ANALYSIS OF BURNING WOOD IN THE TRANSIENT STATE AND THE APPLICATION TO STRUCTURAL DESIGN

BY

ROBERTA VELIZ
KIMBERLY GUZMAN

SENIOR PROJECT REPORT

Submitted in partial fulfillment of the requirements
for the degree of Bachelor of Science in Architectural Engineering
at California Polytechnic State University

San Luis Obispo, California

Senior Project Advisor

Kevin Dong, SE
Richard Emberley, PhD

June 2020

ACKNOWLEDGEMENTS

Special thanks to
David Morrisset
Tam Do

ABSTRACT

Determining the extent of the contribution of exposed timber on compartment fire dynamics in open floor plans is a complex process. Designers traditionally used compartmentalization design methods which create spaces where flashover is likely, given the fuel load and ventilation conditions. However, due to the large geometric dimensions and spread of fuel, fires in open floor plans are more likely to remain as localized or traveling fires. As such, an understanding of not only ignition potential but also flame spread is critical to characterizing the contribution of exposed timber. An integral step in characterizing the potential contribution is through an analysis of the transient phase of burning of timber and the phenomena of self-extinction in this phase of burning. A series of material characterization experiments were conducted on Douglas Fir Larch samples to observe the behavior of timber in transient burning under a wide range of heat fluxes. For each experiment, the temperature gradient was recorded with thermocouples while the mass loss rate was measured using a load cell. The rate of conduction into the virgin timber, critical heat flux and the mass loss rate needed for sustained burning were all calculated to provide bounding limits to flame spread and self-extinction. These experiments showed that the transient mass loss rate is significantly higher than the average steady state in exposed wood and that there are nuances from latent heat of vaporization that notably affect the charring rates. This project begins to develop the effects that the transient state can have in burning wood and its charring rates. As a result, it was found that the mass loss rate during the transient state is significant and thus should be considered for the design of exposed timber. These studies should be further developed and tested to help refine charring rates during the transient state and with larger scale tests begin to be applied towards the structural engineering of exposed wood under a fire event.

KEYWORDS: Transient Burning; Exposed Timber; Open Floor Plan Architecture; Charring Rates; Fire Safety; Mass Loss Rate

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Around the globe, the use of structural engineered lumber is becoming a popular building material because of its sustainable properties, cost and aesthetic qualities[1]. Timber highrises have gained rampant popularity in places like Europe, Australia, and New Zealand and are starting to spread to other places around the globe.

In order to keep up with the visions of architects, the built environment has seen an increase in the use of engineered timber[2], with new products such as cross Laminated Timber (CLT), Nail Laminated Timber (NLT), Glued-Laminated Timber (glulam), Dowel Laminated Timber (DTL), and Structural Composite Lumber (SCL) to name a few [2-5]. Many of the leading architectural groups continuously identify the general trends of this decade to focus on open and multipurpose spaces, experimenting with new construction methods with a focus on passive sustainable dwellings[6].

As architects and engineers have worked together to push the current boundaries of timber design, building taller and spanning longer spaces, these new building techniques still need to be tested to fully understand their behavior in different load types and combinations (i.e. wind, earthquake etc.) and although not typically considered a load, predicting fire dynamics in this typology of building becomes crucial to the lifesafety of the occupants. One of the main constraints architects and engineers have with innovative timber designs is designing something which will be deemed safe by their corresponding fire safety jurisdiction. In contrast to other common building materials like steel, concrete or masonry-- wood is naturally a combustible material and has the property of charring. The current research on fire safety and structural fire modeling is a multinational effort to better understand the complexities of the chemistry of charring and decomposition of wood. Many countries have their own prescriptive fire codes for timber that limit the percentage of exposed timber, set limits on heights and number of stories[7]. The prescriptive timber fire codes have been written with a basis of hour fire ratings in accordance with the standard furnace test and change based on the use, building occupancy and importance. The protective measures taken can either be active or passive; this report is focusing on passive fire protection systems, inherent to the building materials, structure and architecture.

Over the last century, performance based approaches have been permitted to be used by a variety of building codes to analyze the performance of buildings under various loading conditions. The Western U.S. began to see a shift in the design philosophies of structural engineering around the 1970's and 1980's, leaning towards a performance based design rather than a prescriptive method, notably seen in highly developed earthquake engineering analysis [8]. The shift to performance based design was due to the fact that this analysis can provide better engineered solutions and predict building performances with greater accuracy[9]. Despite major advances in both fire safety and structural fire modeling, the current techniques for fire rating building elements have largely remained the same since their development in the early 1900's. Most of the large structural fire failures in the last couple of decades notably the WTC and the Windsor Tower in Madrid have had “unexpected” fire dynamics when compared to the idealized conditions of the standard fire test. The assumption that the standard furnace test was designed to model complete compartment burnout was not adequate for predicting the performance of a building element in a traveling or localized fire event. Traveling fires, in addition to varying in intensity as a function of distance and time, have burning durations much longer than the traditional design methods[10]. An integral step in characterizing the potential ignition contribution of a traveling fire relies on understanding the transient phase of burning timber and the phenomena of self extinction.

2. HISTORY OF FIRE PROTECTION CODES AND BACKGROUND

2.1. A Brief History of Fire Codes

The origin of the standard fire tests started in New York in the late 19th century[11]. There was a big change in the style of architecture and building construction methods were quickly changing with the drive to build higher while the density of the city rose. At this time, the building construction industry had many self proclaimed fireproof buildings without formal or standardized testing[12]. The standard fire test emerged from the need for a comparable way of testing fire. Since the emergence of the standard fire test, it was considered that the most severe fire conditions would be reached in the steady state stages of a fire. From the start, the importance of compartmentation was understood, the need for walls and floors of a building to contain the fire in a compartment was one of the first techniques in passive fire suppression, especially in such a dense urban core like New York[12].

Some of the preliminary tests done in 1902 had a deflection criteria of a member as the basis for passing or failing a fire test. The test called for a sustained 'average' gas phase temperature equivalent to 927ºC (1700ºF) for four hours (with peaks to1093 ºC (2000ºF)), hose stream cooling, and finally residual testing to higher loads (four times the sustained fire service load) for a further 24 hours[12]. If the member still maintained the deflection criteria stated then it was deemed safe, and passed the test. At this time it was believed that no ordinary room could have enough material to sustain a 1700ºF fire for more than 30 min. In the years following, amendments and iterations were made by notable fire engineers. Even as early as 1920, the limitations of using the standard furnace test were widely known, mainly its irrelevance of being a comparative means of representing a real fire. Ingberg and other contemporaries tried to come up with a better way to correlate a fire severity to the standard fire curve and developed the Equal Area Concept, Maximum Temperature Concept, Minimum Load Capacity Concept, and Time-Equivalent Formula based on different metrics[13].

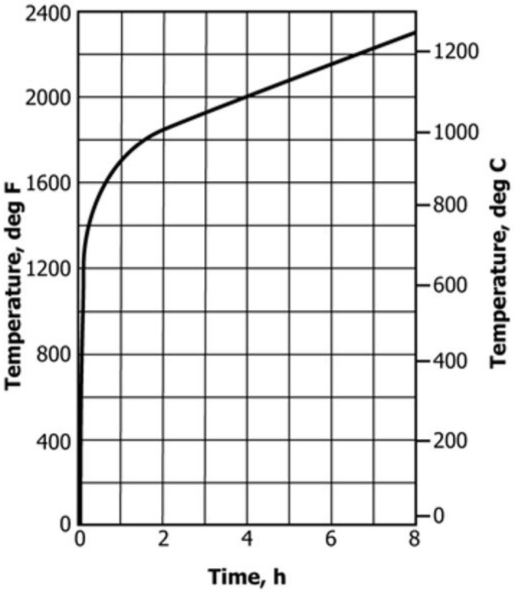


Figure 2.1-Standard Fire Curve [26]

Margaret Law noted that the standard temperature-time curve is not representative of a real fire in a real building,in practice it is physically unrealistic and actually contradicts knowledge from fire dynamics. One of the issues pertained with maintaining a high intensity fire for a prolonged time and the ways the temperature was regulated in the tests. She also noted that the then current duration of fire exposure in the standard test (or the time equivalent exposure) should be revisited; and most important to structural engineering, the loading and end conditions were not well defined – and clearly cannot represent the continuity, restraint, redistribution of loads, and membrane actions in real buildings[10]. Today, prescriptive based fire structural design and codes are heavily based on these same concepts of equivalent fire severity, and inherently oversimplify the behaviour of a real fire and the structural performance of the building is still estimated using these assumptions.

2.1.1. The Standard Fire Curve vs Reality

In the standard fire resistance test the fire resistance time is an arbitrary time based on equivalent areas under the time temperature curves and overlooks some of the important behaviours of a real fire in a room. Because of the constraints of the furnace test, a fire hour rating derived from a standard furnace test does not correlate to actual time in a real fire event. Similar to the burning duration of the standard fire test the heat flux in a real fire varies greatly based on the geometries and ventilation of a room. The standard compartmentalized tests are not standardized , compartment sizes usually range from about 9’x 9’x 9’[14] to 11’ x 14’x 10’[10] and are intended to represent a typical room size. Thermal loading or the supply of heat energy varies from furnace to furnace, changing based on the geometry or lining. Comparisons between materials must be made in the same furnace with the same testing conditions and any deviation from them will render the results useless.

3. MODERN BUILDINGS AND THE GAP IN STRUCTURAL FIRE ANALYSIS

Prescriptive fire design is based on national and international standards and codes and that when followed and applied correctly a building is “code compliant” and according to the legal jurisdiction has the minimum requirements for being “safe”. A typical solution from a prescriptive approach is encapsulation (ie. covering interior structure and facades) with gypsum board or another fire resistant material/coating. This solution, although effective in retarding decomposition of the material completely hides the exposed timber interiors which is a highly sought after aesthetic[15]. Another approach that is gaining more popularity in the United States is structural fire performance based design.

In regard to protecting the wood against a fire event there isn’t any specific analysis performed other than affirming that hour ratings for wood assemblies and members are met. A major shift in the way engineers perform fire analysis happened after the events on 9/11. Up until that event, it was generally accepted that prescriptive fire ratings using the standard furnace curve were conservative. Following the World Trade Center event, more attention was given to the actual behaviour of structures in “real” fire events especially concerning the longer spans notable in open floor plan office buildings[16].

3.1. Notable Timber Buildings

As heavy timber becomes more popular, it is now more common to see plans for timber high rises and the successful construction of timber buildings in different parts of the world. The design for heavy timber buildings vary widely from low to high rise structures with interior layouts varying from highly compartmentalized to open floor plan. The difference between the fire behaviors in these designs isn’t really accounted for in the prescriptive code requirements. Some well known timber buildings among the structural engineering community are the John W. Oliver design building, the UBC Brock Commons, and Stadthaus among others. These buildings are popular because of their use of timber in innovative ways and for pushing the boundaries of timber construction.

The John W. Oliver Design Building, which is located within the University of Massachusetts, Amherst, is a great example of a building with open floor plans throughout its construction. The design process of this building was highly influenced by the collaboration of three departments at the school, the Department of Landscape Architecture and Regional Planning, the Department of Architecture, and the Department of Environmental Conservation’s Building Construction Technology [17]. The building was originally designed to be a steel structure but it was decided by the various campus departments mentioned previously to design and build it out of timber because of the material’s sustainability and for future learning opportunities for those departments that it housed. The firm in charge of designing the building was LWA with help of Equilibrium Consulting and Simpson, Gumpertz & Heger for the structural design. The building is organized around a two story central atrium which serves as a flexible gathering space with movable partition boards. It is a four story building with the first floor housing exhibition and lecture space, laboratories, fabrication and materials testing shops, dining and classroom space, the second and third include studios, classrooms and offices, and the smaller fourth floor contains studios. The main occupant spaces are open with minimal wall usage. This building's gravity framing system is made out of exposed glulam beams and columns. The composite floor system is cross laminated timber (CLT) slabs with concrete topping and it has CLT shaft walls for stairs, elevators, and mechanical shafts[17] The lateral resisting system consists of CLT shear walls and glulam bracing designed for the governing seismic loads.This building is a Type IV Construction which allows for the use of exposed engineered wood members, but because of this the approval of this building by codes was a challenge the engineers faced. Due to the innovative ways timber was used in this structure with few precedents, the engineers used a performance based approach to design the building. With testing of the material and other techniques they proved the safety of the structure [17].

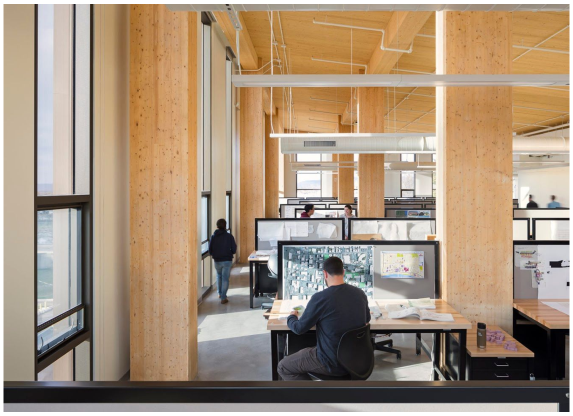
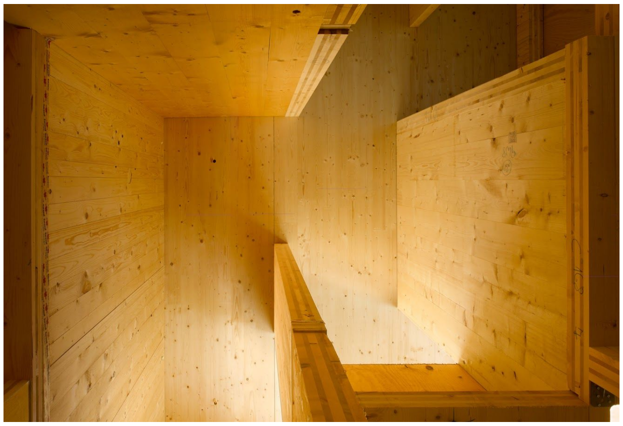


Figure 3.1-John W. Oliver Design Building structure (Top Left) [17]
Figure 3.2- John W. Oliver Design Building Interior (Top Right) [18]
Figure 3.3- John W. Oliver Design Building Atrium (Bottom 3) [18]

Similarly, the UBC Brock Commons in Vancouver Canada, is another mass timber building that has common areas open with no partition walls to separate their spaces. It is an 18 story tall building with a total building height of 174 feet. The choice of timber as the building material was purposely selected because of its sustainability and versatility. The firm in charge of the design of this building was Acton Ostry Architects Inc.and Fast & Epp Structural Engineers was in charge of the structural design. This building encompasses common areas, serves as an academic research site, and houses residential spaces ranging from single-bed studios to 4-bed accommodations. The upper 17 stories are composed of mass timber above a concrete podium and two concrete stair cores. Each timber floor structure consists of 5-ply cross laminated timber panels supported by glulam columns.[4] To help provide fire protection USG Sheetrock® Brand UltraLight Panels Firecode® X (UL Type ULIX) were installed as well as designing some parts of the building to be made up of a series of repetitive, highly compartmentalized small rooms to help contain flame spread in the event of a fire [19]. Designing this building with innovative techniques using a performance based design instead of a prescriptive one didn't come easily. As previously mentioned with the John W. Oliver Design Building, approving the design by building codes for the UBC Brock Commons building was a challenge the design engineers had to take on to prove the design was up to safety requirements.

Figure 3.4- Brock Commons Structure (Left) [20]
Figure 3.5- Brock Commons Interior (Right)[21]

On the other spectrum of building floor plans, Stadthaus, located in Hackney, London, is a building in which most of its layout is designed very similarly to a compartmentalized structure. The firm in charge of designing this building was Waugh Thistleton Architects with the consulting of Techniker Ltd for the structural design. This building is nine stories tall with a total building height of 95 feet and consists of a total of 29 residential spaces. The upper eight floors are made out of timber and the first floor is made out of reinforced concrete. The choice of material was made due to its known sustainability quality. It's structure includes no beams or columns using only a timber core to provide stability; it's made out of cross laminated timber panels that are used as the load bearing walls and floor slabs. This material was chosen for its higher density to help with both acoustics and fire resistance. For this building, a series of tests were conducted on the cross laminated timber to ensure its fire resistance was 90 minutes and that once ignited, the material thickness was enough to form a protective char layer [22]. Each residence is divided by the CLT panels making sure each space is separated, thus creating a perfect model for a compartmentalized design[23-24]. A typical room size is about 10'x15' which is compatible with typical standard furnace test parameters.



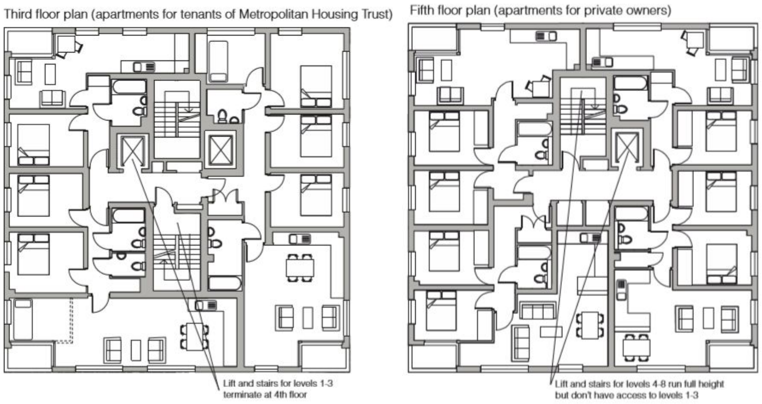


Figure 3.6- Stadthaus Building Exterior (Top Left)[22]
Figure 3.7- Stadthaus Building Interior (Top Right)[23]
Figure 3.8- Stadthaus Floor Plans (Bottom)[24]

3.2. The Shortcomings of Prescriptive Fire Design

As mentioned in Section 2.1, the prescriptive fire approach has been mainly developed with the strict assumption of the standard fire curve. The issue arises when the geometry of a building isn't compartmentalized, that is inherent in a standard furnace test. What seems like a small architectural change (ie. removing a wall and placing columns) greatly impacts the fire dynamics by changing the geometry, airflow, and potential fuel of the fire. Since the demand for combustible open floor plans exists, there is a need to develop performance based approaches to thoroughly understand the dynamics of fire to ultimately create safer buildings.

3.2.1. Transient State Analysis

Historically fire analysis relied on the steady state burning as it is easier to calculate and encompases the general behavior of the decomposition of the material. Steady state burning is a state in which there is a energy balance between the energy going into the material and the rate of material loss-- the char layer, the energy into the system and decomposition of the material are all in a balance therefore it becomes a useful tool to calculate the charring rate for that specific state and material. It's important to have a definition for the regimes and in this study, steady state is defined by having a less than a 5% difference in material loss compared to the peak. Before steady state is reached the char layer must be present to mitigate the material loss and energy in the system. The char layer becomes a sort of insulation for the rest of the material and is an integral part of the balance needed for steady state. In the transient state, the wood has not developed the char layer when first exposed, this decomposition rate peak is visible at the beginning of the transient state [Fig 3.9].

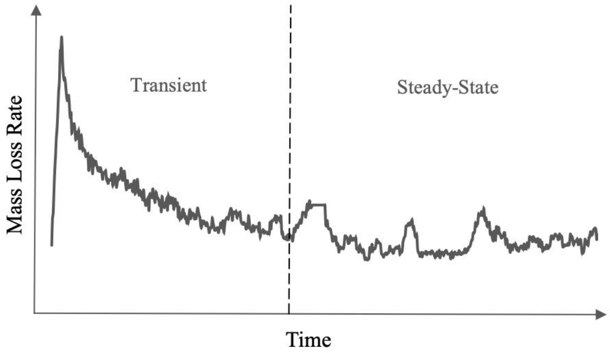


Figure 3.9- Example of Mass Loss Rate of Timber Over Time[25]

For combustible materials, like timber, there is a range of heat fluxes in which deterioration (mass loss and charring) is present but doesn't have the sufficient energy to ignite the material. In order to fully understand the real behavior of fire in a structure it is imperative that the transient state is properly characterized. Transient behavior directly influences the progressive material loss and properties of the timber and is central in understanding the duration and extent of burning. Therefore, considering the transient state results in a more accurate prediction of residual strength in members a better sense of the overall spread and extent of a fire, and the overall fire dynamics in open floor plan concept buildings.

4.TESTING AND METHODOLOGY

4.1.Test Objectives

The behavior of steady state burning has been extensively studied in the past; the objective of this series of experiments is to observe the behavior of timber in the transient state under a wide range of heat fluxes. The tests are designed to explore the behavior of timber in the transient state, gathering information about the mass loss and the temperature gradients in the virgin timber as it is preheated. Performing a test that records internal temperature of the wood involves temperature gathering instruments embedded into the sample; due to the added mass of the thermocouples and moving center of mass as the wood chars, taking mass data simultaneously would deem the results unreliable. For this reason, two separate tests will be performed, providing mass loss and thermal gradient data.

4.2.Mass Loss Test

The mass loss test is used to gather the information on the mass loss over time. This, alongside video footage, can help identify key events in the progression of the transient burning and visualize the mass loss rate between heat fluxes.

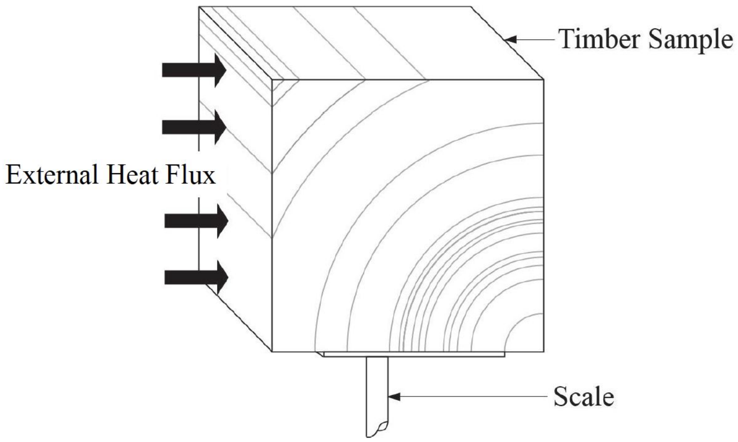


Figure 4.2- Mass Loss Test Setup

4.2.1.Test Setup

Materials List
Douglas Fir- Larch 1 Green Wood Blocks Cut to Dimensions
Vertical Mass Loss Cone Calorimeter
Data Logger with Scale
Go-Pro6

A conical heater was used to provide a uniform external heat flux to simulate a fire exposure. The mass loss data was used to determine the transition from transient to steady-state behavior as well as the mass loss rate at the moment of self-extinction.

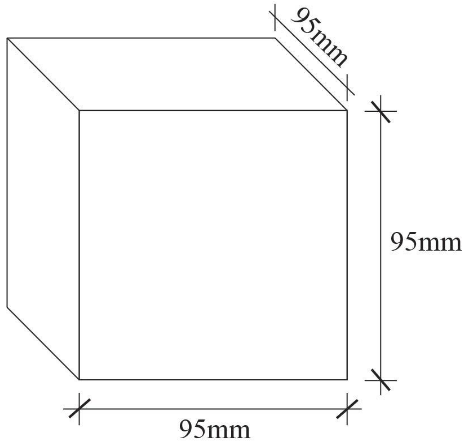


Figure 4.1- Block Dimensions

4.3. Thermal Gradient Test (Thermocouple Test)

The thermal profiles measured with the thermocouples were used to determine the rate of conduction through the char layer, as well as, the thermal penetration depth past the pyrolysis zone, highlighting the rate of conduction into the virgin timber and also the thickness of timber that is affected by a thermally induced reduction in mechanical properties.

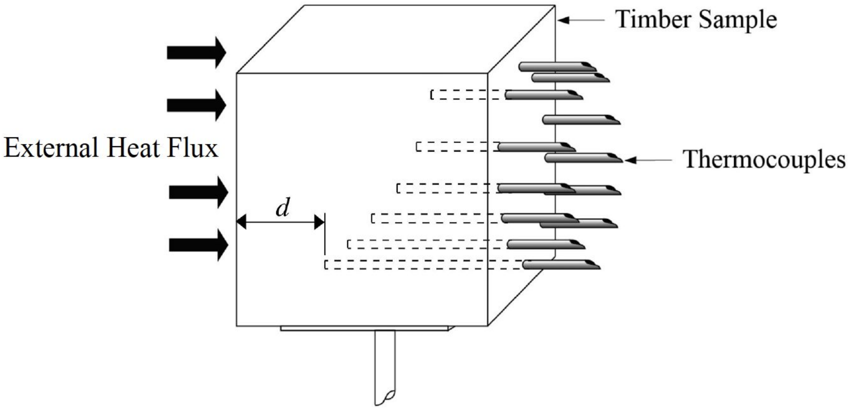


Figure 4.3- Thermocouple Test Setup

The depth "d" shown in Figure 4.3 varies for each thermocouple from 2mm to 57mm with 5mm increments changing between each.

4.3.1.Test Setup

Figure 4.4- Photograph of Thermocouple Testing Setup

Materials List
Douglas Fir- Larch 1 Green Wood Blocks Cut to Dimensions and Pre-Drilled
Conical Heater
(12) ⅛" DIA. 10" Sheathed Type K Thermocouples
Thermocouple Stand
Hot Glue
Data Logger
Go-Pro6

A conical heater was used to provide a uniform external heat flux on the sample. Using the same size and type samples as the mass loss test, the thermal gradient test used 1/8" diameter, 10" long thermocouples and each sample had 12 concenticrally spaced drilled holes with a 5/32" diameter. The thermocouples were placed into the sample at a 5mm spacing, with depths varying starting at 2mm from the exposed face. In order to prevent the sample from tipping over while the mass is decreasing, the thermocouples were held in place with a thermocouple stand propped up from behind as shown in Figure 4.4.

5. DATA AND RESULTS

The comparative results of mass loss rate are presented in Figure 5.2. The data shows the comparison between different heat fluxes and exposure time, note that the data has been normalized at time of ignition to ease comparison. Raw data was smoothed using a fifteen-point moving average.

The following are the names and criteria used for the events.

Exposure: When the aluminium shield is completely removed and the heat source is bearing on the specimen. The tests begins and is denoted as time 0:00.

Ignition: This is determined as the moment in which the exposed face of the sample is ignited with help of the pilot ignitor. Ignition was denoted when flames were present.

Reduced Flames: This event typically follows ignition and is denoted when the flames on the face of the exposed face are reduced to about a centimeter above the sample. It's noted that cracks on the wood can cause taller flames to be visible but those are dismissed.

Edge Burning (E.B.): This was recorded anytime the pattern of the burning was seen to wrap around the block and could potentially produce discrepancies in the data. It is denoted with top (T), bottom (B), left (L), and right (R).

Reignition: This is denoted as having the flames go past the 1 centimeter boundary in height. Not counting any localized crack flames.

End Test- Mass Loss: A minimum of 1 minute of constant burning without any flames on the front face, noting crack propagation and assuring reignition is not caused by cracks or knots in the wood. The exposed face has a char layer and all flames are no longer present, smoldering red embers and flames on deep cracks are allowed.

End Test- Thermocouple: Constant burning without any flames on the front face, noting crack propagation and assuring reignition is not caused by cracks or knots in the wood. The exposed face has a char layer, smoldering red embers can be present but flames must not be present before ending.

Table 5.1- Discrepancies In the Temperature Profiles with Respect to Time

Heat Flux	Depth Affected	Duration of Time	Description
20 kW/m^2	na*	na*	na*
25 kW/m^2	22 mm	26 min - 33 min	Temperature remained at 100℃ from the 22 mm and deeper were considerably less than the exposed face
30 kW/m^2	12 mm	10 min - 15 min	Temperature remained at 100℃
	12 mm-22mm	13 min - 22 min	The temperature difference between 7mm and 12mm was about 100℃ The temperature difference between 12mm, 17mm, and 22mm ranged between 25-50 ℃
	27 mm	25 min - 30 min	Temperature remained at 100℃
	27 mm	27 min - 36 min	The temperature difference between 22mm and 27mm was about 125℃ The temperature difference between 27mm and 32mm ranged between 10-25 ℃
35 kW/m^2	17 mm	17min - 24 min	Temperature remained at 100℃
	17 mm	18 min - 40 min	The temperature difference between 12mm and 17mm was about 100-125℃

*There were no discrepancies in the general trend of the curves. There were no instances of a temperature due to moisture migration.

Table 5.2- Heat Flux and Charring Rates

Heat Flux	Time When 300℃ Isotherm Crossed a Thermocouple	Charring Rates (mm/min)
20 kW/m^2	20 min	na*
25 kW/m^2	16 min 24 min 32 min	0.625 , 0.625
30 kW/m^2	15 min 22 min 32 min	0.714, 0.5
35 kW/m^2	12 min 28 min 30 min	0.3125, 2.5**

* There was only one instance in which the 300℃ isotherm crossed a thermocouple therefore analysis on depth affected, and time duration could not be gathered.

** The moisture migration greatly affected the calculations of the charring rates. The moisture content of the wood could affect the magnitude of the moisture migration. There was a lag in charing due to this between the first two sample points resulting in a low (0.3125mm/min) charring rate and the same phenomena caused the subsequent thermocouple to heat up with a considerably faster rate (2.5mm/min).

Table 5.3- Mass Loss Rate Peaks

Heat Flux	Mass Loss Rate Peaks (g/m^{2}s)
30 trial 1	16.62
32 trial 1	17.59
32 trial 2	15.98
35 trial 1	14.77
35 trial 2	15.92

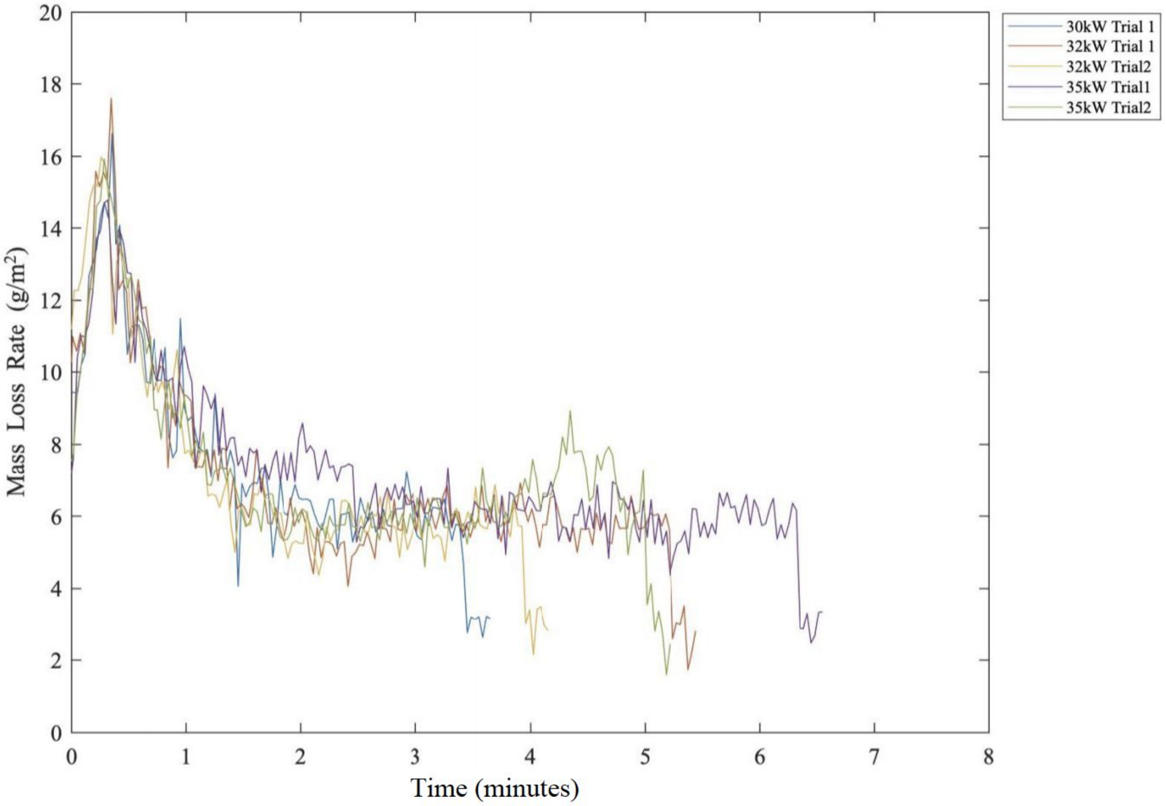


Figure 5.1- Comparison of Mass Loss Rate for Different Heat Fluxes with Ignition at t=0

The Figure 5.1 shows an overview of the different heat fluxes ranging from 30-35 kW/m^2. The time to reach ignition varies between samples and in order to facilitate comparison between tests they are adjusted with ignition at t=0 minutes. There is a general trend of mass loss rates peaking around 15-18 g/m^2 with the transient state/ steady state transition at about 2 min after ignition. There is a discrepancy in the general trend with the 35kW/m^2 trial between 4 and 5 minutes after ignition, that peak corresponds to a reignition of the timber that can be seen in Figure 5.4- C and D. Peaks like the one mentioned can be averaged out with a higher sample size and are a result of the individual natural properties like cracks or knots.

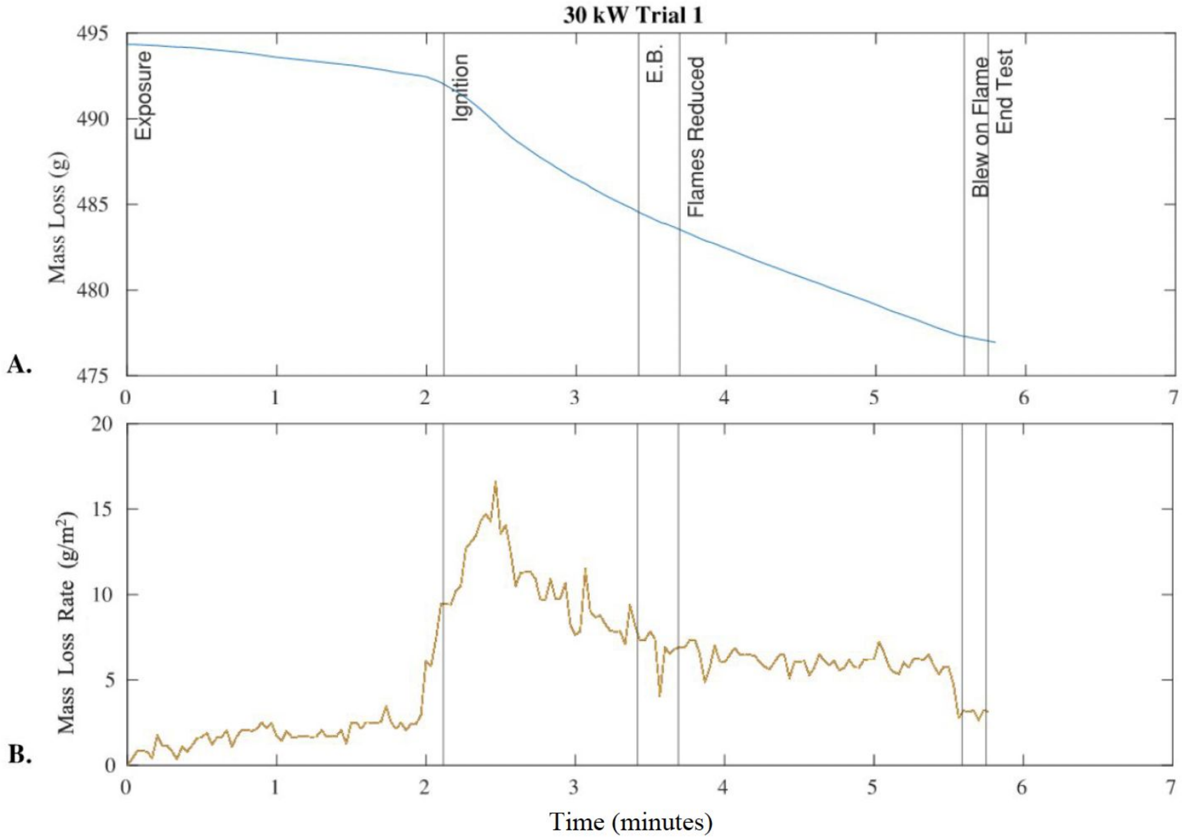


Figure 5.2- Mass Loss Test 30 kW Trial 1 (A. B.)

The charts in Figure 5.2 show peak mass loss rate of 16 g/m^2 and a total test duration of 5:40 minutes. At 5:35 minutes there was a disturbance on the sample and it was noted as such other than that there were no significant events.

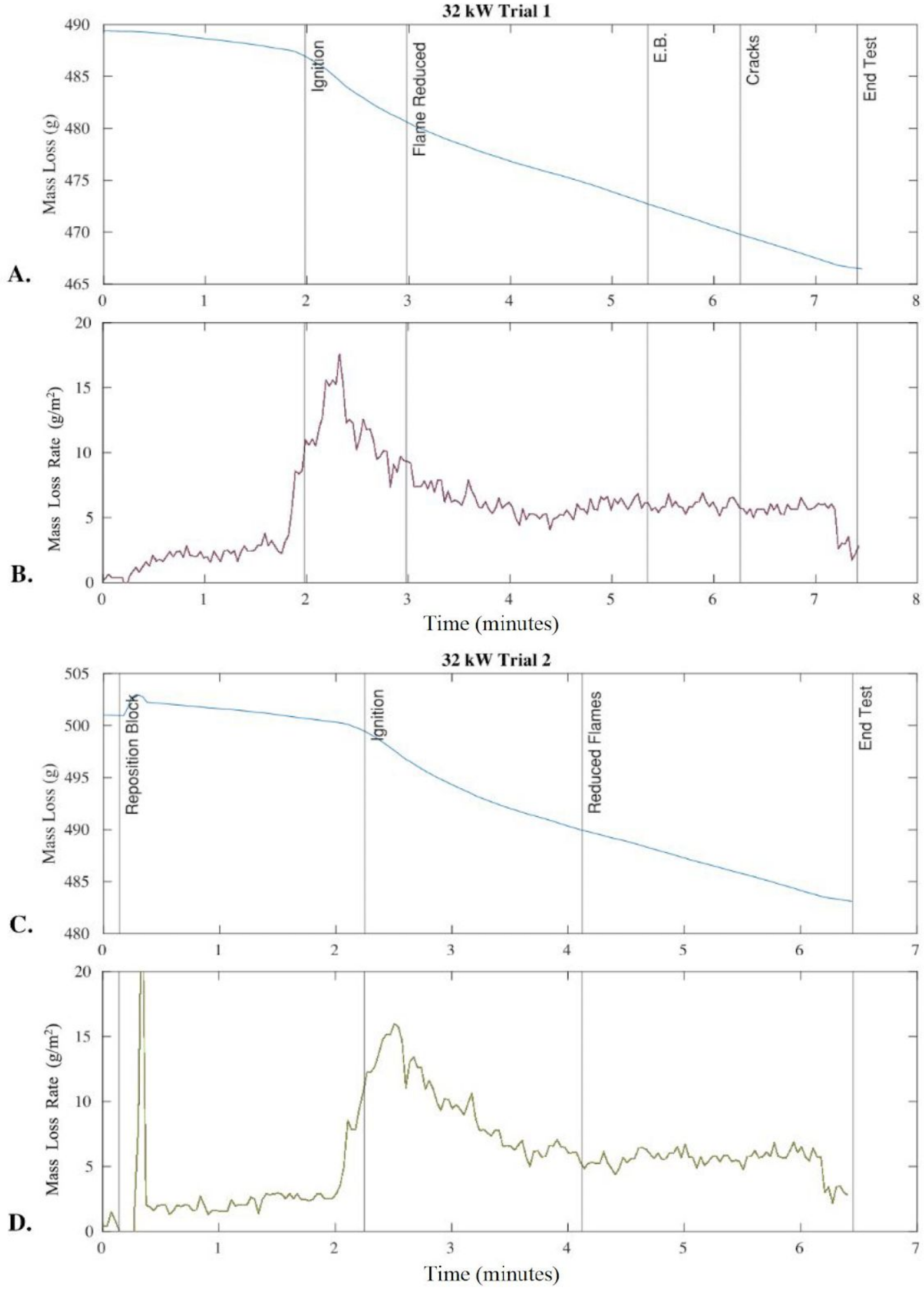


Figure 5.3- Mass Loss Test 32 kW Trial 1 (A. B.) and Trial 2 (C. D.)

Between the two trials there is a difference in time to reach ignition and total duration of the test. In Figure 5.3 (C and D) within the first 10 seconds a repositioning of the block caused a large peak to be recorded in the mass loss rate, this does not affect the rest of the data.

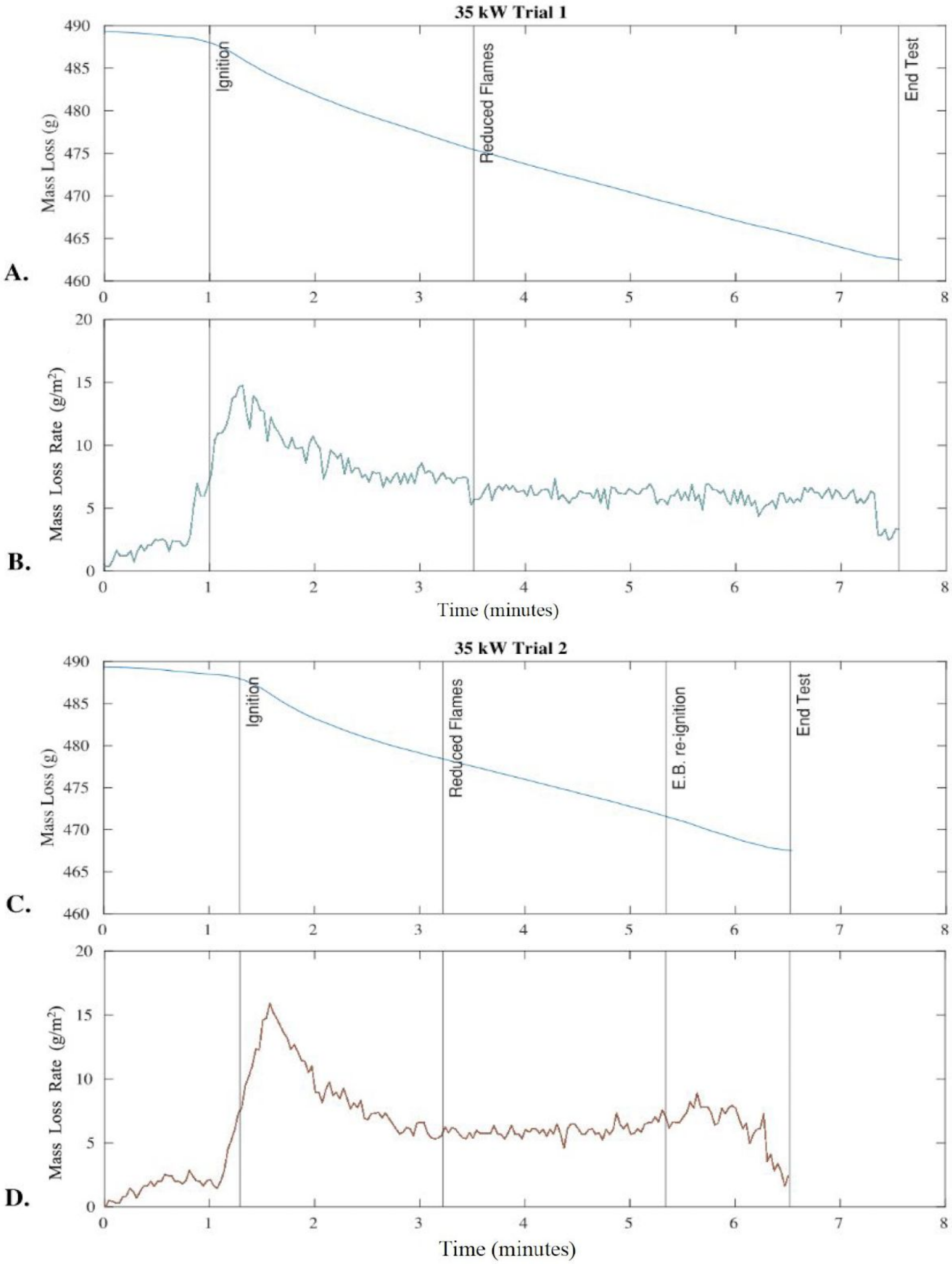


Figure 5.4- Mass Loss Test 35 kW Trial 1 (A. B.) and Trial 2 (C. D.)

In Figure 5.4 (C and D) there is a slight peak that shows a reignition zone around the 5:25 minute mark. This discrepancy corresponds to a large crack in the wood causing the reignition.

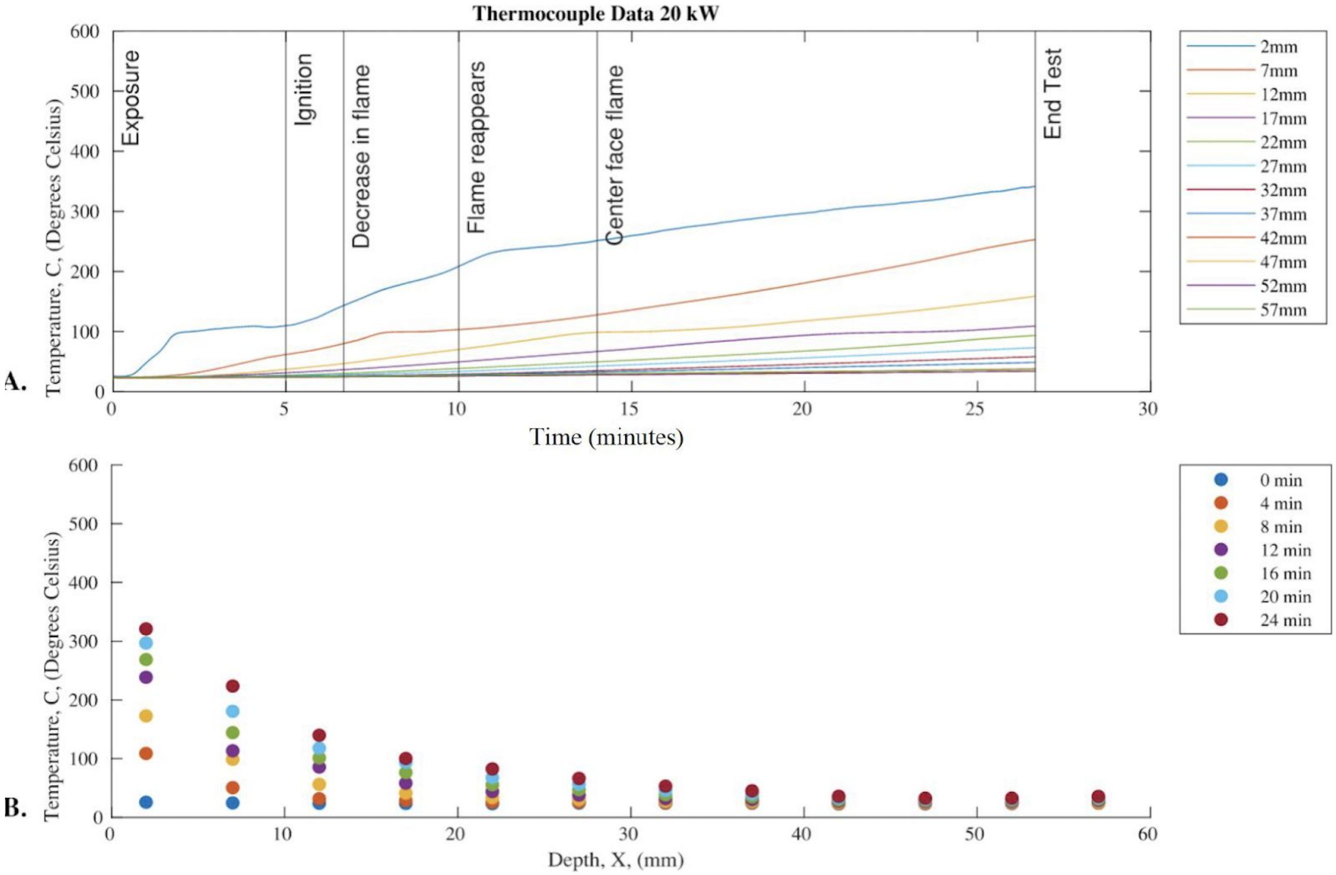


Figure 5.5- Thermocouple Test 20 kW (A. and B.)

Figure 5.5 shows a temperature gradient for 20 kW/m^2 test without any moisture migration or any notable discrepancies.

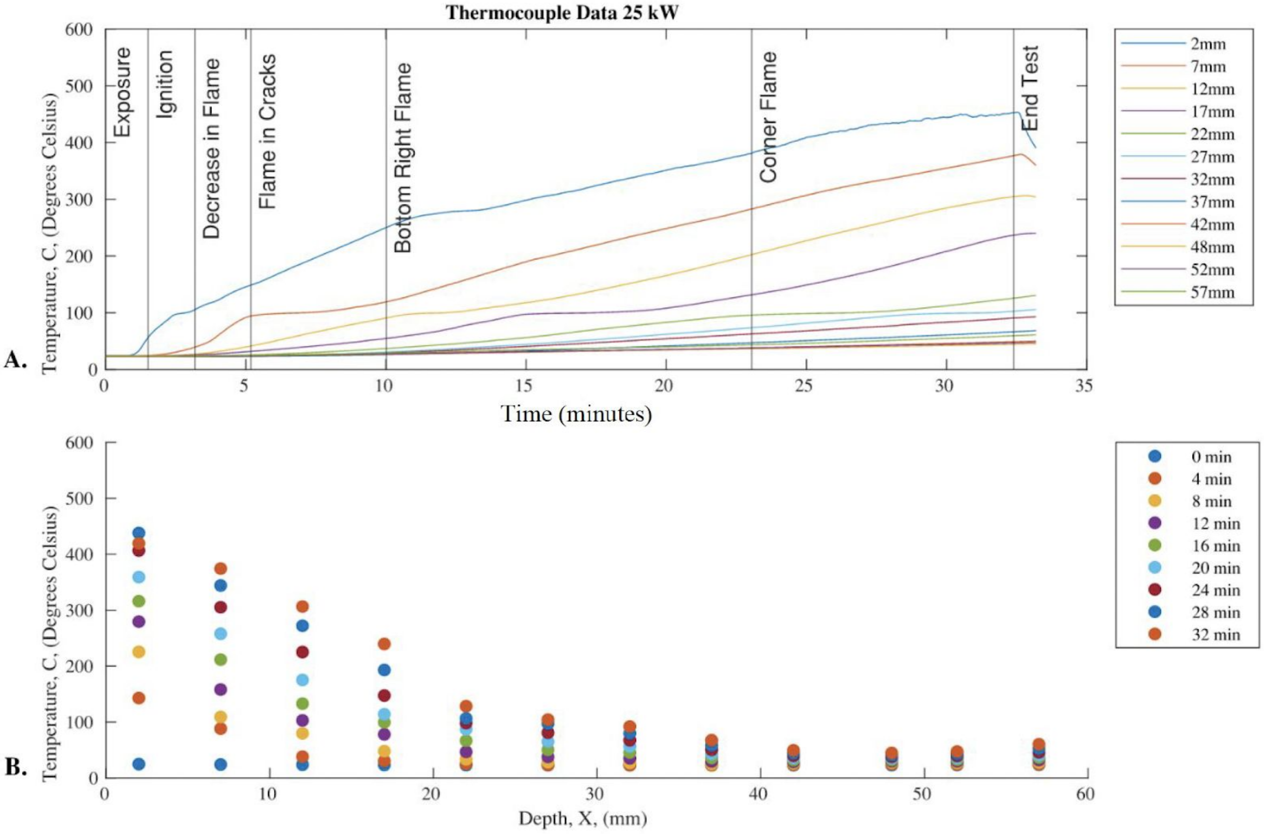


Figure 5.6- Thermocouple Test 25 kW (A. and B.)

In Figure 5.6 B there is a noticeable discontinuity in the temperature gradient as depth increases, this is due to moisture migration creating a lag in the time it takes for the heat to reach far into the specimen. This phenomena is more clearly seen in an animated version of this graph and the data corresponding to these events are in Table 5.1.

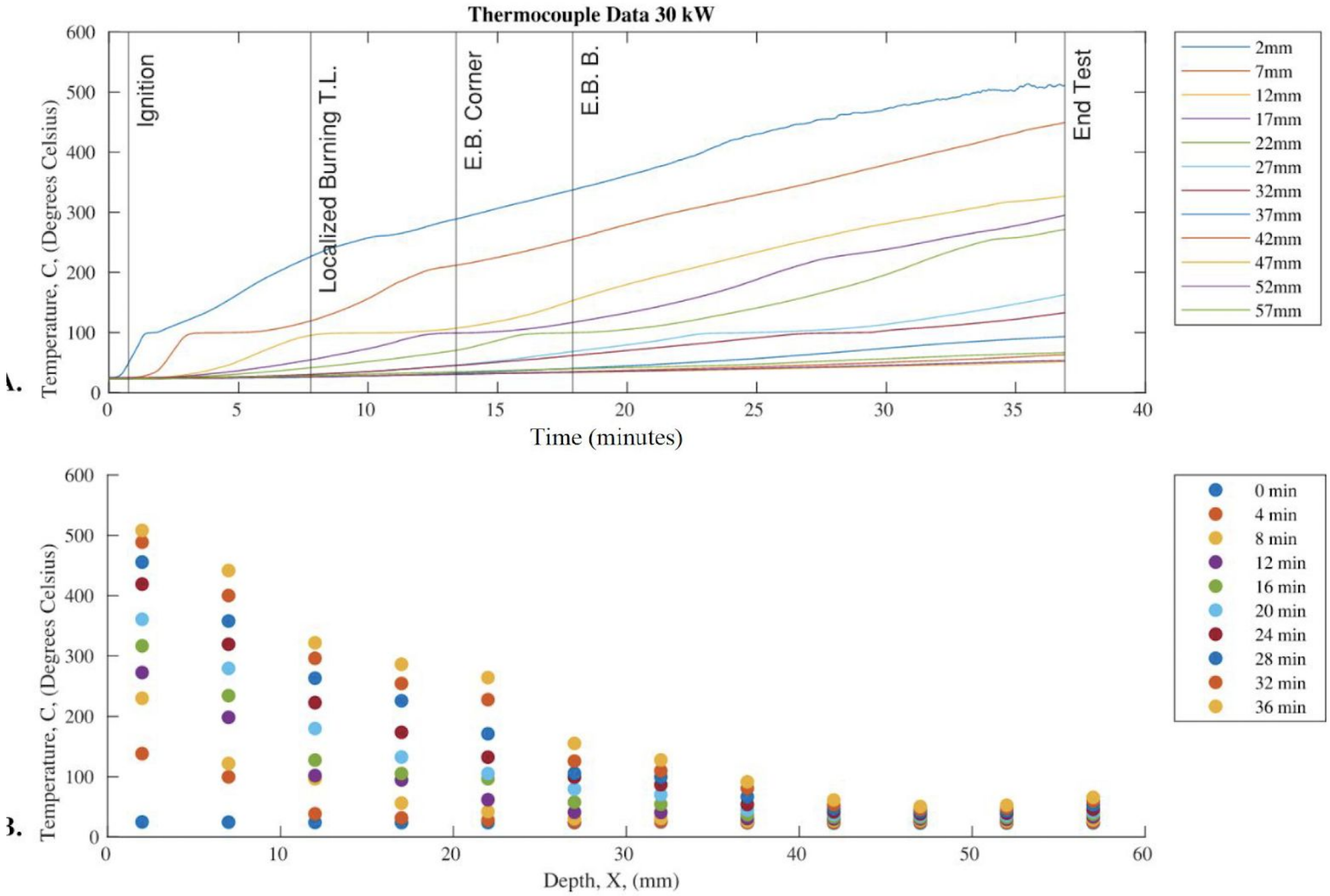


Figure 5.7- Thermocouple Test 30 kW (A. and B.)

In Figure 5.7 B there are two noticeable discontinuities in the temperature gradient plot, those which are detailed in Table 5.1. This test ran long enough to have several data points cross the 300℃ isotherm that corresponds to the char layer front thus there was enough data to calculate charring rates (Table 5.2).

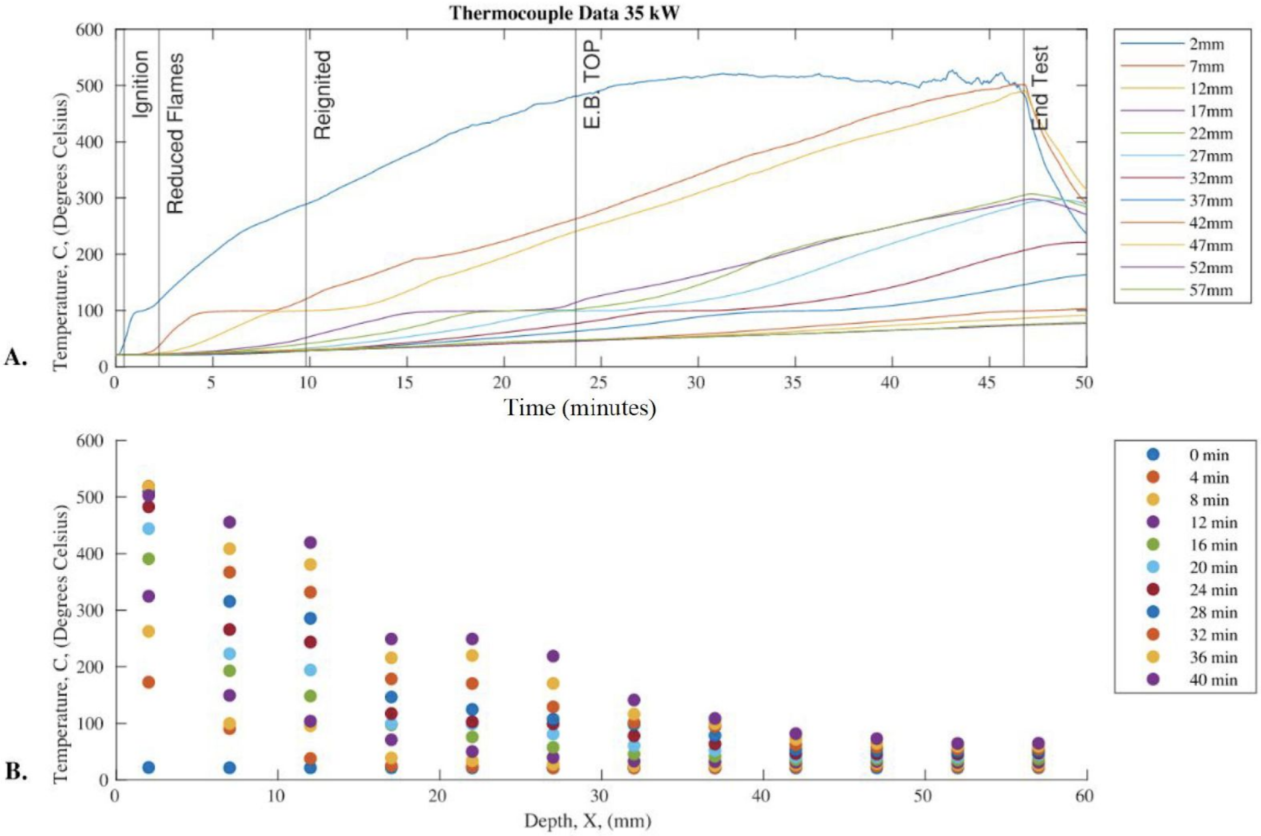


Figure 5.8- Thermocouple Test 35 kW (A. and B.)

Similarly to Figure 5.7, Figure 5.8 B has two noticeable discontinuities in the temperature gradient plot, those which are detailed in Table 5.1. This test ran long enough to have several data points cross the 300℃ isotherm that corresponds to the char layer front thus there was enough data to calculate charring rates (Table 5.2).

7. CONCLUSION

As buildings with exposed timber become more common among architects and engineers, it becomes important to understand the material behavior when exposed to fire. Structural engineers design for failure states to make sure the structure remains safe, including during an earthquake, but not necessarily during a fire, which is more common to occur. For regular, short buildings the prescriptive analysis to design for earthquakes is satisfactory. A performance based approach is used for more complex, irregular, or special use buildings when a better approximation is required or requested. Similarly, to describe the effects a fire will have on an exposed timber structure through a prescriptive method approach would not be appropriate since the full effects of the fire would not be captured. To design exposed timber for a fire event, engineers would have to use a performance based approach to understand how the charring rates of exposed wood differ to timber structures built and fireproofed using prescriptive methods enabling engineers to design timber members for material loss in a fire event.

In order to understand the full effects a fire would have on an exposed timber structure with varying layouts, from compartmentalized to open floor plans, one must understand the behavior of wood during a fire event. When studying the behavior of burning wood there are two regimes that exist and need to be understood and studied. These are the steady state and transient state. Steady state can be described as being the time at which wood reaches a constant mass loss rate during a fire event while the transient state is characterized as having a high initial peak in mass loss. To design for a fire event on timber structures, prescriptive methods use the steady state fire regime to estimate the charring rates to use when designing wood members. These charring rates would not appropriately characterize the mass loss of exposed timber since there could be more loss occurring during the transient state before the steady state is reached. This project studied the transient state of burning wood and the effects this could have on the structural design of exposed wood structures.

During the study, two separate tests were run to begin the material characterization of burning wood in the transient state under a wide range of heat fluxes. The first test was a mass loss rate test used to capture the information on the mass loss of wood over a period of time. With the use of video footage, key events which affected the mass loss rate in the progression of the transient burning were identified, such as the effect of cracks in the wood and reignition. The second test was a thermal gradient test which measured the thermal profiles using thermocouples distributed throughout the sample to determine the rate of conduction through the char layer and the thermal penetration depth past the pyrolysis zone. With both these tests, Table 5.2 shows approximate charring rates during the transient and steady state that were able to be determined using the time when the 300℃ isotherm crossed a thermocouple. The results show that the transient state mass loss rate is significantly higher than the average steady state and that it followed a similar trend in the heat flux ranges of 30-35 kw/m^2. Current assumptions for mass loss charring rates taken from the steady state zone don't include this peak, thus minimizing the effects of the high material loss in this initial state. It was also observed that there were nuances from the latent heat of vaporization that can greatly affect charring rates at different depths in the specimen, this moisture migration creates a visible delay in the thermal penetration shown in Figures 5.5-5.8. The moisture content of the wood is a factor that needs to be considered in future testing, the wood used in this study was green thus the moisture content was greater than what would be expected in a timber building using kiln dry wood or even lower moisture contents due to prolonged ambient exposure. When performing time dependent performance based calculations for exposed timber, like traveling fires, the actual effect of the transient state and the time delay of the latent heat become crucial in calculating accurate results. Decay in these initial exposures would be crucial to approximate the development of the fire.

These explorations are the first step towards determining the full scale effect of the duration and magnitude of the transient state burning of a fire and the direct effects it has on the decay rates of buildings made out of combustible materials, like wood, in open floor plans. It is important for future studies to conduct a wider range of samples and heat fluxes through the entirety of burning duration to see the full extent of transient burning and minimize outlier effects that can come with the natural properties of wood.

8. OUTLINE OF FUTURE WORK

Properly characterizing the influence of timber and the transient phase on the fire behavior of an open floor plan is vital to adequately providing structural fire engineering solutions. This study is just a start in trying to understand the complex dynamics of the combustion process and behavior of timber. The list below is by no means exhaustive and outlines possible tests to continue the research.

- Testing wood with different moisture contents (ie. kiln dry, green) in order to determine if the latent heat of vaporization remains significant for charring rates.
- Redefining the conditions for self-extinction to get data for the full duration of the burn and decay. Criteria for self extinction in future tests shall be met with complete extinction of flames and embers. By increasing the duration of the tests more charring rates can be determined further into the burning times.
- Broadening the range of heat fluxes to see the effects that higher or lower heat fluxes have on the charring rates.
- Testing different types of wood and see the full effect of knots and cracks in wood when it comes to flame duration.
- Tests to see the strength of the material after the char has developed and seeing the material properties.
- Larger sample sizes to verify the scalability of the tests.
- Full compartment tests to see how orientation and interaction of the floor and wall affect fire dynamics.
- Perform tests for longer duration and change the criteria for extinction so that the full effects of the transient burning are captured. The test duration can range from 20 min to hours depending on how long it takes for the criteria to meet

REFERENCES

1. Robbins, Jim. “As Mass Timber Takes Off, How Green Is This New Building Material?” *Yale E360*, Yale School of Forestry & Environmental Studies, 2019.
2. ReThink Wood. “Mass Timber In North America.” *ReThink Mag*, 31 Oct. 2016.
3. “The John W. Olver Design Building at UMass Amherst: Building and Construction Technology: UMass Amherst.” *Building and Construction Technology*, UMass Amherst | Department of Environmental Conservation, 7 Nov. 2019.
4. “Brock Commons Tallwood House.” *Think Wood*, 2018, www.thinkwood.com/our-projects/brock-commons-tallwood-house.
5. “Mjøstårnet.” *The Skyscraper Center*, Council on Tall Buildings , 2020, www.skyscrapercenter.com/building/mjostarnet/26866.
6. “Architecture Trends for 2019 and 2020.” *Grupo Azulev*, 21 Nov. 2019, azulevgrupo.com/en/blog/architecture-trends-2019-2020.
7. Gerard, Robert, and David Barber. “Fire Safety Challenges of Tall Wood Buildings.” *Research Foundation - Fire Safety Challenges of Tall Wood Buildings*, The Fire Protection Research Foundation , Dec. 2013, www.nfpa.org/News-and-Research/Data-research-and-tools/Building-and-Life-Safety/Fire-Safety-Challenges-of-Tall-Wood-Buildings-Phase-2.
8. Hamburger, Ronald, and John D. Hooper. “Performance-Based Seismic Design.” *Aisc.org*, NASCC: The Steel Conference, Apr. 2011,

www.aisc.org/globalassets/modern-steel/archives/2011/04/2011v04_performance_based.pdf.

9. Chopra, Anil K. *Estimating Seismic Demands for Performance -Based Engineering of Buildings*. 13th World Conference on Earthquake Engineering, 2004, *Estimating Seismic Demands for Performance -Based Engineering of Buildings*.
10. Bisby, L., Gales, J. & Maluk, C. “A contemporary review of large-scale non-standard structural fire testing”. Fire Sci Rev 2, 1 (2013). https://doi.org/10.1186/2193-0414-2-1
11. Stewart P and Woolson IH, 1902. “Making Buildings safe: Fire Proof Materials and methods of construction”. *New York Tribune,* October 19 1902, https://chroniclingamerica.loc.gov/lccn/sn83030214/1902-10-19/ed-1/seq-17/.
12. Gales, J., Maluk, C., and Bisby, LA (2012). “Structural fire testing- where are we, how did we get here, and where are we going”. 15th International conference on experimental mechanics: *Fire symposium.* July 22-27, 22pp.
13. Hull, Walter A., and Simon H. Ingberg. “Fire Resistance of Concrete Columns.” *Archive.org*, National Bureau of Standards, 1925, archive.org/details/fireresistance1925272hull.
14. Peatross, M.J. and Beyler, C.L., 1997. “Ventilation Effects On Compartment Fire Characterization”. Fire Safety Science 5: 403-414. doi:10.3801/IAFSS.FSS.5-403
15. Hakkarainen, Tuula. *Journal of Fire Sciences* , 1 Mar. 2002, journals.sagepub.com/doi/abs/10.1177/073490410202000207 4.

16. Lamont, S. & Lane, Barbara & Jowsey, Allan & Torerro, Jose & Usmani, Asif & Flint, Graeme. (2006). Innovative Structural Engineering for Tall Buildings in Fire. Structural Engineering International. 16. 142-147. 10.2749/101686606777962549.
17. WoodWorks. *Inspiration through Innovation* . WoodWorks Council , 2017, *Inspiration through Innovation* .
18. Leers Weinzapfel Associates. “John W. Oliver Design Building.” *Architectmagazine.com*, Architect, 10 Apr. 2018, www.architectmagazine.com/project-gallery/john-w-olver-design-building_o.
19. *Brock Commons at University of British Columbia Project Profile*. USG Corporation ,WB2900-USA-ENG/5-17, 2017, *Brock Commons at University of British Columbia Project Profile*.
20. “UBC Aquatic Centre and Brock Commons Tallwood House.” *Acton Ostry Architects*, Acton Ostry Architects Inc, 20 Apr. 2018, www.actonostry.ca/2018/04/20/ubc-aquatic-centre-and-brock-commons-tallwood-house/.
21. Acton Ostry Architects. “Brock Commons – Tallwood House.” *Vancouver*, The University of British Columbia, vancouver.housing.ubc.ca/residences/brock-commons/.
22. “Stadthaus.” *The Skyscraper Center*, Global Tall Building Database, 2017, www.skyscrapercenter.com/building/id/19918.
23. “Murray Grove.” *Waugh Thistleton Architects* , 2010, waughthistleton.com/murray-grove/.

24. Pryce, Will. “Stadthaus, 24 Murray Grove, London Case Study.” *Trada Technology*, Trada, 2009.
25. Emberley, Richard L. Fundamentals for the fire design of cross laminated timber buildings. PhD Thesis, School of Civil Engineering, The University of Queensland,2017.
26. “ASTM E119 - 20.” *ASTM International - Standards Worldwide*, June 2020, www.astm.org/Standards/E119.htm.