business and personal service (offices) occupancies
    - Mercantile (retail) occupancies
    - Industrial occupancies

15. If you have worked on wood design projects, what type of wood products were specified, even if only to conceptual design? (Please select all that apply)
    - Light frame
    - Engineered trusses
    - Engineered Wood Products e.g. I-joist, Laminated Veneer Lumber (LVL), Parallel Strand Lumber (PSL), etc.
    - Glue Laminated Timber (Glulam)
    - Cross Laminated Timber (CLT)
    - Nail Laminated Timber (NLT)
    - Dowel Laminated Timber (DLT)
    - Other
16. If you selected 'Other' or want to elaborate on your selection(s) for Question 15, please do so here.
17. How would rate your passion for wood projects?
    - 1 – Not passionate
    - 2
    - 3
    - 4
    - 5 – Very passionate
18. What is your personal motivation behind working in wood design? (Please select all that apply)
    - Sustainability
    - Biophilia/Aesthetic
    - Challenge/Innovation
    - Other
19. If you selected 'Other' or would like to elaborate on your selection in Question 18, please describe your personal motivation(s) behind working in wood design.
20. Does your desired career path include continuing working in wood design?
    - Yes, for the near future
    - Yes, for the remainder of my career
    - Yes, when the projects arise
    - No
21. How would you rate your enjoyment of your current career in wood design?
    - 1 – Not enjoyable at all
    - 2
    - 3
    - 4
    - 5 – Very enjoyable

<u>Optional Questions</u>

The following set of questions are all optional. These may be considered as identifier questions, therefore it is left up to your discretion to answer any or all questions.

22. If you have completed a post-secondary program, which institution did you attend (If you have attended multiple institutions or are currently enrolled, please only list the most recent/current institution)? If you have not attended a post-secondary institution, please leave blank.
23. Which company/organization do you work for?

24. Which Province/Territory is your company/organization located? Please select one:
    - Alberta
    - British Columbia
    - Manitoba
    - New Brunswick
    - Newfoundland and Labrador
    - Northwest Territories
    - Nova Scotia
    - Nunavut
    - Ontario
    - Prince Edward Island
    - Quebec
    - Saskatchewan
    - Yukon
    - Prefer not to answer
25. How large is your company/organization?
    - Small (less than 20 employees)
    - Medium (20 – 99 employees)
    - Large (100 – 500 or more employees)
    - Unsure how many are employed
    - Prefer not to answer
26. Have you received training which addresses equity, diversity, and inclusion in the workplace?
    - Yes
    - No
    - Prefer not to answer
27. If you responded "Yes" to Optional Q5, please elaborate on the topics of the training.
28. Have you received training which addresses barriers in the workplace that certain populations can face?
    - Yes
    - No
    - Prefer not to answer
29. If you responded "Yes" to Optional Q7, please elaborate on the topics of the training.
30. Do you have any additional feedback you would like to add regarding wood in the design and construction industry?

Appendix C: Certificate of Human Participants Review Sub-Committee Approval of Research Project

OFFICE OF RESEARCH ETHICS (ORE)
5th Floor, York Research Tower,
4700 Keele Street, Toronto ON
Canada M3J 1P3
Tel 416-736-5914, Fax 416-650-8197
www.research.yorku.ca

Memo

To:	Chloe Jeanneret, Civil Engineering
From:	Alison M. Collins-Mrakas, Sr. Manager and Policy Advisor, Research Ethics *(on behalf of the Chair, Human Participants Review Committee)*
Issue Date:	Tue Jun 21 2022
Expiry Date:	Wed Jun 21 2023
RE:	**The Link between Timber Professional Engineering and Equity, Diversity and Inclusion** **Certificate #: e2022-219**

I am writing to inform you that the Human Participants Review Sub-Committee has reviewed and approved the above project.

Should you have any questions, please feel free to contact me at: 416-736-5914 or via email at: acollins@yorku.ca.

Yours sincerely,

Alison M. Collins-Mrakas M.Sc., LLM
Sr. Manager and Policy Advisor,
Office of Research Ethics

RESEARCH ETHICS: PROCEDURES to ENSURE ONGOING COMPLIANCE

Upon receipt of an ethics approval certificate, researchers are reminded that they are required to ensure that the following measures are undertaken so as to ensure on-going compliance with Senate and TCPS ethics guidelines:

1. **RENEWALS:** Research Ethics Approval certificates are subject to annual renewal.

   Failure to renew an ethics approval certificate or (to notify ORE that no further research involving human participants will be undertaken) may result in the **closure of the protocol**. No further research activities may be undertaken until such time as a new protocol has been reviewed and approved. Further, **it may result in suspension of research cost fund and access to research funds may be suspended/withheld**.

2. **AMENDMENTS:** Amendments must be reviewed and approved **PRIOR** to undertaking/making the proposed amendments to an approved ethics protocol;

3. **END OF PROJECT:** ORE must be notified when a project is complete;

4. **ADVERSE EVENTS:** Adverse events must be reported to ORE as soon as possible;

5. **AUDIT:**
   a. More than minimal risk research may be subject to an audit as per TCPS guidelines;
   b. A spot sample of minimal risk research may be subject to an audit as per TCPS guidelines.

FORMS: As per the above, the following forms relating to on-going research ethics compliance are available on the Research website:

1. Renewal
2. Amendment
3. End of Project
4. Adverse Event