BIM AND FIRE SAFETY ENGINEERING FOR WOOD STRUCTURES

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Abstract

This thesis provides a map for Fire Safety Engineering (FSE) practitioners who are navigating the complicated and under-studied research area of mass timber in fires and how such a project would fit into the BIM design process. The thesis expands the field of knowledge on how architectural features correlate with fire dynamic outcomes of full scale CLT compartments, provides baseline fire metrics for Eastern Hemlock without any existing published data, and provides a wholistic interpretation of the performance of a traditional mortise and tenon timber frame connection in a fire test, also without any existing publications. The thesis also provides an option for how each project might be included in BIM and any research or requirements that would allow for total integration, as well as the potential benefits.

I dedicate this thesis to the people who want to progress the Architecture, Engineering, and Construction (AEC) industry into a world where we prioritise environmental stewardship, quality of life, opportunity, heritage, and innovation in the beauty, form, and function of our built environment.

Acknowledgments

I would like to give a huge thanks to my supervisor Dr. John Gales. He continuously works hard to bring opportunities to students like me. Without his encouragement, this thesis would not exist. John's advice with applying for scholarships, writing conference/journal papers, experimentation and research, and general career advice, has been vital to my academic growth. His patience and contributions can never receive enough thanks.

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I would like to acknowledge my extended family and friends for believing in me, encouraging me, and aiding me. I am so grateful for the countless discussions, reviews, and feedback over the years. I would especially like to thank Penta Ledger for copy editing.

I would like to thank my aunt, Terry Ledger, owner of t-squared design studio inc. for being an inspiring mentor; a career woman in the residential design world. Over the years, she has taught me everything I know about interior design, drafting, forming construction drawings, and the needs of architects and building departments. I am so grateful for the invaluable start to my career and support.

Last but not least, I would especially like to acknowledge my parents, Alison and Matt Davidson, for their love, continuous support, and encouragement. At a young age they taught me to follow my passions and instilled me with the belief that I can accomplish anything to which I set my mind. Their passion for woodworking and construction has been foundational to my career, ambitions, and to this thesis.

Statement of Contribution

The work herein has been influenced by several contributors. The thesis takes a modified manuscript format where each chapter has been adapted from a previously published paper or will be adapted as a published paper. The author of this thesis is also the primary author of published papers and has undertaken advice and input from other co-authors but has performed all original research and original writing during their pursuit of a Master's degree.

Chapter 3 is based on:

A. Davidson and J. Gales, "BIM and Fire Safety Engineering - Overview of State of The Art," International Journal of High Rise Buildings, vol. 10, no. 4, pp. 251-263, 2021.

Chapter 4 is based on:

A. Davidson, J. Gales and P. Kotsovinos, "THE IMPACTS OF ARCHITECTURAL CHANGES ON FIRE DYNAMICS; THE CASE OF TIMBER COMPARTMENTS," Proceedings of the Canadian Society for Civil Engineering Conference,(in press) 2023.

Table of Contents

CHAPTER 1

Introduction

Therefore it was the discovery of fire that originally gave rise to the coming together of men, to the deliberative assembly, and to social intercourse. And so, as they kept coming together in greater numbers into one place, finding themselves naturally gifted beyond the other animals in not being obliged to walk with faces to the ground, but upright and gazing upon the splendor of the starry firmament, and also in being able to do with ease whatever they chose with their hands and fingers, they began in that first assembly to construct shelters.

... they next gradually advanced from the construction of buildings to the other arts and sciences, and so passed from rude and barbarous mode of life to civilization and refinement.

-Vitruvius, The Ten Books on Architecture, 1st century BC

1.1 GENERAL

Almost 2000 years ago, Vitruvius argued that from fire came assembly, construction, and civilization. While how humans discovered fire is debateable, it can certainly be agreed that without fire or the buildings that make up our homes, towns, and cities, we would not be the "civilized" society that we are today. Today's society includes freeways spanning 18 lanes of traffic connecting some of the densest cities in modern history. Skyscrapers reach for new taller heights, and heritage buildings are being demolished, preserved, restored, or rehabilitated. Today's society, with all its successes (democracy, rights, and freedoms, etc.), still faces many challenges. The most impeding of which is rapid climate change.

If emissions continue as they have in the past, the global temperature average is projected to be 6°C warmer by the end of this century [1] and may exact serious implications for society. These changes in temperature cause sea levels to rise, currents to change, heavy rains and snowfalls, and many other natural disasters [2]. Since 2000, the frequency of extreme weather events in the USA has increased by almost 200% [3]. The cause of global climate change is mainly attributed to greenhouse gases, primarily carbon dioxide emissions. It is essential that humankind work towards better environmental stewardship in every industry.

The Canadian construction market is worth about $356 billion [4]. Embodied carbon in construction materials contributes to approximately 9% of CO^2 emissions and buildings demand 34% of the world's energy consumption [5]. Making a difference in the Architecture, Engineering, and Construction (AEC) industry can have a positive impact on the environment. The demand for more sustainable buildings coupled with technological advancements in the AEC industry has resulted in a resurgence of wood as the construction material. Wood is a renewable resource unlike the energy and carbon intensive materials of steel and concrete. Wood has a great strength-to-weight ratio and one of the lowest thermal conductivities, making it a superior product for acoustics, and biophilic attributes. Canada has an abundance of wood and the best sustainable forestry program in the world with 40% of the world's certified forests [6]. Constructing timber buildings over 10 stories has been made possible by advancements in engineered wood products such as glulam and CLT. Building with mass timber as a solution to the climate crisis has been gaining popularity. The construction of tall mass timber buildings has increased 256% since 2017, and the trend is expected to continue [7].

Though the construction of tall mass timber buildings is relatively new, wood is an historical building product. Indigenous peoples of Canada lived in wooden structures long before the European invasion of the 1600's. Since then, Canadian construction has evolved from longhouses, to log homes, to mass timber frames. Nowadays many of these heritage buildings are in danger of being demolished as their true value is not fully recognized by the public. In the pursuit of environmental stewardship and the preservation of cultural heritage, finding ways to ensure the continued life of these monumental structures is important.

Despite all the positive qualities of using wood, there are some drawbacks that have hindered its full potential. Some of the greatest challenges of using wood include its ability to decompose and its susceptibility to fire. The materials variability in properties makes it difficult for engineers to predict how it might perform under any circumstance, particularly in the event of a fire, and especially when it comes to the analysis of aged timbers. Probabilistic models of wood's behaviour in fire is relatively unknown and understudied [8] despite societies technological advancements or the historical uses of wood, including the million years humans have been burning it [9].

Fire Safety Engineering (FSE) is an integral part of the design of tall timber structures – and any structure. Fire safety is influenced by a multitude of variables including architectural layout, material properties, fenestrations, HVAC, fire safety systems like sprinklers and alarms, occupancy, evacuation routes, smoke development from the burning of finishes and furnishings. The multi-variable complexity of FSE requires a high degree of collaboration between FSE practitioners and other designers.

Projects that use Building Information Modelling (BIM) have been known to increase efficiency while reducing conflicts, error, and miscommunication [10]. BIM is a data rich environment which organizes all information to do with a building from conception to end of life. BIM is often perceived to be a 3D modelling software that allows the automation of construction drawings, material lists, etc. but is capable of more than most realize. The usefulness of BIM has been well recognized and countries such as the United Kingdom have a BIM mandate for projects in the AEC industry [11]. A fully developed BIM will contain all the necessary data for FSE which can reduce the need for remodelling, thereby increasing design project efficiency. The improved efficiency and reduced error generated from utilizing BIM has the potential to improve the FSE process for wood structures dramatically. The compatibility between BIM and FSE seems obvious, yet designers have been slow to adopt the use of BIM for FSE and there is lacking research regarding their compatibility. The result is a general lack of knowledge and functionality regarding the utilization of BIM for FSE, which in turn creates strenuous workloads for practitioners where projects may end up taking more time and resources than typical similar projects.

1.2 MOTIVATION

The motivation for this thesis is to explore how BIM can be used for FSE of timber structures, both new, and heritage. The FSE industry is still developing its understanding of fire dynamics, analysis, and design techniques. The structural engineering of wood structures is also undergoing research development as engineered timber products undergo continuous innovation. Whatever lack of research and understanding there is regarding these two subjects, the gap exists more so in their combination: fire analysis and design of mass timber structures; the thermo-mechanical response. BIM is also an evolving research subject matter. Due to BIM's potential benefits and for some projects, and its mandated use in some cases, it must be considered. If one were to think of each topic as a "pie" of literature, the literature involving the overlay of any two topics is smaller. The body of literature involving all three topics (Fire, Wood, and BIM) is even smaller still. The novelty of it means that current literature has not yet come to a consensus on how the three topics interact with one another. This motivated a holistic approach to understand how fire, wood, and BIM might be considered together to further the design and understanding of preserving and building wood structures.

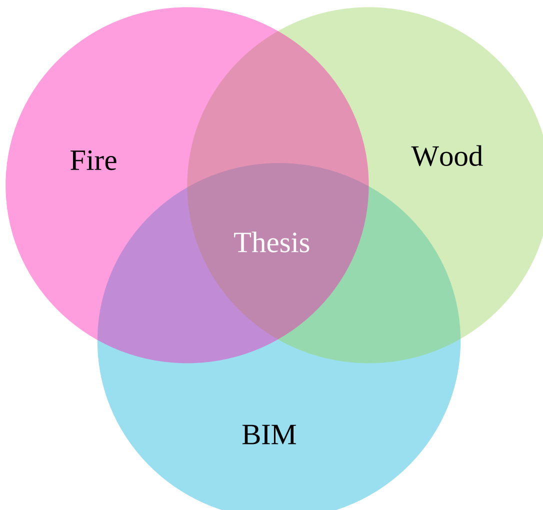


Figure 1-1: Visualization of BIM-Fire-Wood literature topics

It is essential that research progresses FSE for wood structures. It is necessary that discussions on how FSE will fit into the BIM start taking place. All three topics could have a thesis in their own regard. Due to the evolving and developing nature of FSE, Wood and BIM, a holistic approach is taken. This thesis can serve as the first step in providing practical guidance to practitioners embarking on the FSE of a BIM mandated wood building project. Whether the project be a new build or the rehabilitation of an historic timber frame, the information in this text will likely change the lens through which an engineer views BIM, FSE, and Wood.

1.3 SCOPE

This research project aims to progress industry understanding on how wood structures perform in a fire and how the BIM environment can model that performance. After an holistic literature review regarding integration of FSE and Wood within BIM, an overarching road map as to the possibilities of FSE-BIM integration regarding the different stages of a building's life cycle is provided. The author chose to focus on structural fire engineering. The current understanding regarding fire dynamics within a CLT compartment is considered, and how it can be included in BIM. New research on charring rates of heritage wood is presented, and how it can be included in BIM. New research on the fire performance of a heritage connection is presented, and how it can influence calculations occurring in BIM. Anything beyond these topics is excluded and considered out of scope. Each fire-wood project focuses on only one potential BIM application, though there may be many.

1.4 RESEARCH OBJECTIVES

The overall research question is: How can BIM be used for FSE of wood structures? The following objectives contribute to answering that question.

1. Provide FSE practitioners with a basic understanding and guide on how BIM might fit into their future projects.
2. Improve multi-disciplinary understanding through BIM by using the analysis of current research on CLT compartment fires.
3. Investigate the fire performance of heritage wood materials for fire smart BIM objects.
4. Investigate the fire performance of a heritage traditional mortise and tenon connection, and how this can be used for FSE within a BIM environment.
5. Provide the FSE practitioner and researcher with key takeaways that can be applied to future fire safety design project, whether BIM is used or not.
6. Identify the greatest challenges of BIM integration, the potential benefits, and areas for future research.

1.5 OUTLINE OF THESIS

The thesis format is a manuscript. Chapter 2 gives some brief technical background regarding the mechanics of wood in fire and Building Information Modelling (BIM). This chapter can be completely skipped by the practitioner who already has a basic understanding of wood, fire dynamics, and BIM. Any of the other chapters could be read in any order. However, it is recommended to read the thesis from beginning to end. The chapters follow along the beginning stages of a timber building's fire safety design, starting with conception.

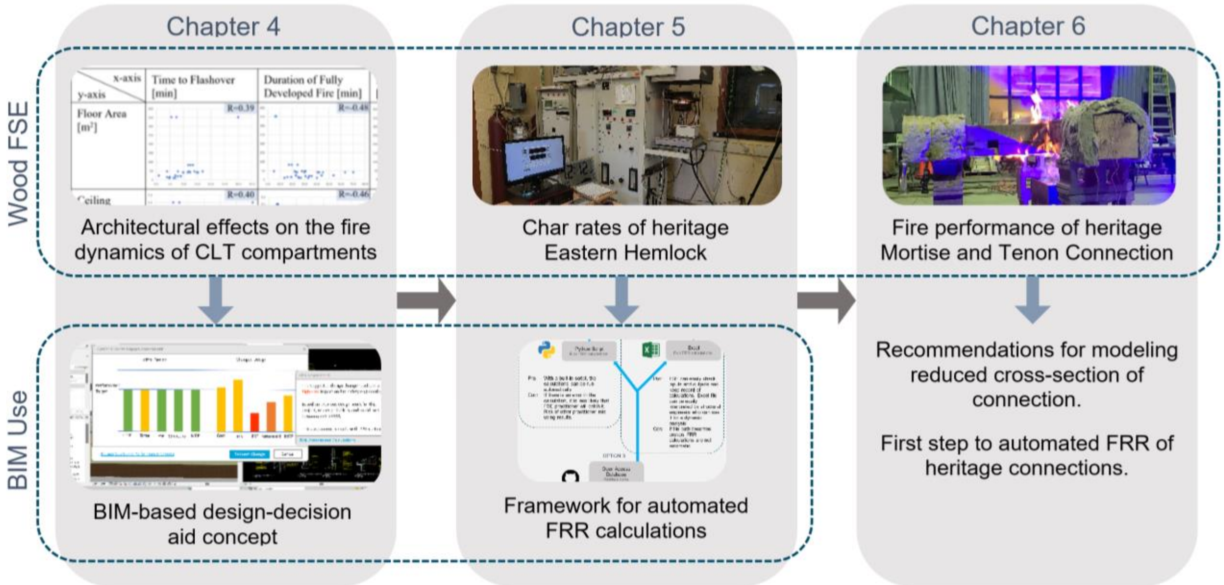


Figure 1-2: Graphical Thesis Outline

Chapter 3 provides an in-depth literature review of BIM for FSE of wood structures and is a slightly modified version of a paper previously published by the author and supervisor Dr. John Gales, in CTBUH Journal, for which the author was also the first author. The literature review provides the reader with a basic overview of the thesis topic. The different applications and subtopics discuss current research and future directions for BIM and FSE data management, fire smart BIM objects, automated code checking and model compliance, structural fire dynamic integration, emergency evacuation integration, BIM and construction fire safety, BIM and fire safety operations, BIM and fire rescue, and uses of extended reality and fire safety.

Chapter 4 analyses the current understanding of fire dynamics in CLT compartment fires based on 33 real full-scale compartment fire tests. For the purpose of identifying the impacts of architectural features on fire dynamics, fire dynamic outcome metrics such as peak HRR, duration of fully developed burning, time to "Flashover", and maximum temperatures reached were plotted against architectural feature metrics such as floor area, ceiling height, amount of exposed timber on ceiling and walls, opening factors, and fuel load density. The scatter plots are then used to identify research gaps and correlations which might signal a strong relationship between two of the variables. A BIM-based alert system for aiding design decisions and cross-disciplinary awareness is conceptualized and highlights how research data can be used in a BIM environment.

Chapter 5 provides baseline data on the fire performance, including char rates, of Eastern Hemlock as a species where no current published data exists. This research will help FSE practitioners when evaluating historic timber frames in Ontario, Canada. This testing series revealed HRR data, mass loss rate data, smoke production data, and char rate data. The char rate data is compared to a non-linear char rate model used in American standards and the linear model used in Canadian standards. The char rate data is used as a FSE parameter within a conceptual smart BIM object framework.

Chapter 6 builds on the research from chapter 5. In this chapter, a full-scale fire test on a heritage traditional mortise and tenon connection built from Eastern Hemlock is performed. This research provides information on the fire dynamic behaviour of a burning tradition connection where no such literature exists. The results can be used to evaluate the Fire Resistance Rating (FRR) of heritage timber frame buildings. It can also be used for the development of thermo-mechanical simulation models in the future. The traditional mortise and tenon connection was burned on its side allowing for a worst-case-scenario where the wooden dowel are directly exposed and the 2 in. wall of the mortise is directly exposed to the methanal pool fire. The use of narrow-spectrum illumination was able to filter out light from the flames and get a clear visual of the charring mechanisms happening on the surface throughout the test. Thermocouples were also employed. The char was removed afterwards to reveal the real reduced cross section after a fire.

CHAPTER 2

Technical Background

When trees burn, they leave the smell of heartbreak in the air.

-Jodi Thomas

2.1 INTRODUCTION

The following information is intended to aid the reader in understanding the technical concepts required for recognizing the issues and challenges related to the thesis topic. Technical info on wood in fire and Building Information Modelling (BIM).

2.2 BUILDING WITH WOOD

The benefit of wood is that it is renewable resource. As trees grow, they capture CO^2 from the air, and when they are used, that carbon is stored away rather than being released back into the environment. This makes many wood products carbon negative. Wood has a good strength to weight ratio, is easy to work with, has the ability to dampen vibrations and improve acoustics [12]. It has exceptionally lower thermal conductivity than alternative structural materials such as steel and concrete. Wood is also, by all standards, a beautiful material. Many people around the world and across cultures enjoy the warmth and the texture of wood.

The organic nature of wood however means that it can decompose and inherently variable possessing defects. Wood falls victim to rot, biota, sun damage, and fire if not properly maintained.

2.2.1 A History of Building with Wood

Wood has been integral to societies' development and has been used to make spears for hunting, furniture, pottery, wheels, and chariots. Wood has been used to construct boats, build churches, produce medicine, and through its conversion to paper, promote and preserve knowledge throughout the world.

Just because wood is organic and may not outlast other materials such as steel, does not mean that a wood structure cannot last a long time. The Horyuji temple is the oldest standing building constructed over 1,300 years ago [13]. Wood buildings have been a part of China's culture since the Ancient China and the Shang dynasty (1600-1046 BCE) and is characterized by columns arranged in series, connected with wood beams [14]. The connections where jointed mortise and tenon connections built to allow for movement and flexibility during an earthquake [14]. The Viking era has a notorious reputation for its craftsmanship with the earliest evidence of a wood plank ship dating to 350 BCE [15]. The log cabins everyone is familiar with originated in Scandinavia around 5,500 years ago [16]. The longevity of wood structures has stood the test of time.

2.2.1.1 Wood Structures in Canada

Figure 2-1: Reconstructed Longhouse at Ste-Marie Among the Hurons. Image obtained from The Canadian Encyclopedia, courtesy Ste-Marie Among the Hurons [17].

Canadian Indigenous people were constructing with wood long before the European settlement of the 1600's. Plains nations built teepees, a mobile building. The longhouse, pit house, and plank house were more permanent structures, which were all constructed from wood. When the settlers did come, they brought knowledge of building log cabins and timber frames from Europe with them. The construction techniques for the complicated wood structures were starting to be lost since Europe had lost most of its old growth forests by then [16]. Log home construction quickly became popular with settlers due to its simplicity. No nails were needed, and the logs did not need to be hewn. The thermal mass also proved sufficient for insulation.

Figure 2-2: A. Replacing the top round of a heritage log cabin B. Employing traditional methods for constructing a saddle notch. Photos courtesy of Matt Davidson.

As settlers became more comfortable, they began building larger structures such as the barns that can be frequently spotted throughout the Canadian Landscape. These soaring structures are almost cathedral like and were made possible with easy access to old growth forests and the employment of mortise and tenon connections.

Figure 2-3: A. Dilapidated barn exposing timber frame B. Mortise and tenon connection.

2.2.1.2 Modern Engineered Wood Construction

In the mid-1990s, Austria developed what we know as Cross Laminated Timber (CLT) [18]. CLT is an assembly of glue-laminated lumber where the different layers use pieces spanning in criss-cross directions, as shown in Figure 2-4 A. The high-strength high-stiffness properties of CLT have made it suitable for floor slabs as well as structural walls. CLT combined with Glulam (beams constructed from laminated lumber in one-direction – shown in Figure 2-4 B), has allowed for the high-rise construction of timber buildings. The tallest mass timber building constructed to date is 25 storeys [7].

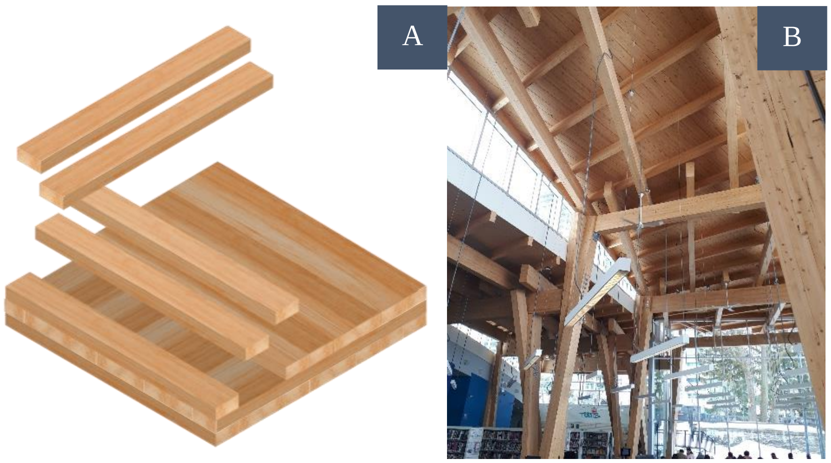


Figure 2-4: A. CLT Assembly (Think Wood [19]) B. Glulam frame (courtesy John Gales)

2.2.2 Properties of Wood

2.2.2.1 The Anatomy of Wood

THE ANATOMY OF A TREE

There are two different classes of trees, commonly referred to as softwoods and hardwoods, although this is not always accurate. Botanically, a softwood is a conifer tree, usually with rough bark, triangular-shaped crowns with branches that hold needles that stay year-round. Botanically, a softwood is an angiosperm [12]. They have broad leaves and flowers and seeds enclosed in a fruit. The majority of Canadian hardwoods are deciduous, meaning the leaves fall off annually. Mainly softwoods are used in construction, although some timber frames are built with oak.

The tree is composed of 3 main parts, as shown in Figure 2-5: the crown, the stem (ie. trunk), and the roots. When the stem of a tree is cut through, growth rings are visible, and each ring indicates one year's growth. As a tree grows, it gains another ring (per year), and grows from the tips of its branches, not from the base of the tree [12]. In the centre is the 'pith' of a tree, and on the outside, the rough organic structure, is the bark. The bark does little for the wood structurally and is removed during the manufacturing of lumber.

After some years, the wood at the very center of the tree no longer carries sap from the roots to the crown. It changes chemically becoming “heartwood” which often appears darker [12].

In general, as a tree grows older, it grows taller, but this may be affected by different growing conditions or genetics. Altitude, access to water, forest density, etc. all have an impact. No tree is exactly the same.

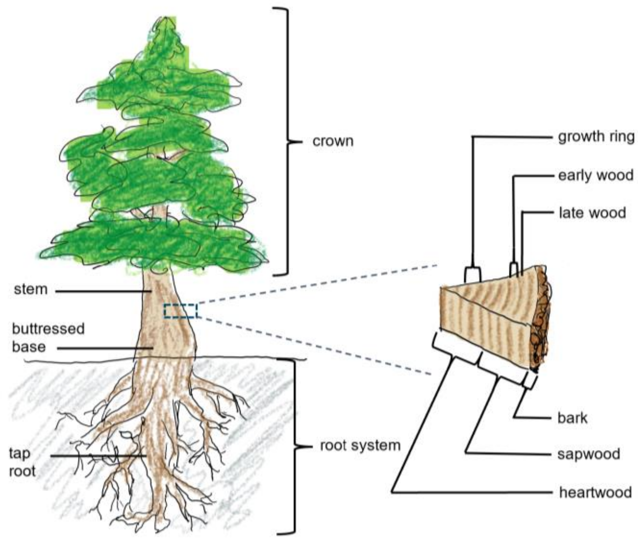


Figure 2-5: The structure of a tree (adapted from [12])

THE CELLULAR STRUCTURE OF WOOD

The dark part of the ring is the late wood; when the tree grows very slowly and has little access to sun or water. The tracheids, which are essentially molecular level carbon tubes/straws running vertically from the roots to the top of the tree, make up the ‘grain’ of the wood. Due to the deprived state of the tree during the winter months, the tracheids are not able to grow as fast or as large, so they appear tighter on a molecular level and manifest as the dark lines seen in the rings of a cut tree [12]. The light part of the rings is the early wood, formed during the spring when tracheids have relatively large cavities/lumens and thin walls [12].

The cell wall structure as shown if Figure 2-6 B. is composed four walls: The primary wall, and the S_1, S_2, S_3 layers. The outermost layer, the primary wall, is formed during the cells first development and the microfibrils are arranged in an irregular manner [12]. The S_1, S_2, S_3 layers contain organized microfibrils arranged at different angles for added strength and stability and determine, ultimately the strength of the wood itself [12].

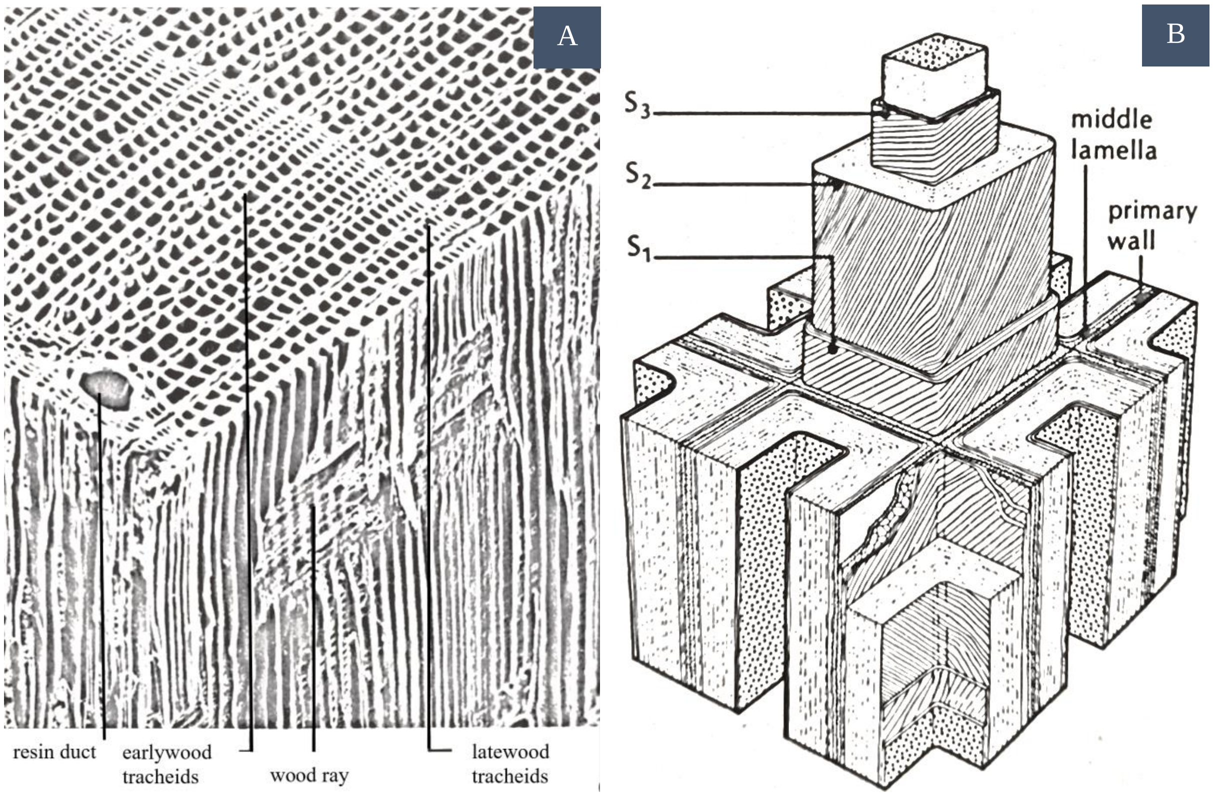


Figure 2-6: A. Molecular structure of wood B. Cellular structure of tracheids [12]

The molecular structure of wood is what gives it its affinity for moisture as well. The cell walls hold moisture referred to as ‘bound water’ and any excess moisture shows itself in the cell cavities, called ‘free water’ [12]. The fibre saturation point (FSP) is the point at which all water is drained from the cell cavities, but the cell walls remain saturated, usually around 30% [12]. When wood is dried below the FSP, the cells contract and the wood begins to shrink. If moisture is reintroduced, wood will absorb moisture from the air and swell.

THE CHEMISTRY OF WOOD

Dry wood cells are composed of about 50% carbon, 44% oxygen, 6% hydrogen, and 0.1% nitrogen [12]. Chlorophyl present in the leaves or needles absorb radiant energy from the sun and use it to create complex chemical compounds. These compounds include Cellulose (40%), Hemicellulose (23-30%), and Lignin (19-33%) [12]. The lignin is used to bind the cellulose together to make a kind of “fiber glass” structure of which the tracheids are composed [12].

DEFECTS IN WOOD

The following definitions are obtained from *Canadian Woods: Their Properties and Uses*, by J. Mullins and T.S. McKnight [12].

Knots: What used to be a tree branch embedded in the cellular structure of the tree stem. Knots disturb the continuity of the fibre molecules, creating a weak link in the structural make-up of the tree.

Pitch Streaks and Pockets: Pockets of excessive resin. It is also a discontinuity in the molecular fibres. Also often referred to as pith flecks.

Cross grain: Refers to any condition where the cellular fibres are not arranged parallel with the axis of the tree. There are special categories of cross grain: curly, wavy, interlocked grain, and spiral grain. The extent of cross grain in areas surrounding knots are approximately proportional to the size of the knot.

Shakes and Checks: Shake sometimes refers to all cracks in the standing tree but often referred to in the meaning of 'ring shake'. Ring shake is the separation of growth rings within a tree. Checks can occur longitudinally and radially when a log is drying out, the check starts at the outside and cracks towards the center. Shakes and checks occur to relieves stresses though ring shake can sometimes occur if the stem in injured.

Brash Wood: Wood that has low resistance to shock producing brittle failures. It often occurs in light weight woods composed of large thin-walled tracheids, which looks like large annual rings. It can also be caused by compression wood.

Compression wood: Densely packed cells in response to standing tree conditions such as consistent strong winds and snow. This condition is coupled by the presence of tension wood, where the opposite phenomenon occurs.

2.2.2.2 Degradation of Wood

FUNGI

In Canada, fungi is the number one cause of wood degradation (insects in other climates) [12]. Two categories of fungi organisms exist, one uses only the foods stored inside the wood such as sap and molds, while the other attacks the cellular make-up of the wood itself [12]. Some trees produce fungicidal chemicals which repel fungi, while other woods need only a spore to land on a moist surface to begin the wood's degradation [12]. Fungi slowly, yet surly eats away at the wood's biomass. For fungi to thrive, it needs moisture, therefore, wood should be kept dry especially when used in structural applications.

INSECTS

Pinholes, wormholes, powder post, and layering are some of the degradation phenomena caused by insects [12]. Essentially, the insects digest or burrow through the wood, leaving the wood riddled with holes and ultimately compromises the structural stability of the wood.

FIRE

Fire is an exothermic self-perpetuating chemical reaction that occurs between the wood and oxygen with enough applied energy. When the wood is heated, it undergoes a physical change where charring occurs at the surface and a gaseous form of carbohydrate is released. The gaseous carbohydrate then undergoes an exothermic reaction with atmospheric oxygen, releasing energy in the form of heat and light. The heat produced from the flame perpetuates the creation and release of gaseous carbohydrates. Complete combustion produces gaseous carbon dioxide and dihydrogen oxide (water). Incomplete combustion also produces carbon monoxide and other organics. Carbon monoxide is toxic and causes fatality.

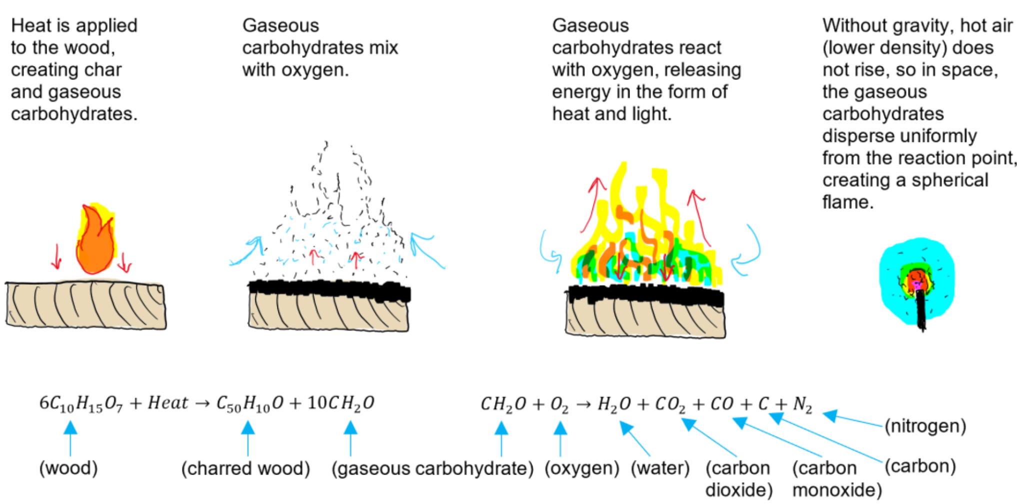


Figure 2-7: The physical and chemical reaction occurring when wood burns

As the wood burns, the chemical make-up on the surface changes leaving behind char (mostly carbon). The carbon in the char is void of the more volatile chemical compounds which have already burned off. Carbon/char still undergoes combustion but at a much slower rate. As the wood heats, the fibres contract. Eventually, the charring of the fibres causes enough stress on the fibres that small fissures occur across their grain, and so begins the classic quilted look of char. Over the duration of the wood burning, the temperature can propagate deeper into the wood, moving the char front deeper as well. The char has virtually no structural strength, but it does have some insulating qualities.

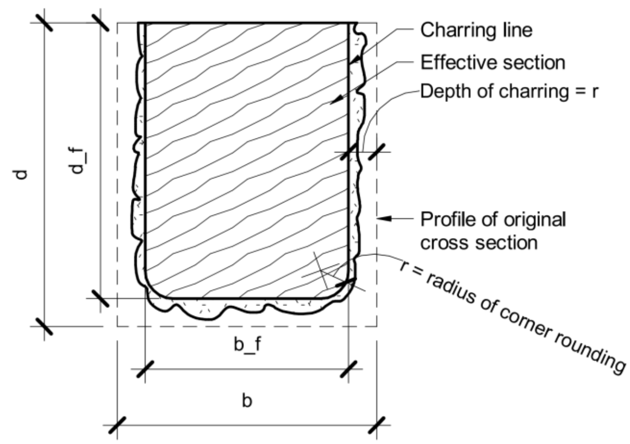


Figure 2-8: Corner rounding effect of burning timber (Adapted from [20])

When wood burns, a phenomenon called corner rounding occurs. The wood on the corners of an exposed timber are receiving heat from two sides, causing the wood to decompose more quickly. The radius of the corner rounding effect is taken as the depth of charring [20]. The effect of corner rounding causes a further reduction in the cross-sectional area that remains as wood.

2.2.2.3 Mechanical Properties

IDEAL STRENGTHS

The density of wood is a good indicator of its strength. Lighter woods will typically have larger tracheids with thin-walled cells which is not ideal for strength, whereas higher density woods indicate thicker walled cells. A well-established relationship between relative density and strength can be seen in the table below. These relationships can be used to estimate the strengths of wood whose values are not published.

Table 2-1: Functions relating mechanical properties to relative density of clear, straight-grained wood (adapted from [12])

	Relative density-strength relation	
	Green Wood	Air-dry wood (12% Moisture Content)
Static bending		
Fiber stress at proportional limit [MPa]	$70.3 \cdot G^{1.25}$	$115 \cdot G^{1.25}$
Modulus of elasticity [x10^9 MPa]	$16300 \cdot G$	$19300 \cdot G$
Modulus of rupture [MPa]	$121 \cdot G^{1.25}$	$177 \cdot G^{1.25}$
Work to maximum load [kJ/m^3]	$245 \cdot G^{1.75}$	$223 \cdot G^{1.25}$
Total work [kJ/m^3]	$710 \cdot G^{2}$	$501 \cdot G^{2}$
Impact bending		
Height of drop causing complete failure [mm]	$2900 \cdot G^{1.75}$	$2400 \cdot G^{1.75}$
Compression parallel to grain		

Fiber stress at proportional limit [MPa]	36.20·G	60.33·G
Modulus of elasticity [MPa]	20100·G	23300·G
Maximum crushing strength [MPa]	46.4·G	84.1·G
Compression perpendicular to grain		
Fiber stress at proportional limit [MPa]	20.7·$G^{2.25}$	31.9·$G^{2.25}$
Hardness		
End [N]	16600·$G^{2.25}$	21300·$G^{2.25}$
Side [N]	15200·$G^{2.25}$	16800·$G^{2.25}$

Where G represents relative density of oven-dry wood, based on the volume at the moisture condition indicated.

REDUCED STRENGTH

The strength of wood can be reduced by a number of factors such as the aforementioned defects in wood or the degradation of wood. The moisture can also have an effect on the strength. Once wood dried beyond its FSP, shrinkage occurs, followed by increased strength and stiffness, should no defects occur [12].

The slope of the grain in the cut lumber has an effect on strength as well. An adjustment factor can account for this and is calculated using an equation by Gurfinkel from 1973 [12].

Equation 2-1: Reduction factor accounting for slope of grain in cut lumber (adapted from [12])

$$slope\ of\ grain, \frac{1}{s} = \sqrt{\left(\frac{BC}{AC}\right)^2 + \left(\frac{CE}{AC}\right)^2} = \sqrt{\left(\frac{1}{x}\right)^2 + \left(\frac{1}{y}\right)^2}$$

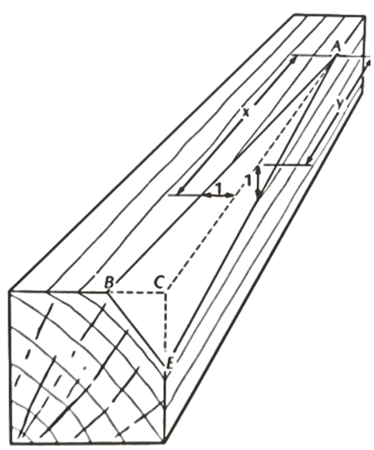


Figure 2-9: Reduction factor accounting for slope of grain in cut lumber [12]

There is consensus that the natural aging of wood does not have a clear relationship with any kind of strength reductions. However, long term loading and creep can negatively impact the strength of wood.

DESIGN STRENGTH

The design strengths seen in resources such as the *Canadian Wood Design Handbook*, CSA 086 are not the ideal strength or tested average strength of wood necessarily. Typically, the design strength for a wood species is 2.1 x the average calculated value to ensure that 95% of the time, the presumed (design) strength value will be the actual value of the member [12], [21] [22]. The mechanism in which testing, and calculations are carried out for determining design strengths such as extreme fibre in bending strength are detailed in the *Canadian Lumber Properties* handbook [22].

2.2.2.4 Thermal Properties

THERMAL EXPANSION

The radial and tangential thermal expansion coefficients for oven-dry wood are calculated as follows:

Equation 2-2: Thermal Expansion

$$\alpha_r = (32.4G + 9.9)10^{-6} per\ K$$

$$\alpha_t = (32.4G + 18.4)10^{-6} per\ K$$

Where G is the specific gravity. Typically, shrinkage due to loss/gain of moisture is more severe than thermal expansion.

MOISTURE CONTENT

The moisture content of the wood does influence the rate of spread but a study by Anderson and Rothermel found that there were no apparent effects on the energy release rate or the geometrical characteristics of the flame (flame length, depth, and angle) [23]. The results suggest that initially there may be a longer time to ignition, but once ignition occurs, the fire carries out almost the same as wood with a lower initial moisture content.

MASS LOSS

The mass loss rate is helpful for defining how a material is contributing to the fire. There are typically two stages in burning wood: the transient stage and steady-state burning. Research done by Emberly et al. found that the critical mass loss rate (steady state burning) was dependent on species but not density [24].

CHARRING

Char begins to take form when the wood reaches temperatures of around 300°C [25]. Currently, codes use linear char rates, which have been taken as the average char rate of wood exposed to a standard fire-resistance test [21]. However, the U.S. has accepted a non-linear char rate model developed by White and Nordheim as seen in equation below [26].

Equation 2-3: Non-linear White and Nordheim char rate

$$t = mx_c^{1.23}$$

Where t is the time (min), x_c is the char depth (mm), and m is the char rate coefficient (min/mm$^{1.23}$) calculated using the following equation:

Equation 2-4: Char rate coefficient

$$m = -0.147 + 0.000564\rho + 1.21\mu + 0.532f_c$$

Where ρ is the oven-dry density of wood (kg/m^3), μ is the moisture content (%), and f_c is the char contraction factor (dimensionless) and can be obtained from tests. The char contraction factor (f_c) is calculated by [21]:

Equation 2-5: Char contraction factor

$$f_c = \frac{thickness\ of\ residual\ char\ layer}{original\ thickness\ of\ wood\ layer\ that\ was\ charred\ (char\ depth)}$$

The char contraction factor, as well as linear char rates can be determined under constant heat flux. Using different test durations to burn the wood, the samples can then be cut in half and the char depth measured [27]. Char depth can be measured using a cone calorimeter that has the ability to expose a sample to a constant heat flux inhibiting one-dimensional heat transfer as an alternative to the standardized fire test.

Studies have shown that the age of the wood has an impact on the char rate as well, although this is not considered in current char rate models [28].

SPECIFIC HEAT

Specific heat is the amount of heat required to raise the temperature of 1g of wood by 1°C. It is not affected by species or relative density and can be calculated using:

Equation 2-6: Specific Heat

$$specific\ heat, c = 0.226 + 0.00116T$$

Where T is the temperature in degrees Celsius. Wood has a relatively high specific heat.

THERMAL CONDUCTIVITY

Thermal properties, however, are not typically listed by species, but rather calculated theoretically using numerical models based on the density and Moisture Content (MC) of the wood. One such thermal property is thermal conductivity. Wood in general has a very low thermal conductivity which, according to Environment Canada, is "approximately 5 times lower than that for building with brick, 14 times lower than that for concrete, and 370 times lower than that for steel" [12]. The theoretical thermal conductivity of a species can be calculated using Equation 2-7.

Equation 2-7: Thermal conductivity for wood with MC less than 40%

$$K = 0.2236G(1.39 + 0.028M) + 0.165$$

Where G is the basic relative density and M is the moisture content (%), gives thermal conductivity K ($W/(m^2 \cdot c.mm)$). For a moisture content above 40% however, a separate equation applies:

Equation 2-8: Thermal conductivity for with MC above 40%

$$K = 0.2236G(1.39 + 0.038M) + 0.165$$

THERMAL DIFFUSIVITY

Thermal diffusivity signifies the rate at which heat can be absorbed from its surrounds. It is the ratio of thermal conductivity to the product of density and heat capacity. The thermal diffusivity of wood is much lower than other materials which is why wood does not feel particularly cold or hot when touched. A typical value for wood is $0.161 \times 10^{-6} m^2/s$ [21].

2.2.2.5 Emerging Trends and Research Needs

Currently, linear char models do not capture the insulating effect of the char layer. The linear char model is not dynamic in a sense where, change in heat flux or time can influence it. Future research would do well to investigate a parameterized char rate model. Additionally, more investigations into the effects of aging on char rates for different species is needed.

2.3 BUILDING INFORMATION MODELLING (BIM)

There are many stakeholders involved in the life cycle of a building. All stakeholders have their own requirements for the functionality of a building. For example, an owner requires that the building be within a certain budget and easy to maintain and operate. Users require a certain amount of floor space and washrooms. Architects require certain materials and shapes to take form. Engineers require the beams and columns to be of a certain size. The list goes on. All these requirements comprise building information.

Building information needs to be captured, stored, and shareable. For instance, a structural engineer needs to reference the architectural requirements to infer the structural requirements. The data-structure of all the information regarding a building is called a Building Information Model. The process of creating, updating, and managing this is called Building Information Modelling (BIM). The British Standards Institute defines BIM by stating:

BIM is the management of information through the whole life cycle of a built asset, from initial design all the way through to construction, maintaining and finally de-commissioning, through the use of digital modelling. It's all about collaboration - between engineers, owners, architects and contractors in a three dimensional virtual construction environment (common data environment), and it shares information across these disciplines. [29]

Essentially, BIM is a process; a data-driven methodology for building asset management from a building's conception to design, to construction, to operation, and to end-of-life. It allows real time updates and collaboration among everyone involved in a project.

2.3.1 Principles

The principles below summarize those outlined by BuildingSMART International (BIM standardization institute) [30] and British Standards Institute [29] serve as the foundation of BIM.

2.3.1.1 Interoperability: People, Processes, and Technology

More fundamental to BIM than technology is the set of processes involved in the collaborative approach to information management. These processes (outlined in BIM standards) are enabled by technological advances. Accessibility to building information by stakeholders is paramount to efficiency, safety, and precision.

2.3.1.2 Collaborative Engagement

A key success indicator is the magnitude in which stakeholders are involved throughout the whole supply chain, including manufacturers, owners, project and construction managers, architects, and engineers. Openly sharing information with other disciplines to promote collective problem solving and coordination is vital. Data formats should be open and agile.

2.3.1.3 Start With the End in Mind

Decisions regarding building assets are often rushed and made using the wrong or incomplete information. To avoid rushed decisions requires the involvement of end users and contractors during early stages to ensure informed planning and so that design changes are not needed for constructability nor operational purposes. BIM allows multiple disciplines to view the building design goals more easily andallows changes to be made more efficiently. The further along a project, the harder it is to make adjustments and design changes.

2.3.1.4 Digital Asset

Information/data itself has value in the marketplace and this is why a complete BIM model is an asset. For the BIM model to be valuable, it must be well structured, organized, and complete. Building information requirements need to be established at the beginning of a project. What information is needed, when it is needed, who needs it, and why they need it must be clearly defined to ensure a successful and smooth process.

2.3.1.5 Security & Sustainability

A security-minded culture must be cultivated. Processes for creating, sharing, validating, and quality checking information must ensure trust through accuracy and safeguarding. The information must be stored in a way that it is accessible to future users in the long-term. The information must also be protected against users with malicious intent.

2.3.2 Benefits of BIM

While the full potential of BIM is yet to be understood, the benefits of BIM have been well established by means of case studies. The benefits listed below highlight why BIM is being used and adopted in the AEC industry.

2.3.2.1 Improved Efficiency

During a building's design and construction, BIM has been shown to improve the efficiency of the whole process by eliminating redundant tasks. For instance, when a design change is made using CAD, the user must go into every view and re-draw the changed aspect. In BIM however, the model just needs to be changed once and other views will automatically update.

2.3.2.2 Enhanced Collaboration

With multiple disciplines contributing to BIM, conflicts can be easily identified. Clash detection is a major benefit of using BIM. Typically, Mechanical, Electrical, and Plumbing (MEP), will each create their own designs and drawing sets based on the architectural plans. The architect will then compile these drawing sets for the final construction drawings. However, the traditional workflow does not allow the disciplines to view what the other disciplines are planning, which can result in overlapping systems that are not physically possible, like a conduit running through an exhaust vent.

2.3.2.3 Reduces Error and Rework

BIM allows users to easily identify the latest version of the model. This allows designers to ensure they have accurate information which reduces error and possible re-work later on in the project. Clash detection also reduces error and re-work.

2.3.3 BIM Models

For the BIM model to be useful, the data (building information) must capture the various elements that make up a building with varying detail. Some elements are physical in nature (a beam/column/wall) while others are logical (rooms). Some elements have relationships with other elements. For example, a window or door is hosted in a wall. Toilets are hosted in a wall/floor. Plumbing connects to plumbing fixtures. These relationships are often determined by rules within the BIM modelling tool (a window cannot be placed without a wall to host it). The quality, contents, and organization of the BIM model is critical to for use by stakeholders and their tools [31]. To ensure a complete and accurate BIM model, practitioners should follow standards and best practices.

2.3.3.1 Level of Development (LOD)

As a building's design develops, the details of the building's components become clearer. At the beginning stages, conceptual masses and layouts are used. As the project progresses, materials and assemblies may be decided. Later, material manufacturers are decided, and materials purchased. Each building element can undergo similar levels of development. The LOD allows for production of material lists, shop drawings, product data lists, and more. Different elements may develop at different rates, meaning that a BIM model is likely to have varying LODs within the project. While the USA gives a vague description of what each LOD entails, the UK provides a more detailed specification for LOD requirements, which is being progressively adopted globally and reflected in International Standards (ISO 19650) [31].

2.3.3.2 Model Organization

How the BIM model is organized is arguably the most important consideration. Model organization should follow a standardized format. The data-structure itself should follow a standardized format to allow for interoperability. A common data environment (CDE) is where a BIM model should be defined. A CDE allows for one space where all collaborators' models and information are stored. For legal and security reasons, different stakeholders do not have the ability to modify other stakeholder models. For example, and architect cannot change the structural engineer's model. The CDE must be structured in a standardized way for the information to be useful to current and future users. The standardized data structure used for BIM is called Industry Foundation Classes (IFC). The IFC standard specifies how model elements are defined and interact.

2.3.4 BIM Uses

2.3.4.1 Project Considerations

How a BIM model is organized is often determined by the project delivery approach. Contractual obligations and liabilities hold different parties responsible, and these are reflected in BIM. A project delivery method that is gaining popularity in Canada and compliments BIM is Integrated Project Delivery (IPD). An IPD is structured to reward cooperation between design and construction teams, reducing communication related issues that result in wasted time and resources. The approach involves a lot of up-front documentation that benefits from building information management and BIM. In the figure below, the MacLeamy Curve illustrates how an IPD/BIM workflow capitalizes on the ability to impact cost and performance over time versus the cost.

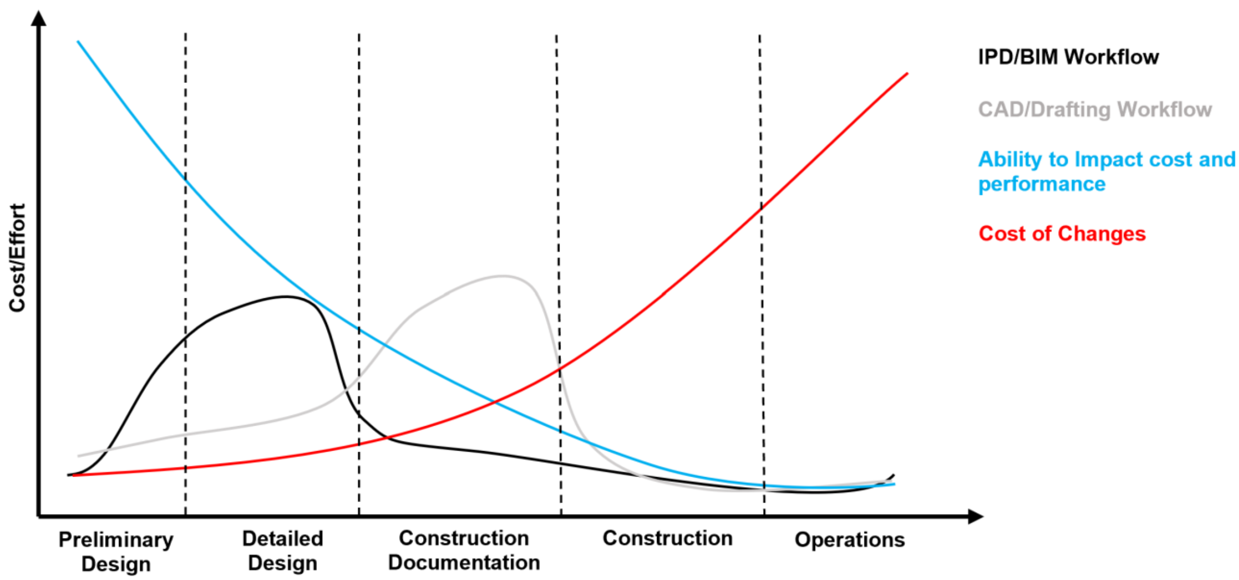


Figure 2-10: MacLeamy Curve (adapted from [31])

2.3.4.2 Stakeholder-specific Uses

Owners and operators of buildings can use BIM to visualize and review design options in a cost-effective manner during the design phase. The fully developed BIM provides useful as-built information regarding the building asset and can even be modified to serve as a digital twin that can provide live analytics on building use and performance.

Designers use BIM for phase planning (ie. 4D modelling), design authoring (tracking changes), reviewing, cost estimation (with automated material lists), programming where algorithms are used for parametric design and generating design options based on the requirements, and for engineering analysis (eg. energy analysis).

Constructors use BIM for 4D coordination and scheduling, site utilization planning, digital fabrication, record modelling (as builts), and handover. Suppliers and manufacturers are also using BIM to create smart BIM objects that involve a high LOD and contain analysis information for designers and owner/operators.

2.3.5 Current Limitations and Research Needs

Some of the greatest challenges facing the uptake, use, and success of BIM is the lack of standardization. Many software have not adopted IFC. Additionally, many projects do not fully develop their BIM models or use standardized information management processes. The different uses of data structures (not using IFC file formatting or standardized information management) make interoperability extremely difficult and reduces the probability that the model will remain useful to future users.

Another challenge is the lack of BIM education. Many people think of BIM as 3D modelling when in fact, it is more about information management throughout the building life cycle. Industry use of the technology is growing faster than education systems and firms are producing BIM knowledgeable practitioners. With a lack of BIM-savvy practitioners, the accuracy, completeness, and usefulness of BIM is undermined.

2.3.5.1 Ethical Considerations

The use of BIM is part of a larger fourth industrial revolution (digitization) within the construction industry. The first industrial revolution caused large populations to dislocate, communities and neighbourhoods were destroyed, and the environment was negatively impacted [32]. Some of the most profound ethical considerations regarding digitization and automation enabled by BIM are job security and data privacy [32]. Additionally, there exists ethical biases built into technology such as BIM that are extremely difficult to identify and quantify [33]. When the NYC fire department first started using models to determine where fire companies should be located, criterion influenced by economics and political pressures had the negative influence of removing companies from ghetto neighbourhoods experiencing higher frequencies of fires [34]. With growing automation, labourers are particularly impacted by new technology progressively replacing jobs. While automation can eliminate danger for workers, it can also eliminate the need for some workers. Since generally, those who work in laborious jobs typically do not perform well in school, replacing those who are more inclined to perform the laborious, sometimes dangerous jobs, has its own ethical considerations since re-education for another job is more difficult for the demographic being replaced [32]. The use of BIM and digital twins is already demanding different cognitive involvement than before, which could influence the demographic of hires in the future. The impacts on the wider economic and sociopolitical outcomes are not well understood and requires further investigation [32].

The advancing 4th industrial revolution also increases the risk and harm of cyber attacks. As buildings become smarter and more integrated with digitization, creating an industrial cyber-physical system (ICPS), cyber security and data privacy become paramount [35]. Many building components such as HVAC systems and door locks can be connected to the Internet of Things (IoT) that allows remote users to monitor and perform tasks. One form of cyber attack is to block the transmitting communications and prevent the object from performing the task (ie. circulating air) or manipulate the objects (ie. unlocking doors). With regards to the BIM model during the design phase, practitioners need autonomous security to the digital reflection (model) of their work since they are liable for their work. Certain restrictions on certain users can improve the security-liability-responsibility aspect. For example, only a structural engineer can change the size and specification of a beam.

2.3.5.2 Future Research

Socio-economic impacts need to be studied further and the biases within BIM technology need to be identified. Within BIM, research regarding approaches to cyber-security and record keeping needs further development. Risk analysis on the impacts of cyber threats and compromised information models also require further research. Lastly, research regarding methodologies for training practitioners and students on BIM need further development.

There are many additional areas for research regarding BIM since it is a developing technology utilizing digitization of the built world. As AI and construction innovations advance, the applications, uses, and processes of how building information is managed will develop as well.

CHAPTER 3

BIM and Fire Safety Engineering – Overview of State of the Art

We could do things as we've always done them in the past or we could look to the future.

-Christoph Leitgeb

3.1 INTRODUCTION

Fire safety engineering (FSE) is one of the most critical specializations to include in the design of a tall building yet is often excluded from the Building Information Model (BIM) and integrated design process. Fire safety systems are interdependent on building and structural geometry, HVAC, mechanical, and electrical systems. The high degree of system interactions requires the professions to collaborate early on for building optimization to be possible. To save time and ensure accuracy, the fire safety engineer and practitioner need to know about design changes from other disciplines as they happen. BIM is an opportunity to streamline multi-disciplinary collaboration, but it is not being used for fire safety in industry.

The fire design process can range from a prescriptive approach to performance based. The prescriptive approach can be prone to errors but is often a less laborious, faster design. Performance-based design allows opportunity for new and more economical solutions to be utilized. The simulations and analysis involved however, are a time consuming and laborious process [36]. Fire safety does not stop at design. It is important for the building's entire life cycle that safety is maintained. The construction phase, monitoring of fire safety equipment, and emergency evacuation management should all be considered.

Building Information Modelling (BIM) can be utilized to manage the fire safety of a building during all phases. Projects that use BIM increase in efficiency while reducing conflicts, error, and miscommunication [10]. BIM is a way to organize all data associated with a building, including geometrical data visualized with 3D representations. BIM is not a software or a data set meant just for design. Algorithms can analyze and process the data to provide design options, check codes and regulations, create material lists, etc. A fully developed BIM would contain all the information from various disciplines for a fire safety engineer. The compatibility between BIM and fire safety design seems obvious yet has struggled to advance in structural (fire) engineering compared to other specialties. This is owing to several factors, the most prominent being the reliance on other disciplines for the data inputs that FSE needs, whereas other disciplines have their own domain specific sub-model [37]. Additional misunderstandings of BIM have resulted in limited views on its application and capabilities [38]. A lack of knowledge has resulted in BIM's adoption in fire engineering being slow as benefits and lessons learned are not realized or shared by practitioners.

Once the FSE sector embraces BIM, FSE may be included in a project's integrated generative design process. Inclusion in this process would allow buildings to be optimized to include fire safety effects from the beginning of the design process. Generative design that includes FSE would allow for new alternative solutions to be generated based on logical rules and design objectives [39]. Other AEC sectors have been taking advantage of this BIM tool and although the inclusion of FSE would likely have significant effects on overall life safety in a building, it has been lagging in technological advancements and industry understanding [39].

The purpose of this chapter is to provide an holistic overview of contemporary advancements and technologies related to using BIM for FSE. A summary and comprehensive analysis of existing published research and projects where BIM is used with FSE is provided. The analysis identifies to the reader what frameworks are used for various BIM integration purposes. The frequency of specific software use is also highlighted, providing the reader with an overview of what has been working and identifying research trends. A road map indicating when certain BIM and fire integration methods are most appropriate during the life cycle of a tall building is provided. This chapter will provide, for the first time, a foundation of knowledge and direction to proceed with planning how to integrate fire safety design into a dynamic BIM.

3.2 LITERATURE REVIEW

The literature review began by indexing articles and papers on how BIM technology has been used for fire safety engineering. Since technology changes rapidly, priority was given to more recent literature (as of 2021) to detail state-of-the art methodologies for integrating fire safety and BIM. From 2019-2023, a surge of literature was published regarding the subject, indicating that industry has identified the gap and is working to resolve it. This literary review, therefore, builds upon the author's previous efforts to undertake such a gap analysis. All the literature was retrieved from online search databases such as Google Scholar and Omni. Boolean search methods such as "BIM", "Building Information Modelling", "Fire", "FSE", "engineering" were all used in varying combinations. Journal papers, conference papers, and trade magazines were all considered. After a paper was identified, a preliminary screening (checking abstract and conclusions) was done to ensure that the document specifically related to utilizing BIM for FSE. During review, software, sponsors, BIM uses, and BIM applications were manually catalogued. Once the literature was reviewed, it became evident that BIM technology was being used for a variety of fire safety purposes, spanning from a building's conception to a fire event. The various applications of BIM and fire safety that emerged from the study make up the subsections below. They have been organized in sequential order of their application from conception to fire emergency management, indicating where the technology has been appropriately applied. To identify research trends and areas where research might have the greatest future impact, the details of technology used such as software, file formats, programming languages, etc. were examined. The subsections below identify, describe, and discuss the latest technological advances in digitizing the field of Fire Safety Engineering.

3.2.1 BIM & FSE Data Management

One of the greatest challenges facing the use of BIM today, is the data-structure and schema itself. Particularly regarding the establishment of a "golden thread of information" for FSE. The "Building a Better Future" regulatory review report that resulted from the Grenfell Tower fire (72 casualties) refers to the vital "golden thread of information" as a digital record throughout a building's lifecycle tracking everything from design intent to construction, operations, and any changes along the way [40]. By having a record of design decisions and changes made to a building overtime, and those responsible for the changes, non-conforming unsafe decisions can be more easily identified and prevented, and responsible parties held accountable. The idea is that the building information can be transferred to new owners of the building and be accessible throughout a building's entire lifecycle. For this to happen, the data schema must remain accessible for the next 50 years, requiring long term data storage and a data structure that is non-proprietary (open) and standardized.

Currently, there are many different digital data structures and file formats. The leading international and open (free) standardized data structure for BIM is Industry Foundation Classes (IFC) developed by buildingSMART, an international non-for-profit organization. IFC files and buildingSMART schema are all open, free, and well documented. Open-source means that the data structure is transparent and open for the public to see, use, and collaboratively participate in its development. This is an important feature for establishing a golden thread of information. Industry Foundation Classes (IFC) are the best available and most widely utilized standardized way to categorize digital elements and enable automated data transfer, which is essential for the data stored within the object to be useful [41]. Researchers have mainly applied COBie and IFC open standards to their BIM models [42]. A common misconception is that these are two different standards but in fact, COBie is actually a Model View Definition (MVD) data specification for the IFC model standard [43]. IFC models, however, can be misused and improperly classified, but Wu and Zhang have created an algorithm to fix this problem [44]. Currently, IFC standardization specific to fire performance parameters is yet to be developed and currently under research [45] [46]. For the time being, practitioners have been manually adding required parameters using formats specific to the software being used or creating an IFCExtension. Using an internationally accepted standard data-structure solution is also beneficial because it allows for various software to be fully compatible with exchanging one file type as opposed to having to translate its own data structure to numerous other data structures for interoperability between software[1]. Even in other disciplines where software fully and accurately sends IFC files, most software only supports one-way exchange for sharing data (Figure 3-1 A). Ideally, there is one BIM from which sub-models pull data and sync to (Figure 3-1 B). In this way, the main model in Figure 3-1 B can be the digital fingerprint for the building design and can be the final model delivered to the owner without a requirement for proprietary software.

[1] Software that is compatible with IFC data exchange is listed on buildingSMART International's website under 'IFC certified software'

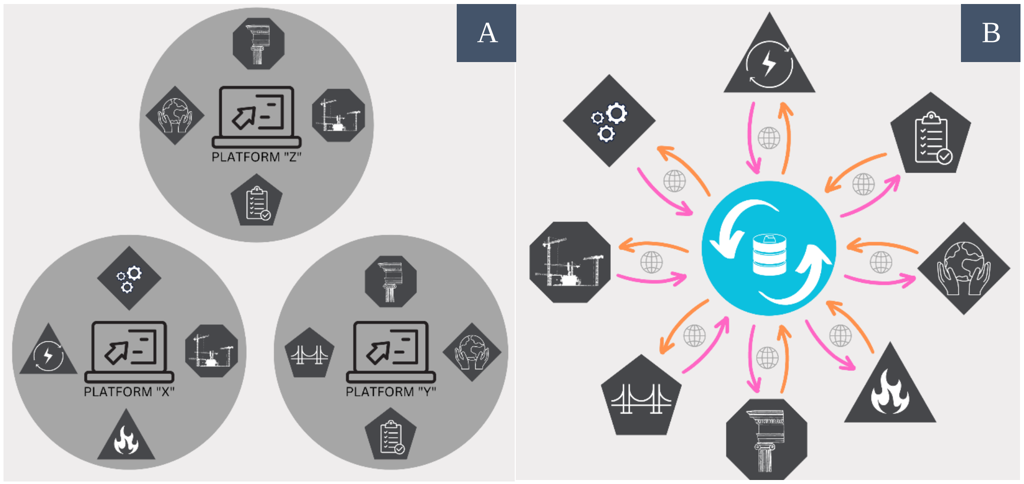


Figure 3-1: BIM management networks

Understanding that BIM is an ecosystem of data for a given construction project is necessary to reap its full benefits. Once the BIM framework and data management plan has been decided upon (the first step for a project utilizing BIM), data analytics can start to be employed. There is a multitude of literature on BIM frameworks, data management plans, and contractual obligations, but is considered out of scope for this thesis. In many industries, analysis of large bodies of data has been explored as a way to give companies a competitive edge. It is often used as a tool for pointing companies, designers, developers, etc. in the right direction by providing statistical insights based on pre-existing data. The data-driven statistical approach is the foundation of Machine Learning (ML) and modern Artificial Intelligence (AI). Material reduction factors used in Limit State Design approaches is also based on data-driven statistical insights. The example demonstrates that data-driven statistical insights are an acceptable approach to engineering yet, even with advancements in informatics, structural and fire engineering lack data sets. In a 2021 analysis by Naser et al., six public databases were examined, three were structural tests and three were fire tests [47]. The fire engineering databases had over 91% less data points to infer from than structural engineering databases had. Naser et al. used statistical calculations as performance metrics to compare the dataset with the ML output and found that all the selected ML algorithms tested were able to properly capture structural and fire engineering phenomena [47]. The fire department in New York City uses a data-analytics application to routinely sort information from five different databases and calculate the fire risk of all buildings under their inspection, leaving the department with a list of prioritizations [48]. In FSE, data-driven ML can be extremely useful considering that many of the current equations used to predict fire dynamic outcomes are idealized to start with. Meaning, a numerical approach could not only provide insight to current theoretical understanding of fire, but it could also prove to be more accurate than some current idealized analytical approaches. A data-driven approach however requires thousands of datapoints which in the case of mass timber compartments, simply does not currently exist, or is proprietary. Like any developing model, some common mistakes made by modellers include flawed assumption, faulty data, and information gaps or cultural divides between the modelers and what is being modeled [34]. In the case of the NYC Fire Department, first attempts at fire modelling caused ghetto neighbourhoods to lose companies (despite high frequency of fires) based on recommendations built on irrational criterion [34].

The need for open databases is evident. At the time of writing, National Institute of Standards and Technology (NIST) has an open "Fire Calorimetry Database (FCD)" containing 238 experiments [49]. The "RISE Fire Database" contains the data from many research projects regarding material testing [50]. With more open-source databases and more transparency, better data informed decisions can be used to drive design. The concept of exploiting Big Data for engineering design is still under development and is lacking in literature [51]. With the datasphere expected to, over the next five years, "be greater than twice the amount of data created since the advent of digital storage" [52], it is fair to assume that data analytics will become a major part of every industry. In AEC, the management of data occurs through BIM, despite underdeveloped construction databases currently from other industries.

It is clear that BIM is a data-rich environment, but it is impractical for disciplines to access the entire multitudes of data in the model. For this reason, a filter needs to be applied to the BIM before exchanging data to another software. This is often referred to as a Model View Definition (MVD). In addition to the lack of development in FSE requirement data structures, there lacks industry specific MVDs for FSE [53]. For FSE, data regarding architectural features, fire protection systems, structural components, building processes and services, operational characteristics (occupancy), fire department response, and even environmental factors are all relevant for a performance-based fire safety design [54].

3.2.2 Fire Smart BIM Objects

Smart BIM components are objects located within the BIM such as doors, windows, fire alarms, fire detectors, etc. and contain additional information on the component's performance. For example, a beam could contain a property parameter such as maximum span, which allows designers to easily choose member sizes [55]. Similarly, a smart BIM component can contain parameters regarding Fire Safety including performance requirements and material properties such as the identification of fire separation walls that can automatically restrict wall penetrations [56] [57]. Embedded parameter needs are still being assessed and identified as research progresses. Most software have a unique way of describing BIM objects and their parameters [58]. For the object to be compatible across the various available BIM platforms, it should be described and classified in a standard format [44]. Since a standard IFC data structure and MVD does not currently exist for FSE, practitioners need to make their own extensions. Kong et al. demonstrated an IFC extension for mapping relationships between objects which is needed to understand how fire alarms, fire doors, and lighting interact with one another during a fire emergency should BIM be used for operations [59]. A demonstration can be seen in Figure 3-2 where a timber column object has been updated to contain the effect of a reduced cross-sectional area after a one-hour fire by utilizing an arbitrary charring rate of 0.88 mm/min.

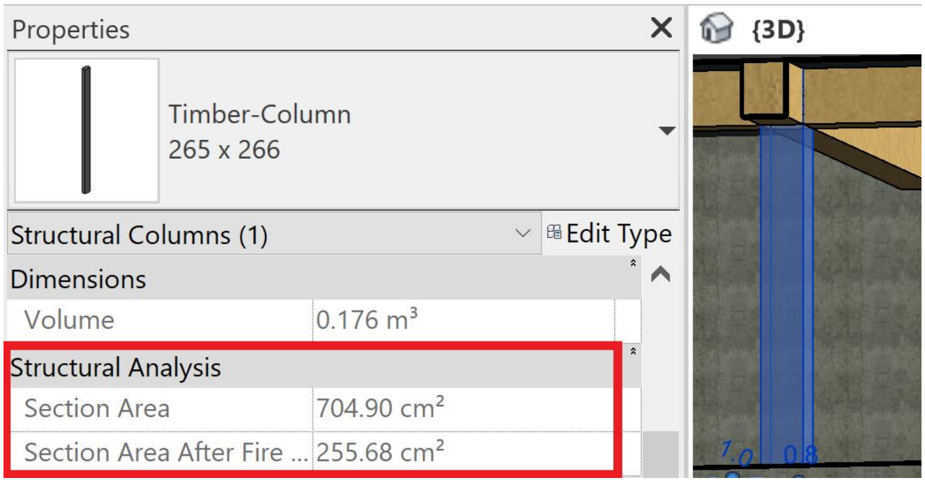


Figure 3-2: Timber column BIM object embedded with fire research data (author's analysis)

A BIM object can be developed to various Levels of Detail/Development (LOD). The LOD for the preliminary design phase includes geometry, location, quantity, and type information. The LOD for the detailed design phase also includes materials, performance requirements, fire resistance, and functional specifications. In the construction management phase, the LOD also includes, but is not limited to, manufacturing and installation data, technical data sheets, operating and maintenance manuals, and certificates of compliance [60]. Objects within a BIM are meant to be updated or replaced as the design progresses, allowing a digital twin of the building to exist throughout its lifecycle.

Developing the smart objects from scratch is a time-consuming process that has urged manufacturers to develop BIM-compliant objects containing information on their fire protection products [60]. Currently, online BIM libraries exist containing smart windows and doors that include energy performance data. Adding smart BIM objects to online libraries is consistently under development and remains a recommended area of further advancement [61]. Since 2019, however, there has been little additional literature published on Fire Smart BIM objects and this is likely due to the lack in IFC data structures and a FSE MVD. Without a standardized format, the data stored within the object cannot be universally shared. Therefore, it is not useful for manufacturers to develop fire smart BIM objects until a standardized digital format is established.

An additional issue resulting from lack of IFC data structures for FireSmart BIM objects is the inability to map object relationship within BIM. Kong et al. created an IFC-Extension for mapping interactions between objects affecting fire safety such as fire alarms, fire doors, lights, etc.

3.2.3 Automated Code and Model-Checking

Researchers, practitioners, and software developers have successfully been able to automatically check BIMs for code compliance. Automated code-checking is being used in many fields due to its increased time efficiency, taking as much as 80% less time than manual methods [62] [63] [64]. Automated code-checking, however, requires a multitude of specific data not always included in the BIM, which increase the need for higher LOD BIM objects [65] [64]. Consequently, few tools are available that extract fire safety data from BIM objects and assess the model for code-compliance.

Most code-checking applications utilize the Application Programming Interface (API) included in BIM platforms to extract and manipulate element properties. The common API for Revit is the visual programming tool Dynamo, and for Rhino, Grasshopper is often used [66]. APIs have allowed the success of many case studies that perform design calculations according to code, identify non-compliant elements, and provide visual feedback [67] [68]. Now there are a number of open-source algorithms that engineers and architects can use to improve the BIM and most of them are written in Python, which is compatible with most BIM platforms [69]. However, users would need to access this information and integrate it into their BIM platform.

In 2018, the state-of-the-art fire code-checking applications were still only able to utilize BIM's geometry with the exception of an object's Fire Resistance Rating (FRR) specification [68]. Earlier research done on developing and testing code-checking applications, identified a need for quality assurance processes [70]. Ren and Zhang address quality assurance in their 2019 and 2021 evacuation code-checking research by developing an algorithm to check that the IFC format of the BIM contains the necessary parameters [71] [63]. Ismail et al. suggest that automated code checking is better to be done in the native file format (such as Revit) to allow for better usability [72]. Many authors who developed and applied code-checking applications within a BIM, consensually recommend future development in increasing LOD BIM fire objects, functionality/performance of code-checking, translation of regulations to computer language, and focus on quality assurance processes. Currently, many international, federal, and regional building code agencies are in the process of translating written code to rule-based formats which can be easily programmed.

3.2.4 Structural Fire Dynamic Integration (Internal and External)

Numerical and algebraic fire calculations can be performed within a BIM platform. Smith and Gales suggested integrating fire as a load case in BIM [56]. The concept of 'fire load' indicates the quantity of heat liberated per unit area when a building and its contents are completely burnt [60]. Amaro et al. developed fire load calculations directly into the BIM model by introducing the characteristics of materials (e.g. weight and specific fire load) and by setting the algorithm in the materials schedule [60]. Later, calculating time-temperature curves for various compartments was also programmed into the BIM although this can require more material property extraction. The calculations will be incorrect if the parameter and boundary conditions are incorrect, exemplifying the need for quality assurance processes. It is also important to consider that calculation methods for fire loads and time-temperature curves may differ across jurisdictions. Even though the calculation process can be automated, it is still essential that experienced professionals are involved.

More complex and dynamic fire calculations require an external platform for simulation. There are over 160 different modelling tools for smoke and fire simulations [73]. The most common fire/smoke simulation tool is Fire Dynamics Simulator (FDS) by NIST, which is an open-source Computational Fluid Dynamics (CFD) based program that has been validated and accepted in industry. Automated direct data transfer of fire parameters beyond geometry for performance-based fire design simulations is difficult and rarely achieved [74]. As a result, engineering models are created from scratch instead [63]. Although automated synchronization between models has been known to save time, an analysis by Vilutiene et al. (2019) of 369 papers on BIM and Structural Engineering indicate that most research has been focused on conception with little application of BIM capabilities [75]. The redundant efforts are a consequence of the fire and smoke simulators incompatibility with standardized BIM formats such as IFC. The issue is being partially addressed with BuilingSMART's IFC4 Software Certification recognizing software which successfully uses IFC data structures [46]. Although fire simulation software developers have expressed BIM compatibility in recent releases, according to the BuildingSMART database, none have any kind of IFC certification. BuildingSMART International currently has an active committee working on a MVD for FSE. Involved researchers Siddiqui et al. have been working on this data specification that would allow full support for fire safety simulation input and output data. Currently, only geometry import is accepted by some FSE tools and there is no framework for simulation results to be exported back into the BIM [53].

Even the most recent and resourceful applications of geometry transfer require multiple steps and third-party software to properly mesh the surfaces. An example of this is the workflow used to transfer the geometry of Canada's parliament building to a Virtual Reality (VR) platform that took eight steps and at least two third-party software [76]. Successful direct-integration on the other hand, tends to be due to the effectiveness of the algorithm developed to automatically reassign IFC-data file names. The research that attempts translating data to IFC varies dramatically in methodology and concludes with much room for improvement. The work of Shi et al. successfully automated data transfer from Revit to PyroSim (an FDS interface) and back into Revit [77]. However, structural analysis is still missing from the framework. Other works have included Agent Based Modelling (ABM) within the framework to combine both fire and evacuation simulations as well as floorplan layout optimization [78] [79]. These frameworks struggle with integrating the results back into the BIM and still involve numerous steps which could be further simplified. Many of the fire modelling research efforts tend to be redundant due to a lack of communication and collaboration [73].

3.2.5 Emergency Evacuation Integration (internal and external)

During an emergency, the most critical concern is for building occupants to evacuate safely. In a real fire scenario, the chances for safe evacuation reduce significantly with time. Evacuation simulations can calculate and predict occupant behaviour during an event and evaluate the resulting risks for building design improvements. The required safe evacuation time (RSET) is a common tool for determining the life safety of occupants in a building on fire. The evacuation time can be calculated and addressed using prescriptive methods or performance-based methods. Prescriptive rule-based methods can be easily integrated with BIM by using code-checking and BIM platform API's for programming route calculations [80].

Integrating performance-based evacuation with BIM has been more successful and frequent than fire dynamics. Unlike fire dynamic simulations, evacuation simulations only need the geometry of the building and not necessarily any other parameters, simplifying the complete integration requirements. Visual programming APIs are frequently used to manually build algorithms that extract and convert geometry into readable formats and program results back into the BIM [62]. Once the geometry data is extracted, it is often then used as boundary conditions for an Agent Based Model (ABM). The resulting simulations can detect blocked egress routes, safest egress route, shortest route, and identify most critical design fire initiation locations [81]. The complexity of evacuation simulations is principally due to the complex nature of human behaviour. How humans respond within a building can change according to geometry, number of exits, size of pathways and exits, signage, previous building layout knowledge, etc. [82]. Due to computational costs, evacuation models often exclude simultaneous dynamic fire and smoke simulations. The shortest path is not necessarily the safest or best performing path, creating a need for hybrid models that are used to thwart this trade-off, providing a more feasible solution [83] [84].

Because human nature is difficult to define and predict, gamified BIM (see 3.2.9 Extended Reality and Fire Safety) has been used to extract human behavioural data in an attempt to improve the behavioral prediction accuracy. In future research, additional data that could be obtained from the BIM and used during evacuation simulations is the effect of communication information (fire alarms, lighting, etc.) and occupant information (demographics and use habits).

3.2.6 BIM and Construction Fire Safety Design

Around 6,400 structural fires (four deaths) occur in the U.S.A. during the construction phase per year, as this is when designers tend to overlook fire safety management [85] [66]. Fire extinguishers tend to be the only fire safety mechanism in place on a construction site [66]. A tool developed by Khan et al. aims to solve this by extracting site rules from the BIM and code, identify fire fighting equipment for installation, bill of quantity for fire fighting equipment, and an escape route plan using the Dulaney triangulation pathfinding algorithm within Revit's API [66]. The escape route plan and fire scenarios are simulated. Escape routes during construction can be evaluated at different phases by considering a BIM that is at least 4D [86]. Two 2022 studies by Sun et al. integrate FDS with BIM to incrementally assess the fire risk at different stages of construction (one considers CLT structures) [87] [88]. They propose to use FSE-BIM integration to educate construction workers at beginning stages to look out for fire risks. The author only found four papers related to this subject. In the future, BIM could utilize safety indexes of site instructions used by construction management to identify and mitigate fire risks before construction begins. Perhaps machine learning could correlate construction methods with fire risk and the BIM AI could suggest alternative designs. Construction is now starting to provide an as-built virtual reality that could also be analyzed for fire risk such as identifying combustible materials close to a heat source.

3.2.7 BIM and Fire Safety Operations

The benefits of a matured digital twin BIM include better property and infrastructure management, as well as fire safety. A digital twin is a virtual replica of what is built. It is a dynamic BIM which processes live data and gives feedback to the building. So far, there have only been preliminary studies of digital twin's application to fire safety [42]. These studies include automatic processing and monitoring of danger and fires and assessing the number and location of people within a building by evaluating sensory data [89] [90]. A building manager can virtually identify temperature, light, smoke, and CO^2 levels in each room. Should any levels breach a specified limit, cameras can be used to identify the severity of the situation [90].

The operation management platform can notify personnel when a fire extinguisher needs to be inspected or manage scheduling of fire drills. Researchers have been able to create apps which can link equipment on site to the BIM using RFID and/or UUID identification tags (ex. bar codes). The Augmented Reality (AR) displays necessary inspection forms and updates the data. The AR allows for virtual information management of FSE inspections regarding fire extinguishing equipment and systems, alarm equipment, refuge escape equipment, fire rescue equipment and protective equipment [42]. For BIM-FSE AR to be possible, the LOD of smart BIM objects should be extremely advanced during the operation phase of a building's lifecycle. The digital twin should include access to maintenance and operation manuals and certifications for various building components. Digital twin concepts have been applied to Mechanical, Electrical, and Plumbing (MEP) in the past, whereas digital fire safety systems such as fire detection, sprinkler systems, and alarm systems are currently under development. To maintain BIM quality, the digital twin should limit visibility to certain users and only include information needed to run the infrastructure management platform smoothly [60].

Sensory data and communication devices can update the BIM or be updated by the BIM by utilizing Internet of Things (IoT) technology [91]. IoT allows individual control over building components. IoT can also allow for simultaneous data updates, allowing simulations to be run in real time. This provides opportunity for identifying potentially life-threatening maintenance jobs such as repairing sprinklers should water reserves be too low.

3.2.8 BIM and Fire Rescue

When a fire occurs in a building, BIM can be used to enhance the fire fighting, evacuation, and rescue efforts. Accurate decision making is important for evacuees to choose the safest path to exit and for fire fighters to rescue people as quickly and safely as possible. Decision making is susceptible to human error and can have negative impacts on evacuation and rescue times. Evacuees can be exposed to dangerous carbon dioxide levels, especially near the end of an evacuation [92]. To improve the evacuation conditions, the fire must be identified early on, occupants and fire departments notified quickly, safe evacuation must be aided, and trapped or stay-in-place occupants must be located. The pre-evacuation time can be improved by quickly identifying the fire and disseminating detailed information to the occupants early on. The evacuation time can be improved by providing detailed instructions for wayfinding. Search and rescue efforts can be improved by providing occupant locations to the rescue team. Another consideration is the safety of the fire fighters. It is important to know the progression and whereabouts of dangerous levels of temperature, toxic gases, CO^2, and smoke. Fortunately, there are a few ways BIM can help with these.

BIMs provide a central intelligence system that when used dynamically, are constantly being updated with sensory input and updating communication devices within the building with fire safety information. A dynamic central intelligence system can command an optimized evacuation. To aid the evacuation, communication devices such as speakers, alarms, lighting, ADSS (changeable exit signs) and mobile devices can routinely be updated with fire safety information during an event [92]. When occupants are given clear instructions to the safest path, they behave more rationally, more efficiently, and are more stable

[90]. An application of this is when ADSS is automatically updated with directions which prevent people from heading towards danger or opening doors that compromise fire compartments. A system developed by Ma and Wu sends an SMS to the occupants notifying them of a fire and having them indicate their choice to evacuate, stay put, or fight the fire [90]. An app is updated with fire locations, fire safety equipment, the safest egress path, and location status. All this information is retrieved from the BIM and can be continuously updated. Information on occupant and fire/smoke conditions can be retrieved from the building to update the emergency status. Simultaneous data updates allow simulations to be run in real time to inform fire rescue teams about visibility, CO^2, and flame spread [91]. Simultaneous simulations allows fire rescue to visualize fire spread and occupant locations within a 3D model of the building. In 2022, researchers Wang et al. came up with four algorithms which when used the building fire ontology, could not only suggest the best route for fire fighters to get aged persons in a long-term care facility, but also what tools they will need (ie. if a window should be broken) [93]. There have been few studies, however, on how real fires might affect Wi-Fi and internet capabilities, which allow the real-time data updates to be possible. Therefore, dependency on such systems would require further research.

The safest path needs to be calculated quickly while an emergency is occurring, making numerical solutions more effective for unpredicted scenarios than evacuation simulations [92]. Research in this area has shown a preference for Dijkstra's algorithm [92] [90] [94]. Dijkstra's algorithm can use geometry and occupant locations extracted from the BIM, which can be done automatically when an emergency is declared. The calculations can be re-iterated as the model is updated with more current sensory data. The downside of this is that complicated factors such as crowd density cannot be fully considered during an event but should have been previously considered in the design phase. An alternative is to have different fire scenarios simulating while the building is functioning and when an event occurs, it is matched to the best-fit simulation [95].

3.2.9 Extended Reality and Fire Safety

Extended Reality (XR) refers to virtual reality (VR), augmented reality (AR), and mixed reality (MR). VR generates a realistic environment with visuals and sounds and a representation of a user's presence in the environment. AR is where artificial information can be accessed in reality. An example of this is when a building manager scans equipment and then gains access to information about it via mobile device. MR attempts to combine VR and AR by making the digital content interactive with reality; a very new type of XR with no defined parameters and little existing applications [96].

Gamified BIM is an emerging field in which BIMs are imported into a gaming engine to simulate a virtual reality [97]. Gaming engines have been developed to be superior at simulating virtual realities with less computational cost and more realistic graphics [98]. In more recent years, the AEC industry has adopted gaming engines for creating virtual realities that help visualize the interior spaces, construction, evacuation scenarios, fire simulations, and building management [97]. Recently gamified BIM is being utilized as the building's platform for maintenance and operations as a way to simplify the database, making it practical for everyday use and easy training [99]. For BIM fire technologies to work, they must be intuitive to use.

One of the earliest applications of Gamified BIM for fire safety was by Ruppel and Shatz's serious game that realistically simulates structural fire scenarios and extracts data to assess human behaviour of users [98]. The game environment includes fire, smoke, explosions, and structural damage defined by FDS boundary conditions. There are numerous other serious games taking similar approaches that currently provide reliable results and realistic visualization effects [82]. Lu et al. develop a serious game for training fire fighters where BIM founded geometry, a structural model, and an FDS model were combined in a game engine [100]. Deng et al. created an Augmented Reality (AR) that guides fire fighters through smoke and the building's layout towards the fire location [84]. Some researchers argue that VR should not be used in practice to simulate evacuations due to lack of validation [83]. The reason pedestrian modelling is difficult to validate is due to the numerous ethical delemas associated with such data collection, particularily when it comes to impairment and simulating a dangerous situation. As the technology progresses, other researchers have been able to show that if participants have previous gaming experience and are aware of the purpose and requirement for accuracy, the data retrieved can be quite useful. Gamified BIM is on the way to become a more reliable, accurate, and consistent solution to engineering simulations as model validation and increased efficiency emerge. Table 3-1 shows the analysis of 39 studies that were done on integrating BIM with Fire Safety Engineering. These studies do not include literature reviews (8 studies). Listed from the oldest studies of the sample (2007) to the newest (2021, time of writing), trends in research efforts can be seen. For example, earlier years tend to focus on integrating fire calculations with BIM, while there was a surge in integrating BIM with evacuation calculations in 2019. Case studies used to demonstrate the research are more frequent in later years, indicating that the technology is improving from concept to use. There also seems to be an increased preference for internal integration in more recent years, eliminating the need for data exchange. Papers in 2019 focused more on performance-based design applications while prescriptive approaches have more available solutions in the market (software). Very few papers have a mathematical approach or analysis which suggests that research is not quantifying the benefit or faults of merging fire safety with BIM. Although the other BIM integration applications demonstrate the increased data acquisition and analysis, building fire code-checking is the only application where research has clearly defined the cost-saving benefit. The proven benefits are critical information for industry if the research is to be utilized in future tall buildings. In fact, only 8 out of 54 papers that the author reviewed had industry partner contributions which suggests a potential for a significant disconnect between what researchers think industry needs and what is actually needed. This missed opportunity to collaborate contributes to why BIM is not being fully utilized by fire safety engineers.

Figure 3-3 shows the primary focus areas of the research being done on integrating BIM with fire safety. In this figure, it is clearly defined that fire evacuation simulations are the most popular for BIM integration. Fire smart BIM objects and fire dynamics follow. Construction fire safety is the most in need of future research with only four papers identified. Out of the author's sample, code-checking is also under-represented, but this could be due to the fact that it is already in use in industry so research regarding this topic is likely more frequent in earlier years than the author's focus. Fire rescue and safety operations are quickly progressing in recent years. Many digital twin platforms are now being advertised in industry (such as ARUP's Neuron) but none advertise fire safety management (to the author's knowledge).

By counting the frequency of framework approaches relative to the primary focus of the BIM integration, it can be seen in Figure 3-4 what method is most prevalent in literature. Since both internal and external integration and prescriptive and performance-based methods can be utilized in one study, the percentages are not interdependent. Smart Objects for example, similarly use both internal and external integration. There has been more focus however on developing smart BIM objects for performance-based design. Of the sample researching code-checking, 67% used internal integration methods, eliminating the need for data exchange. On the contrary, 85% of the fire dynamic integration with BIM uses external integration. Construction safety and code checking both predominantly utilize internal prescriptive integration approaches. From Figure 3-4, prescriptive design tends to be integrated internally within the BIM, while performance-based tends to use external integration requiring data exchange.

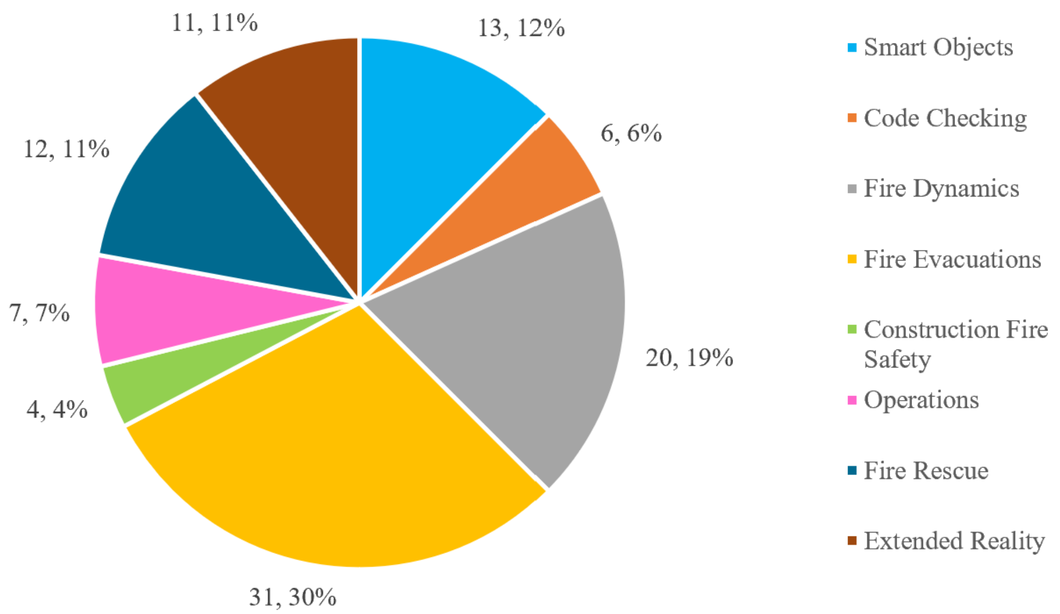


Figure 3-3: Areas of research focus

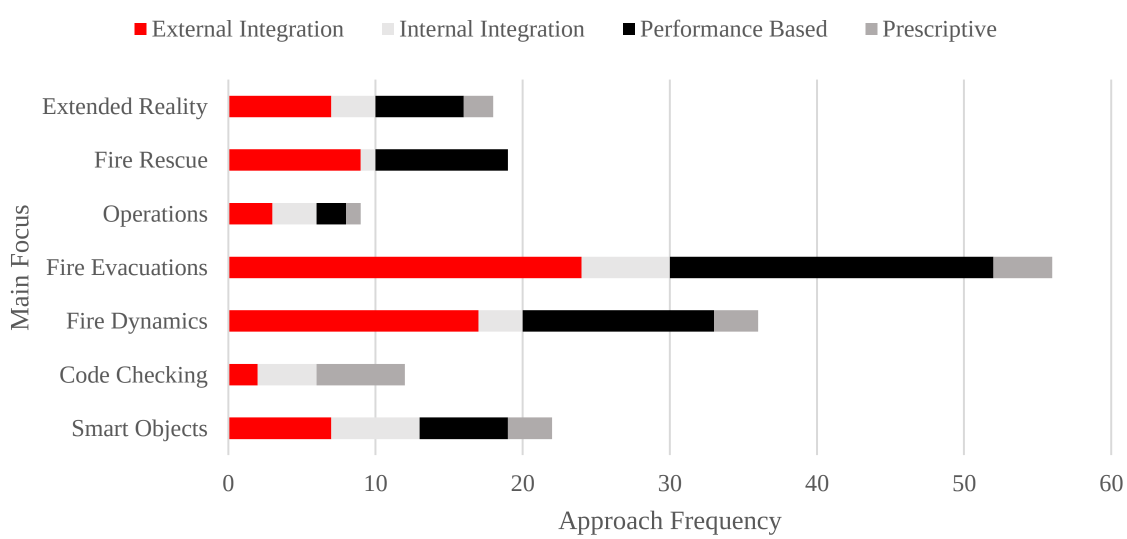


Figure 3-4: BIM integration with fire approaches

Table 3-1: Analysis of studies regarding the integration of BIM and fire safety engineering

Year	Ref	Authors	Primary Focus	BIM	Design	Approach

			Fire Smart Objects	Code Checking	Fire Dynamics	Fire Evacuations	Construction Fire	Operations	Fire Rescue	Extended Reality	Internal Integration	External	Prescriptive	Performance Based	Conceptual	Numerical	Case Study
2007	[58]	Shearpoint & Dimyadi			■							■		■	■		
2011	[98]	Ruppel & Shatz				■				■		■		■	■		
2013	[57]	Shino	■					■			■				■		
2014	[70]	Choi, Choi, & Kim		■		■						■	■		■		
2015	[101]	Wang, Wang, Wang, & Shih	■			■		■				■		■	■		■
2016	[56]	Smith & Gales			■						■		■		■		
2017	[60]	Amaro, Raimondo, Ebra, & Ugliotti	■		■						■	■		■	■		■
2017	[41]	Gao & Xue	■		■							■			■		
2018	[62]	Beltrani, Giuliani & Karlshøj	■		■							■		■		■	
2018	[79]	Cheng et al.				■			■			■		■		■	
2018	[91]	Chen, Liu, & Wu						■	■			■		■			■
2018	[102]	Dimyadi, Solihin, & Amor			■							■		■	■		
2018	[86]	Marzouk & Daoor				■	■					■		■		■	■
2018	[68]	Porto et al.		■							■		■		■		■
2019	[103]	Atyabi, Moghaddam, Rajabifard				■						■		■		■	■
2019	[45]	Eftekharirad	■			■		■	■			■					■
2019	[80]	Fu & Liu				■					■				■	■	
2019	[81]	Mirahadi, McCabe, & Shahi				■						■		■			■
2019	[83]	Ronchi et al.				■					■	■			■		
2019	[97]	Selin, Letonsaari, & Rossi				■				■		■		■	■		
2019	[77]	Shi, Dao, Jiang, & Pan			■							■		■	■	■	■
2019	[78]	Sun & Turkan			■	■						■		■	■		
2020	[94]	Bayat et al.				■						■		■			■
2020	[104]	Bina & Moghadas				■						■		■		■	■
2020	[42]	Chen, Lai, & Lin						■		■	■						■
2020	[69]	Guo et al.				■				■		■		■	■		
2020	[66]	Khan et al.	■	■		■	■				■		■				■
2020	[65]	Kincelova, Boton, Blanchet, & Dagenais	■	■							■		■				■
2020	[89]	Liu, Zhang, & Wang	■					■		■	■		■				■
2020	[100]	Lu, Yang, Xu, & Xiong							■	■		■		■			■
2020	[90]	Ma & Wu	■			■			■	■	■			■			■
2020	[95]	Mirahadi & McCabe			■	■			■			■		■	■	■	■
2020	[105]	Sun & Turkan			■	■			■			■		■		■	■
2021	[106]	Chen, Hou, Zhang, & Moon				■			■			■		■	■		
2021	[84]	Deng et al.				■			■					■	■		
2021	[107]	Diao & Guo			■	■						■		■	■		
2021	[108]	Lotfi, Behnam, & Peyman			■							■		■			■

2021	[92]	Mirahadi & McCabe	■			■			■	■		■		■			■
2021	[53]	Siddiqui et al.	■		■	■						■		■	■		
2022	[109]	Gao et al.							■	■							■
2022	[59]	Kong et al.	■					■			■						■
2022	[110]	Sabbaghzadeh et al.			■	■					■		■			■	
2022	[88]	Sun, Turkan, & Fischer			■		■					■					
2022	[111]	Yang et al.					■				■				■		
2022	[112]	Zhang et al.			■	■						■		■			■
2022	[113]	Zheng et al.			■	■											
2023	[114]	Ismail et al.		■							■		■			■	
2023	[115]	Kanangkaew, Jokkaw, & Tonghong							■	■		■					
2023	[116]	Liu & Wang			■							■		■			
2023	[117]	Liu, Gu, & Hong			■	■						■	■				■
2023	[118]	Mirzaei-Zohan et al.				■						■		■			■
2023	[119]	Parasamehr et al.		■						■		■	■				■
2023	[120]	Wang et al.			■	■						■					■
2023	[121]	Yakhou et al.				■					■			■			■

Technologies being used by researchers for integrating fire safety with BIM is summarized in Figure 3-5. Autodesk Revit is the most used BIM platform along with its integrated API Dynamo. The API is commonly used for code-checking, fire safety operations, and fire rescue. PyroSim is the most used fire simulation tool for integration with BIM and IFC is the most used data exchange format. The evacuation calculation tools are fairly distributed in their use, which may suggest that the evacuation research community is more interested in making the calculation process compatible with BIM.

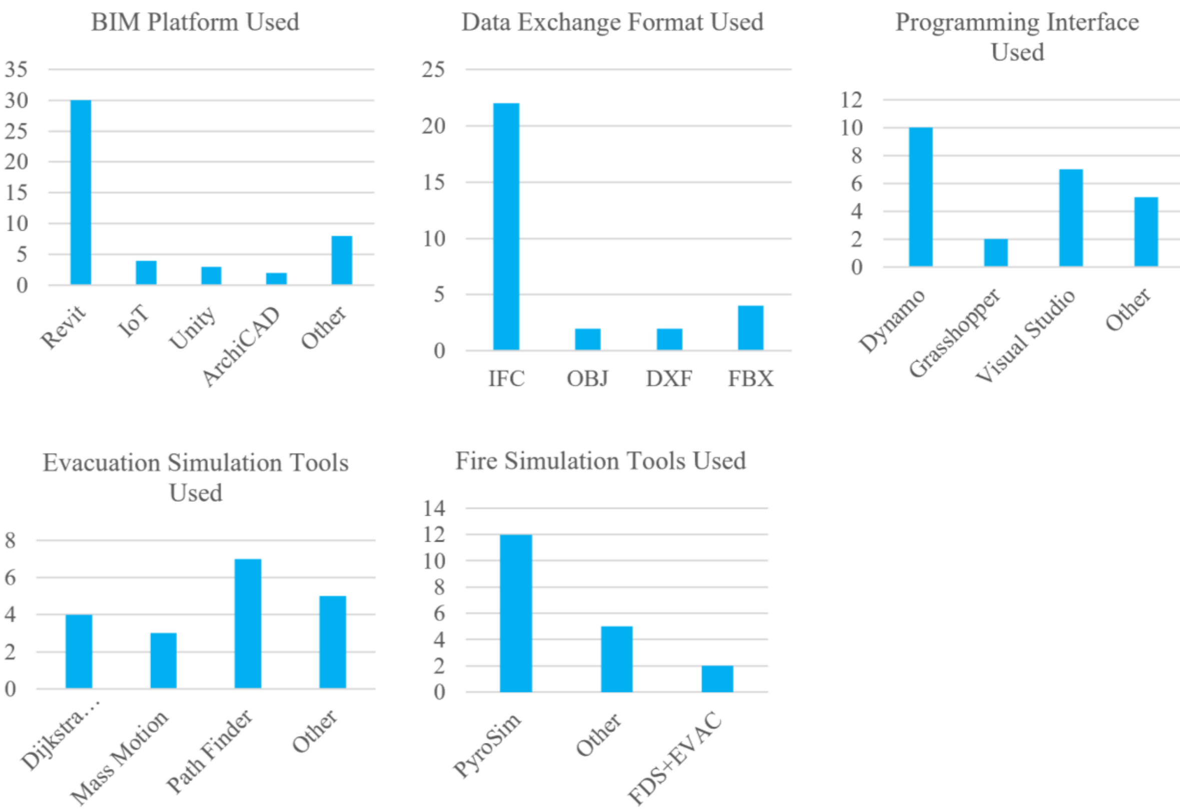


Figure 3-5: Technologies used for integrating fire safety with BIM

3.3 DISCUSSION AND FUTURE RESEARCH ROAD MAP

Growing technology can bring many benefits to the AEC industry. With respect to fire safety engineering, BIM can allow for automated code-checking, manage and automate fire safety operations, store simulation results, and provide a platform for fire emergency management. Simplified calculations for fire and evacuations can be performed within a BIM as well. From analyzing the literature however, there is a need for more research on extracting fire parameters from a BIM and making simulation tools truly interoperable with BIM platforms. Currently, the external integration process involves many time-consuming steps, leaving room for error. The BIM is, however, still useful for providing simulation tools with the building's geometry. The literature reviewed for this study was able to apply fire-BIM integration throughout the entire life cycle of a building and is summarized in Figure 3-6.

Before beginning a new project, the data management plan, quality assurance processes, and permissions must be decided. Everyone in a project must agree for example that they will use IFC classification for their models. If information is missed, it must be quickly identified [63]. Project stakeholders must be notified when a team makes a change in the model. Deciding design change management ahead of time provides structure to the team, reduces errors, miscommunication, and time. Too many information and design changes can drive up cost while too broad of an outline can increase risk of late identification of threats [122].

Figure 3-6: Roadmap to using BIM for fire safety engineering

During the design phase, the LOD of BIM objects begins to be developed in stages, progressing as the design progresses. It is also during the design phase that fire and evacuation simulations must be utilized to identify the worst fire scenarios and plan for occupant safety. Code-checking is also used during this design phase. If the number of penetrations within a FRR wall are exceeded during design, designers can be warned, ultimately preventing the wall from being compromised. A prescriptive approach can also be used for evacuation design although this is less suitable for the complexity of modern tall buildings. By involving the FSE sector from the beginning of early design, FSE can be better integrated into the BIM and included in generative design practices. Ultimately, FSE involvement in generative design would inform stakeholders on design solutions that better consider life safety into the overall design. During the design phase, fire safety during construction should be considered. FSE during the construction phase is an area of much needed further research with the author having only found four papers regarding this [66] [86] [87] [111]. By integrating FSE into the BIM at the design stage, evacuations can be simulated for each construction phase, creating new updated evacuation plans. Fire extinguisher location and installation can also be managed. Many building fires are construction fires and evacuation times change throughout the project.

Construction management of fire safety relates closely with operations management. Operations tend to use more extended reality than other BIM applications. Researchers suggest gamified BIM to be used as a more intuitive platform for operation management. BIM provides a database that can augment real world devices with the virtual one, its digital twin. Digital twins allow for operations and maintenance to better identify fire fighting equipment, their state of repair, and status. It also provides a system for a fire risk analysis of the building and activities to be constantly evaluated in real time. If the occupancy changes, it can be identified and assessed automatically, which can significantly lower the risk of a fire scenario. However, studies that prove this are limited since such systems are slow to be adopted.

During a fire emergency, BIM can still positively influence the outcome of fire safety. As the synchronous digital twin, BIM can monitor sensor input for fires as a way of identifying a fire sooner than a fire alarm. To the author's knowledge, this is yet to be proven. Once the fire is identified and locations of occupants are known, optimized evacuation paths can be calculated and communicated to occupants by smart speakers, mobile devices, and ADDS. Live updates of the fire and evacuation scenario can be provided to the fire fighters to mitigate their exposed risk.

Overall, research efforts on fire-BIM integration are redundant silos of information. For example, fire dynamic simulation integrations could learn from evacuation simulation integrations. It was found that more studies need to shift to real applications of integrating BIM with fire safety. BIM-FSE integration research needs to involve more industry partners who are currently excluded from the technological developments. Additionally, A lot more work needs to be done in interoperability for external integration purposes which is essential for performance-based design. Software developers will have the greatest impact and responsibility in this area. Another identified issue is data management. Permissions and quality assurance processes are essential for the integration to be effective and reliable. For complex buildings, the size of the BIM can be extremely large and may rely on cloud-based storage, which poses risk to security. The LOD of available BIM object libraries is currently not mature enough to supply fire and smoke simulations with enough information. The LOD development task will be greatly influenced by the manufacturing industry where demand for product digital twins is on the rise. Figure 3-7 below summarizes these current issues with the state-of-the-art BIM and FSE integration which require further research and development.

This literary assessment of integrating BIM with fire safety has limitations to its context. The literature analysis is limited in the following ways: (1) The sample selection is subject to personal biases since they were not statistically randomly chosen. (2) Some BIM integration categories have a significantly limited sample size. (3) Sample was limited to English language papers.

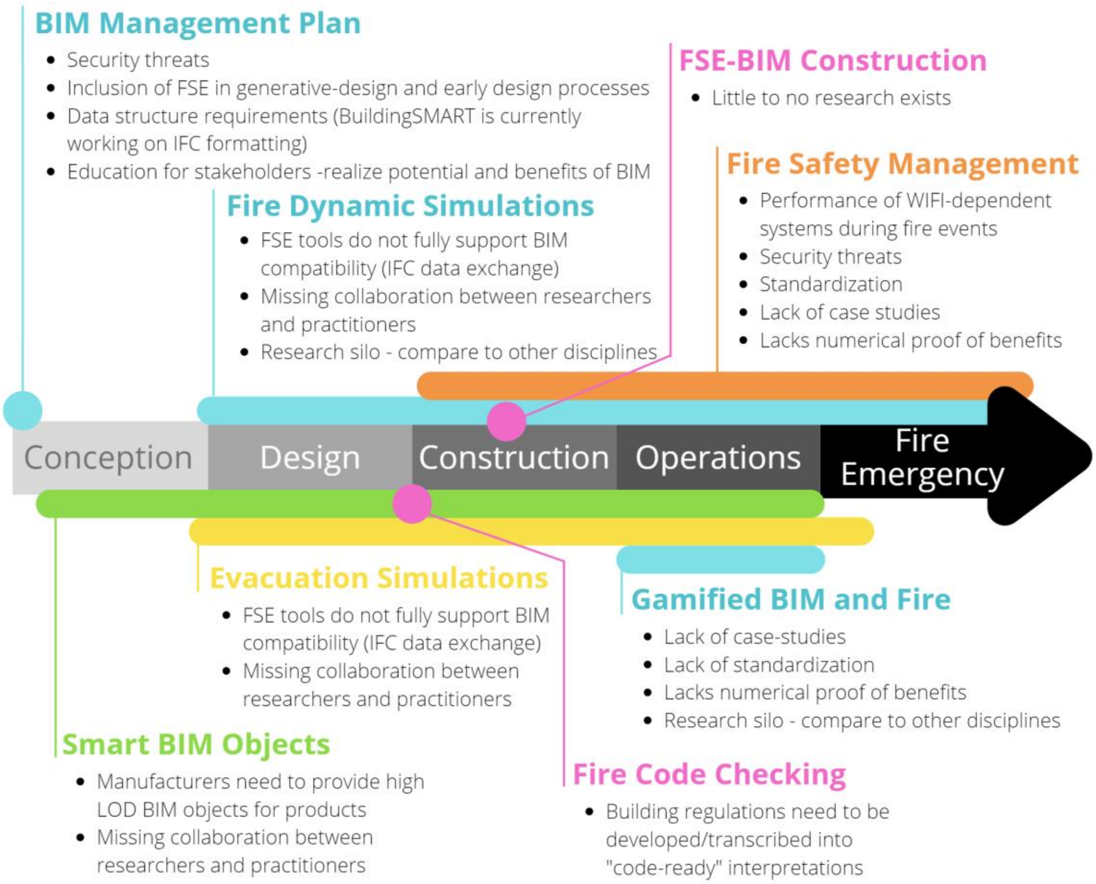


Figure 3-7:Future Research for FSE-BIM Integration

3.4 CONCLUSIONS

Fire safety engineering can utilize Building Information Modelling (BIM) throughout a building's life by participating in the Level of Development (LOD) of smart BIM objects, automated fire code checking, prescriptive fire protection design, data exchange to evacuation and fire simulations, fire safety planning during construction, fire safety management during operations, and fire emergency management. Research in these developing applications indicated the benefit in reducing fire risk but fire code-checking is the only application that has shown cost benefits. Adoption of BIM in fire safety engineering is slow and behind other disciplines which may be improved if research involved more industry partners, as only 8 out of the 54 BIM-Fire papers reviewed involved industry partners. The most commonly used BIM platform, fire simulation tool, programming interface, and data exchange format used in research are Revit, PyroSim, Dynamo, and IFC respectively. Research does not show a preference for a particular brand of evacuation simulation tool. This information may help practitioners when choosing more compatible software for their fire design integration with BIM. The research has gravitated towards integrating prescriptive building codes within the BIM using API for construction operations and checking fire code compliance during design and operations. Performance-based fire design tends to use external BIM integration by exchanging data between the BIM and the simulation tool, usually in IFC format. Emerging technologies such as gamified BIM are progressing capabilities of smart buildings and allowing for fire risk mitigation. All technology and information that should be defined at the beginning of a project when the BIM management plan is specified between disciplines. It is essential that the fire safety engineer be involved from the beginning to make clear their needs and be informed on the building's design objectives. It is during the conceptual stage that technology, software, and data need to be defined from the fire safety perspective. The roadmap provided by the authors in this chapter offer holistic guidance for making such decisions. For BIM technology to reach its potential, industry manufacturers need to provide high LOD fire BIM objects, fire engineers and researchers need to collaborate, software developers need to improve interoperability (the use of standardized file exchange formats - IFC), and building owners and management need to be educated on how use the benefits provided. In the future, it is possible that the digital twin of a large data sample of buildings will be able to collect big data on human and fire behaviour during real events. Applying big data can better inform design practices and base assumptions, ultimately improving the life safety of high-rise buildings. Additionally, FSE would be fully integrated into the BIM collaborative process with other building stakeholders from early design phases, allowing for inclusion in other BIM tools such as generative design. FSE early involvement would ultimately result in an optimized design that truly considers life safety.

CHAPTER 4

BIM for Improved Collaboration in Aiding Design Decisions Impacting Fire Dynamics: The Case of Timber Compartments

It is amazing what you can accomplish if you do not care who gets the credit.

-Harry S. Truman

4.1 INTRODUCTION

The modern use of mass timber has gained momentum over recent years with the innovation and increasing availability of engineered mass-timber products such as glulam and Cross Laminated Timber (CLT). The increasing use is largely because mass timber systems provide an aesthetically pleasing and sustainable alternative. In Canada, there is an abundant supply of sustainably managed wood, making mass timber construction an attractive option. However, wood is susceptible to decomposition, biota, and fire. The variability in properties makes it difficult for engineers to predict how it might perform under any circumstance, particularly in the event of a fire. As a result, the fire design of a modern mass timber building requires careful considerations.

Predicting how a fire will behave in a given building is complex and is affected by the decisions that various professions make, such as those of an architect (geometry, opening sizes, etc.) or mechanical engineer (HVAC). In the case of mass timber building design, where the structure is combustible, fire safety can dictate the buildings design. For this, Salminen and Hietaniemi reason that performance-based fire safety design is the only way to approach mass-timber buildings (larger than 8 storeys) [123]. Performance-based design (PBD) is widely used (albeit labour intensive) to provide economical and optimized design solutions to complex problems. The PBD approach allows an equivalence-based safety design but with potential for greater resiliency in the optimization of protective measures. PBFD optimizes design by using modeling, research, and testing to show with certainty that the performance requirements are met (ie. building will not collapse, and occupants will be safe in event of fire). Given that building codes can develop at a slower rate than the advancement of mass-timber design and construction techniques, the resulting current codes tend to conflict with architectural needs [124]. The architectural conflicts reinforce the mandate for performance-based fire design (PBFD) of mass timber buildings. PBFD is often unavoidable due to the requirement for research, testing, and modeling to better understand the fire dynamics of modern mass-timber structures [125].

While taking a PBFD approach can ease costs by optimizing design where it is needed and saving costs incurred from over-designing, there have been cases where the opposite occurred and the efforts required to carry out the complex design only ended up costing more than any savings that might have been had. Design is an iterative process, meaning there are many changes. If, however, major changes are made nearing the end of the design phase, additional efforts often require a re-design. Late design changes can be very expensive due to the complicated and laborious simulations required for PBFD. While it has been difficult for researchers to accurately predict the effects of change orders, design changes late in the project is one of the leading causes of increased design cost [126]. Qualitative studies have found that changes cause cost increases of around 25% and increase the schedule by 69% on average [127]. In a recent study of 3951 project change-orders by Padala, Maheswari, and Hirani, it was found that 33% where client related (aesthetic and finishing works), 21% were design related (safety), and 23% were related to MEP [128]., accumulating to 77% of design changes affecting fire safety. The cause for these changes varies drastically, but many researchers attribute most to lack of communication, coordination, and change of scope. Interestingly, however, the majority of 338 practitioners surveyed in Yap et al.'s 2019 study, mentioned value engineering as the most significant cause of design changes, with lack of coordination at a close second [129]. The same practitioners named the most significant effect being time delays, then cost increases [129]. Yap et al. determine that to solve the issue of expensive design changes, practitioners must have a shared understanding of design changes and their impacts on one another and be able to collaborate effectively to cocreate optimized solutions (value engineering).

Building Information Modelling (BIM) has become an industry standard for larger construction projects. BIM is an information database capable of containing, organizing, and analyzing everything that has to do with a building, including its geometry in three dimensions. BIM is not a software or a data set meant just for design. Algorithms can analyze and process the data to provide design options, check codes and regulations, create material lists, etc. A fully developed BIM would contain all the information from various disciplines. Fire safety is dependent on building and structural geometry, HVAC, mechanical, and electrical systems. Fire safety engineering is one of the most critical specializations to include in the design of a tall timber building, yet it is often excluded from the Building Information Model (BIM) and integrated design process. For a PBFD to be possible, multiple disciplines need to collaborate early on. To save time and ensure accuracy, the fire safety engineer and practitioner need to know about design changes from other disciplines as they happen. Projects that use BIM increase in efficiency while reducing conflicts, error, and miscommunication [10]. It is an opportunity to streamline multi-discipline collaboration but is not being developed for fire safety in industry. The compatibility between BIM and fire safety design seems obvious, yet it is just beginning to receive attention in structural (fire) engineering literature due principally to the confidential nature of the projects for which it has previously been applied.

Fire Engineers are still in the early stages of understanding how mass timber construction contributes to the dynamics of a building fire. When looking for material on how architectural features impact the fire dynamics of a CLT compartment fire, only a guideline presenting a prescriptive approach to designing CLT buildings existed. There was no reference for non-fire practitioners on understanding how architectural decisions impact fire dynamics. Additionally, the authors found little on the demonstration of a visual notification systems to alert and aid decision makers on how a design decision can impact other disciplines. Like Lovreglio, Thompson, and Feng, no studies could be found on visual aids to parametric design as it relates to fire safety engineering [39].

This chapter explores two themes: (1) the impacts of architectural factors on the fire dynamics of a modern CLT compartment, and (2) how to communicate those impacts to a decision-maker via BIM. Since fire dynamics depend on the decisions made by multiple disciplines, for simplicity, the scope of this chapter only considers architectural features such as geometry, openings, and finishes. Since the idea of a visual alert system for supporting design decisions impacting fire safety is novel in literature and non-existent (to the author’s knowledge) in practice, the scope of this chapter only introduces the concept.

This chapter aims to improve cross-disciplinary awareness and collaboration by: (1) serving as a comprehensive review for stakeholders with limited fire engineering background showing the effects of architectural changes on fire dynamics, and (2) introduce a BIM alert system which informs disciplines on the impact of their design-decisions and changes. The chapter will provide background and recent studies on the matter, the methodology for analyzing the full-scale CLT compartment fire tests, and behind developing the concept for a visual alert and decision-aid system within BIM. The reader will see the resulting correlations the author made between architectural factors and the fire dynamics of a CLT compartment, based on real world data gleaned from full-scale CLT compartment fire tests. The reader will also see how the data and analysis is used within a preliminary BIM alert and decision aid system. The aim is that this study may inspire adoption of such approaches in practice, and ultimately promote and contribute to improved collaboration, cross-discipline understanding, and project efficiency. Improved collaboration and cross-disciplinary understanding are critical achievements for the successful design and construction of new technologically advanced, sustainable, mass timber high rises.

4.2 BACKGROUND

4.2.1 Factors Affecting Fire Dynamics and Design

For flames to burn in a traditional fire three things are needed: heat, oxygen, and fuel. When enough heat is applied to a fuel, with enough oxygen, the fuel will burn. If the fire is smothered, the flames will die. If there is no fuel, there will be no fire. If there is no heat, there will also be no fire. Wood buildings not only contain fuels, but they are also completely composed of fuels. Window and door openings, HVAC, and room size have effects on the oxygen supply. Room finishes and furnishings have various flammability properties, some easier to ignite than others. While heat sources are often well controlled in buildings, there are many uncontrolled and unintentional incidences that can occur and start a fire such as an occupant starting a grease fire in the kitchen. Regardless of the quantity and types of fuels or openings in a room or compartment, most compartment fires undergo four stages in their development. The four stages, as shown in Figure 4-1, are the incipient stage, the fire growth stage, the fully developed fire stage, and the decay stage [25].

During the incipient stage, the fire is relatively small and just beginning. The overall room temperature is not yet greatly affected, and the fire can be put out most easily at this stage. Although, if left unattended, the fire also has enough oxygen to grow and spread to other fuel sources. During the growth stage, the fire is spreading to additional fuel sources, the room temperature is increasing exponentially, and there is a lot of smoke development. At flashover, the point at which the fire becomes fully developed, the room is completely engulfed in flames, has reached room temperatures of 500-600°C, and risks breaking windows and doors in search of oxygen [25]. The heat and toxins generated during such a stage is fatal. Finally, when there is no fuel left, the fire begins to decay. Such extreme changes in temperature can have drastic effects on how materials behave, but for the purpose of this study, the focus will be solely on the fire dynamics.

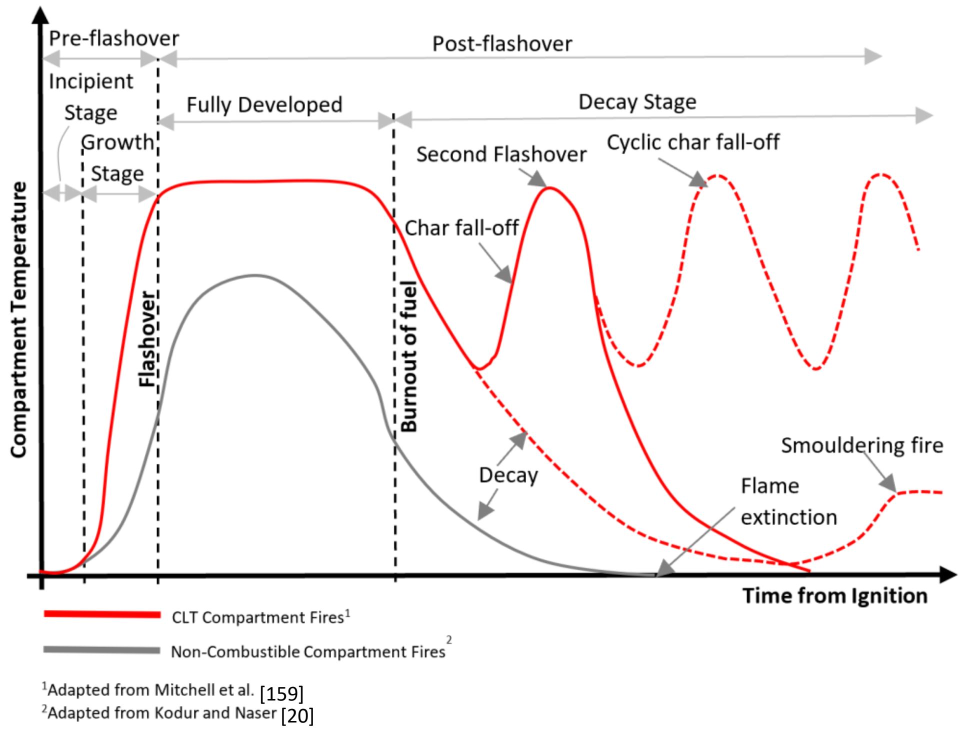


Figure 4-1: Time-Temperature Curve for Compartment Fires

4.2.2 Making Design Decisions and Changes

Information resulting in better cross-disciplinary awareness can lead to more informed decisions about design, minimizing the need for design changes and modifications later. To effectively cocreate optimized design solutions (value engineering), collaboration, and a well-understood knowledge of the impacts of shifting various parameters affecting the design outcome is essential. When making parametric design decisions, the decision maker must remember a multitude of information and that information is interdependent. In the construction industry, this can be particularly difficult given that the decision-makers typically have minimal technical background and little understanding on how one action or design change might impact the various technical fields, or how many resources it would take to carry out the design resulting from that decision. This is especially the case for modern CLT structures and fire engineering. To understand how to relay this information in a way that is useful to decision makers who may not have a background in fire engineering, the Decision-Making Process (DMP) is examined.

Decision-making has been studied extensively in many diverse fields including business, sociology, management, and cognitive science. In the field of building design, however, there are few studies that consider the approaches, methodology, and impacts of decision-making [130]. The lack of studies is surprising considering that in countries like Canada, the construction industry accounts for 7.5% of the GDP, generating about $141 billion annually [131]. Where a few design decisions could save millions, it would be in everyone's best interest to ensure design decisions are made in the most effective manner.

One of the difficulties involved in decision-making regarding a building's design is the complex artistic nature of architecture. How does an artist decide to place a stroke of yellow paint here or there? The creative decision-making process differs from decision making that may only involve numbers. The most energy efficient room for example, would be a well-insulated cube with no windows, but this would be an 'ugly' option and there would be no desire to inhabit this space. With that in mind, Lee and Ostwald surmised from an empirical study where six architectural designers were videotaped during a one-hour parametric concept design exercise, that there existed three Decision-Making Processes (DMPs) in design; conclusive, confirmative, and simulative [130]. In all these processes, the architects had the ability to view a visual 3-D representation of their parametric design and frequently referred to it during iterations and decision-making. The DMPs used during parametric design in Lee and Otswald's study [130] all involve five activities:

1. Goal Setting — Defining the scope and performance criteria
2. Representation — Understanding the nature of the problem
   Relating different aspects to one another and creating a "space" in the mind and algorithm that represents the problem or relating the aspects of the problem in a visual representation (ie. 3D building model) [132].
3. Generation — Create alternative solutions and calculate and simulate performance
4. Evaluation — Evaluate existing geometries, aesthetics, and performance.
   Make decision to keep iterating design or make changes.
5. Revision — Revise parameters, rules, geometry, design, etc.

Each of these activities allowed the participant to refer to the visual representation of their solution and assess it against the goals and criteria of the overall design. So, while algorithms could be used to generate design options and infer decisions, visual assessment was consistently necessary and relied upon.

Where the struggle typically lies in solving problems, according to the well-known researcher on the topic, John R. Hayes, is during the 'Representation' activity: understanding the nature of the problem, the gap between the current situation and design and the desired outcome [132]. The representation process involves relating the different and multiple criteria to one another. For buildings, this relationship can be quite complex. In many of Hayes' studies, he found that participants frequently would use sketches to map out relationships in understanding the problem, which also highlights people's need for visual representation in mapping out relationships for problem solving. For decades, researchers have consistently demonstrated that, for most people, images transmit more information in a shorter amount of time and are easier to grasp and remember. Therefore, the best way to communicate information regarding the impacts of changes on a building's performance parameters, and provide a reference system for design decision-making would be a visual representation of the design parameters before and after the potential change or iteration.

When making decisions, the decision-maker sifts through information, deleting, adding, and interpreting information based on relevance to the problem. Problems cannot be easily understood or interpreted without knowledge relevant to the actual problem. Lack of problem-relevant may contribute to owners and architects making design decisions that significantly impact other specialties without even realizing – because relevant technical information is missing from their arsenal of knowledge. Another phenomenon that can occur when making decisions is the 'optimist phenomena' where the decision-maker is not necessarily failing to use information, but that the information is being used inappropriately [132]. Since it is unreasonable to expect an owner or architect to understand and interpret technical knowledge relating to all the various specialties of a building, it is necessary to find a way to perform some of these decision-making activities for them. To curtail the chances of an il-informed decision, a person who is well-informed with the technical knowledge regarding their field of expertise, needs to provide the decision maker with the appropriate necessary information, in a representation that the decision maker can accurately interpret.

Once the decision-maker has relevant information, the information must be evaluated and compared. In architecture and other artistic realms, information evaluation can be a subjective process. Some factors that affect how a decision is made involves whether the decision is made under certainty, under risk, under uncertainty, and/or under conflict [133]. Depending on the circumstance of the decision and available information, different decision-making strategies and approaches may be taken. For example, if the outcomes of a design change are certain, then an optimization approach may be taken. But if there is uncertainty or risk, for example, if an architect wants an atrium built out of mass timber where all the timber is exposed, then based on previous knowledge, a cost estimate could be made but with a degree of uncertainty, and the fire engineer may inform the architect that there is a fire risk. The FSE information could change the architect's approach to making the decision to add an atrium from an optimization approach to a 'minimizing maximum regret' approach. Therefore, it is important for the specialists with technical knowledge and understanding to communicate effectively to the decision-maker regarding what kind of uncertainty, risk, or conflict may be associated with the design decisions and changes.

4.2.3 Multi-Disciplinary Collaboration and DMP in the BIM Environment

Building Information Modelling (BIM) has been widely accepted as a way for improved collaboration and communication across disciplines in the architecture, engineering, and construction (AEC) industry. Improving collaboration and communication is done through multiple facets such as clash detection, model-sharing, construction sequencing, version tracking, etc. However, researchers, even today, have found that the full potential of this has not yet been realized due to some developing limitations such as poor interoperability between software packages, ill-defined BIM objects containing semantics that other disciplines cannot use nor understand, and laborious management of design variations [134]. Although interoperability between software packages is being addressed by the software developers and the use of Industry Foundation Classes (IFC) data-structures, the individual use of sperate software does not encourage multi-disciplinary parametric design at beginning stages.

Researchers and companies have been working towards one synchronised BIM model that all the disciplines can use in real time. The resulting model is a very large bundle of data. Where to host the data, how to back-up the data, how to secure the data, how to save the data, how to share the data, even what data format to use are all looming questions the industry is trying to answer but are out of scope for this thesis.

To try and improve cross-disciplinary understanding, collaboration, and ultimately coordination in design, researchers have also been focusing on minimizing the impacts of design changes. In a 2022 study by Sacks et al the authors took the approach of solving concerns regarding the propagation of design changes throughout the disciplines as a way of improving overall collaboration [134]. The current best-practice for design change maintenance involves the operations: assess, notify, propose, authorize, and execute [134].

4.2.3.1 BIM and Big Data; Data Driven Decisions

BIM is a data-rich ecosystem. It would be difficult to discuss the benefits and potential of BIM without mentioning data analytics. Using a data-driven statistical numerical approach requires less computing power than an analytical calculation using Finite Element Modelling (FEM). In the case of fire, the analytical solution is complex, as it is not easy to derive numbers (results) from. Alternatively, a numerical approach can more easily produce results that are fairly accurate albeit not the exact solution. That makes the numerical approach useful for the beginning stages of design when design changes are more likely to occur. It is also useful for estimating the magnitude of impacts that a design-change might have on the overall design.

4.3 METHODOLOGY

To develop a solution that can improve the multi-disciplinary understanding between architects and fire engineers with the aim of minimizing design-changes, identifying how architectural features affect fire dynamics within a CLT compartment is the first step. Once effects of architectural changes are quantified, the uncertainty, risk, and conflict associated with the impacts must be identified as well. When effects, uncertainty, risk, and conflict information is obtained, a concept for effectively communicating this to an architect, owner or design decision-maker can be formed.

4.3.1 Review Studies on the Fire Dynamics for Timber Compartments

Since a great deal more data needs to be collected before probabilistic models can be drawn, this chapter will focus on a qualitative analysis of 36 full-scale mass timber compartment tests from 10 studies [135-145]. To understand the realistic nature of a compartment fire, it was necessary to exclude compartment tests whose scale was so small that the ventilation would be insufficient compared to a real-fire scenario. For that reason, compartments with floor areas less than 10 m^2 were excluded from the study. To understand how architectural changes can affect the fire dynamics of a mass timber compartment, the authors have chosen tests which isolated the architectural variables. Thus, tests involving any active mechanical systems (i.e. HVAC, sprinklers) are excluded from this study. The following metrics are gleaned from each experiment: floor area [m^2], ceiling height [m], wall finish [%combustible], ceiling finish [%combustible], floor finish [%combustible], opening factor [$m^{1/2}$], fuel load density [MJ/m^2], time to flashover [min], duration of fully-developed stage [min], maximum temperature [°C], maximum HRR [kW/m^2]. Metrics regarding the fire performance of the CLT such as charring rates were excluded from this study as it was considered outside the scope. The authors also recorded any observations researchers made during the experiments.

Values such as incident heat flux or temperature may have varied according to lo-cation but for the purpose of this study, the most severe/maximum values were recorded. For some metrics, such as ‘duration of fully developed stage’, the time at which the decay phase began was recorded from the experiment’s Time-Temperature curve. For %combustible material finishes, protected CLT was excluded with the assumption that the protection meets performance requirements. The fuel load density excluded the paper finish of gypsum board.

Table 4-1: Full-scale Test Catalogue

Test Numbers	Publication Year	Test Series Name/Institution	Authors	Citation
Test 1	2022	ARUP Codered #1	Kotsovinos et al.	[135]
Test 2	2022	ARUP Codered #1	Kotsovinos et al.	[136]
Test 3	2023	ARUP Codered #4	Kotsovinos et al.	[137]
Test 4-9	2018	NRCC and NFPA in study	Su et al.	[138]
Test 10-12	2018	USA Forest Products Laboratory	Zelinka et al.	[139]
Test 13-15	2014	Carleton	Medina Hevia	[140]
Test 16-20	2021	RISE Research Institutes of Sweden	Brandon et al.	[141]
Test 21-23	2021	CERIB Testing	Weisner et al.	[142]
Test 24-28	2021	NRCC	Su et al.	[143]
Test 29-33	2023	TIMpuls	Engel & Werther	[144]
Test 34-36	2022	Structural Timber Association (STA)	Hopkin et al.	[145]

4.3.2 Identify Fire Dynamic Sensitive Components

For the metric data obtained from the experiments, the table was sorted to exclude the columns of data that lacked 25 points or more. The resulting plotted data includes all architectural metrics and four fire dynamic metrics: time to flashover, duration of the fully developed stage, maximum temperature reached, and maximum HRR reached. The architectural metrics are each plotted against the fire dynamic metrics. The resulting scatterplots are then observed for any patterns and correlations are calculated using MS Excel’s built-in function “CORREL()”.

4.4 RESULTS

	Architectural Factors						Fire Dynamic Outcomes						
	Floor Area [m^2]	Ceiling height [m]	Wall Finish [% comb.]	Ceiling Finish [% comb.]	Opening Factor [$m^{1/2}$]	Fuel Load Density [MJ/m^2]	Time to Flashover [min]	Duration of Fully-Develope d Fire [min]	Time to HRR of 0.5 MW [min]	Time to burnout [min]	Time smolderin g ends [hr]	Max. Temp. [°C]	Max. HRR [MW]
Test 1	352	3.1	0%	100%	0.071	374	5.6	6.4		22.5	38.5	1060	121
Test 2	352	3.1	0%	100%	0.039	377	7.4	6.1		27.0	35	1080	99
Test 3	352	3.1	0%	52%	0.071	394	29.9	6.8		46.0	504	1053	100
Test 4 (1-1)	41.86	2.7	0%	0%	0.030	540	14.9	30.0		134.0		1200	9.5
Test 5 (1-2)	41.86	2.7	0%	0%	0.060	539	15.3	24.0		104.0		1200	12.4
Test 6 (1-3)	41.86	2.7	33%	0%	0.060	549	12.5	23.0		242.0		1200	14.2
Test 7 (1-4)	41.86	2.7	0%	100%	0.030	543	11.5	63.5		159.0		1200	13.1
Test 8 (1-5)	41.86	2.7	33%	0%	0.030	549	11.5	40.5		202.0		1200	9.6
Test 9 (1-6)	41.86	2.7	33%	100%	0.030	546	9.8	70.2		160.0		1200	12.9
Test 10 (1)	83.54	2.74	0%	0%	0.104	550	13.5	19.6		107.8		1100	18.5
Test 11 (2)	83.54	2.74	0%	20%	0.104	550	11.7	24.3		134.0		1180	23.3
Test 12 (3)	83.54	2.74	33%	0%	0.115	550	12.6	17.4		210.5		1150	20.9
Test 13 (1)	15.75	2.5	50%	0%	0.048	532	5.0	19.0	40.0	123.0		1200	4.8
Test 14 (2)	15.75	2.5	56%	0%	0.048	532	5.0	25.0				1200	6.3
Test 15 (3)	15.75	2.5	28%	0%	0.048	532	4.0	16.0	35.0			1100	4.4
Test 16 (1)	47.95	2.73	0%	100%	0.062	560	14.0	22.0		104.0		1200	20
Test 17 (2)	47.95	2.73	49%	100%	0.062	560	8.0	28.0		88.0		1300	30
Test 18 (3)	47.95	2.73	69%	100%	0.062	560	12.0	31.0		84.0		1225	32
Test 19 (4)	47.95	2.73	75%	100%	0.250	560	17.0	5.0		106.0		1150	50
Test 20 (5)	47.95	2.73	65%	100%	0.062	560	4.0	30.0		98.0		1200	30
Test 21 (1)	24.00	2.52	0%	100%	0.216	891	7.0	23.0				1192	
Test 22 (2)	24.00	2.52	0%	100%	0.070	891	1.0	44.0			29	1199	
Test 23 (3)	24.00	2.52	0%	100%	0.043	891	1.0	54.0				1200	
Test 24 (1)	10.80	2.7	0%	0%	0.030	550	6.4	13.6		150.0		1200	
Test 25 (2)	10.80	2.7	11%	10%	0.030	550	4.7	25.3		247.0		1200	
Test 26 (3)	10.80	2.7	36%	0%	0.030	550	7.0	33.0		245.0		1200	
Test 27 (4)	10.80	2.7	19%	100%	0.030	550	4.9	27.1		170.0		1170	
Test 28 (5)	10.80	2.7	3%	100%	0.030	550	4.8	40.2		100.0		1190	
Test 29 V0	20.25	2.4	0%	0%	0.094	1085	9.0	31.0		220.0		1350	10
Test 30 V1	20.25	2.4	0%	100%	0.094	1085	9.0	36.0				1400	8
Test 31 V2	20.25	2.4	50%	0%	0.094	1085	8.0	34.0				1290	9
Test 32 V3	40.50	2.4	0%	100%	0.094	1085	10.0	42.0				1250	16.5
Test 33 V4	40.50	2.4	17%	100%	0.094	1085	10.0	45.0				1220	16
Test 34 (1)	28.50	2.4	0%	0%	0.193		7.5	79.5	4.0	53.5		1000	12.5
Test 35 (2)	28.50	2.4	0%	100%	0.193		7.5	90.5	3.5			1000	50
Test 36 (3)	28.50	2.4	0%	100%	0.193		7.0	83.0	2.0			1000	37.5
Count	36	36	36	36	36	33	36	36	5	25	4	36	28

Figure 4-2:Data obtained from full scale compartment fire experiments

4.4.1 Analysis of CLT Compartment Tests

Data obtained from the full-scale compartment fire experiments in studies [135-145] can be seen in Figure 4-2. All the tests were constructed with CLT panel ceilings. Most of the tests were constructed with CLT panel walls as well. However, if the CLT was protected with at least two layers of gypsum, it was considered by the author to be non-combustible. All the experiments used either furniture, wood cribs, or a combination of both as their fuel load. All tests observed minimal temperature variation along height and moderate to large variation horizontally, depending on the size of the compartment. The first set of full-scale tests (Test 1-3) were CodeRed #1 [135], CodeRed #2 [136], and CodeRed #4 [137]. These tests had the largest compartments of all the experiments which allowed for the potential observation of travelling fires. The authors observed that the fires grew at a faster rate than the standard “fast” t^2 fire, that the fuel-controlled fire would travel across the ceiling faster than it would across the fuel load, standard seals for fire protecting penetrations work for CLT, and that smouldering could continue for over 20 days and was only detectable by infrared.

Compartment Tests 4-9 conducted by the NRC and NFPA in study [138] were all the same size with varying opening factors and exposed timber. All tests with exposed CLT (Test 6-9) experienced delamination and char fall-off, spiking a second flashover in Tests 6-9. This is the cyclic action which can be seen in Figure 4-1 and called for manual fire suppression. Therefore, fire dynamic data as it pertained to the first fully developed stage was recorded while the second fully developed stage was omitted.

Tests 10-12 conducted by Zelinka et al. [139] contained interior walls within the compartment making for a realistic apartment layout. The study also involved moveable loads applied to the ceiling. In Test 12, the exit door was not shut properly, and the wood was slightly damp in parts due to one of the barrels leaking the night before, both of which would have effects on the fire dynamics.

Tests 13-15 by Medina Hevia [140] had two tests (13 and 14) which reached a second flashover due to delamination. For Test 15, a different CLT manufacturer was used whose glue kept integrity throughout the fire. Without delamination occurring, the fire self-extinguished. Low variation in temperatures throughout the compartment were recorded.

Tests 16-20 conducted by Brandon et al. [141], all except for Test 18, had the CLT self-extinguish before the fuel load finished burning. Test 18 was about to reach a second flashover before being manually suppressed.

In Weisner et al.’s study [142] (Tests 21-23), tests were allowed to self extinguish. After smouldering for 23 hours, Test 22 collapsed. Test 23 had a longer fire duration causing deeper charring. The slab of Test 23 eventually collapsed as well. This study highlights the need for firefighters to use infrared to search for smouldering.

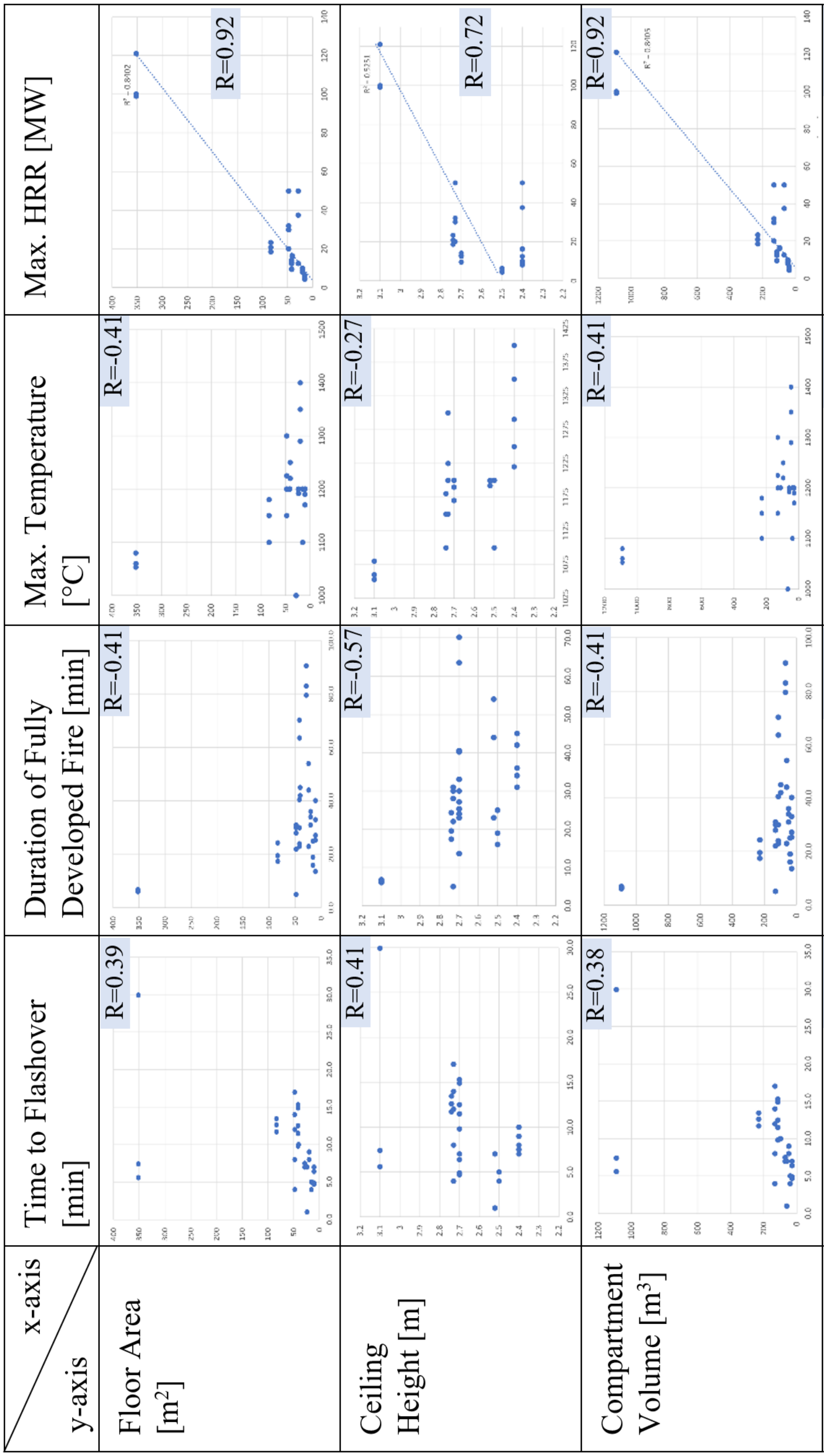


Figure 4-3: Architectural metrics plotted against fire dynamics metrics and their corresponding correlation values (R)

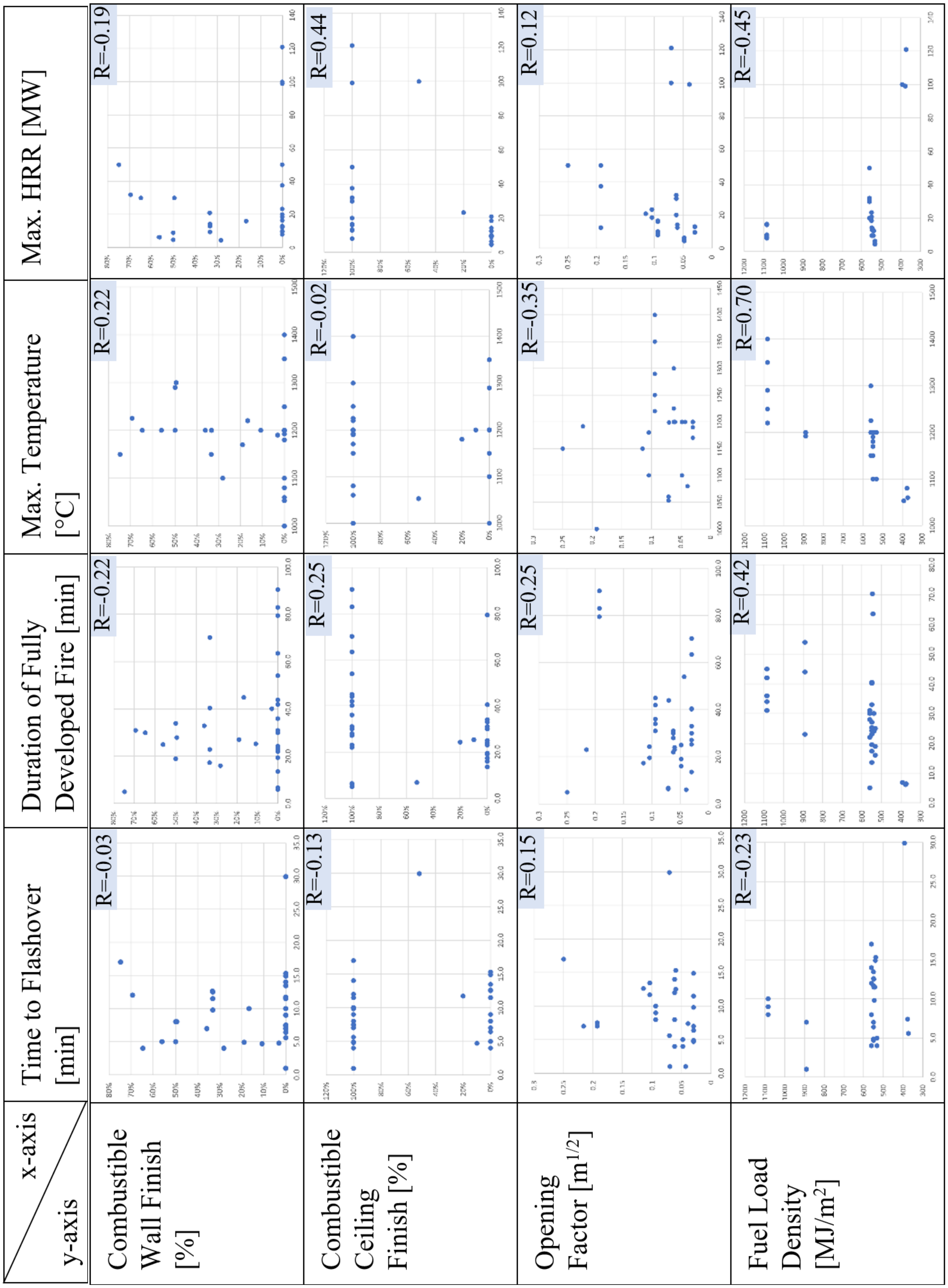


Figure 4-3: Architectural metrics plotted against fire dynamics metrics and their corresponding correlation values (R)

The NRCC conducted Tests 24-28 in [143]. Tests 24, 25, and 27 self-extinguished. For Test 26, small flaming and charring began to occur behind the gypsum board. For Test 28, a small fire behind the gypsum board was able to grow, eventually causing a second flashover.

Tests 29-33 are from the German TIMpuls full scale compartment fire tests discussed by Engle and Werther [144]. In these tests, a higher fuel load of 1085 MJ/m^2 was used which is more in line with actual load densities found in European residences. There was low variation in temperature across the compartment except for during the cooling phase, where some parts of the compartment cooled faster than others. The exposed timber tests displayed a longer fully developed stage of the fire than its baseline counterpart that was similar to the observations made by authors of the CodeReds in [135-137] and as shown in Figure 4-1.

Tests 34-36 were done by Hopkin et al. [145]. In this test series, the walls were constructed of CMU (non-combustible). The ceiling was constructed using CLT. The first experiment of this series had the compartment completely protected from fire while the other two had 100% exposed CLT ceilings. The second and third tests in the series used different kinds of glue for the CLT assembly. In Test 35, the CLT experienced some char fall-off while Test 36 did not. Compartment gas temperatures were fairly uniform where compartments with exposed CLT ceilings experienced higher gas temperatures than the fire with the protected ceiling.

4.4.2 Fire Dynamic Sensitive Components within CLT Compartment Experiments

Once the data obtained in Figure 4-2 was simplified to only include metrics which had at least 25 points, architectural metrics were plotted against fire dynamics metrics in Figure 4-3. In Figure 4-3, each blue box contains the associated correlation value R where 1 is a perfect positive correlation, -1 is a perfect negative correlation, and 0 is no correlation. A weak/low correlation ($R \approx \pm 0.5$) may indicate that there is some involvement of that architectural factor in the fire dynamics but that there is much uncertainty.

4.5 DISCUSSION

Many of the full-scale compartment tests observed second flashovers and underwent cyclic fire stages as seen in Figure 4-1. This effect is caused by failing fire protection and/or delamination and char fall-off. Therefore, it is essential that fire protection be designed and installed properly. It is the author’s opinion that only CLT which uses lamination glue that is proven to maintain integrity during a fire should be used.

When considering the plots in Figure 4-3, it is important to understand that correlation does not establish causation. In this case, because fire dynamic metrics are based on an event which happens within the already established parameters of the architectural metrics, it can be determined that the architectural parameters do, in part, cause the outcome of fire dynamics. However, fire dynamics is very complex and influenced by a multitude of parameters. Therefore, correlation in this case, is an indicator of how likely the architectural metric may affect the overall fire dynamics.

4.5.1 Architectural Changes that Commence the Greatest Impact on Fire Safety Design

Looking at the first column of plots in Figure 4-3 regarding the fire dynamics metric ‘Time to Flashover’, it can be seen that generally, the data correlates most with ‘Ceiling Height’, albeit the correlation is still low. The outliers in the top left-hand corner of the Floor Area vs. Time to Flashover plot are two of the large CodeRed tests and this may be due to the presence of travelling fires. The Floor Area vs. Time to Flashover relationship shows a low positive correlation, indicating that as the size and volume of a space increases, the time to flashover increases. Time to Flashover is important for life safety, as a slow growing fire allows more time for occupants to escape. The tests examined in this study did include fully protected CLT compartments. When looking at the %exposed combustible CLT of walls plot, there is no correlation to time to flashover. For the %exposed ceiling plot, there is relatively no correlation as well, but again, there seems to be an outlier as well as a large space of missing data. The outlier is CodeRed #4 [137], one of the tests with a very large floor area of 352 m^2. The exposed ceiling plot shows a large variation in time to flashover. The fastest growing fires had 100% exposed CLT ceiling which coincides with observations made by Mitchel et al. The large gap in %exposed/combustible CLT ceiling indicates that more tests need to be conducted with more variation to get a better idea of CLT exposure’s relationship with time to flashover. Opening Factor and Fuel Load Density also do not correlate well with time to flashover. When looking at the plotted points how-ever, it can be seen that with a larger opening factor, it is slightly more likely that there will be a longer time to flashover. In general, more studies should be done with greater variations in floor area and %exposed CLT ceilings.

Duration of the fully developed fire is arguably the most important metric regarding the structural safety of a building since the longer the intense burning, the more charring occurs, thereby weakening the structure. When looking at duration of the fully developed fire, there is a low negative correlation with floor area, ceiling height, and volume. Meaning, that the smaller the space, the more likely the duration of intense burning will be, which coincides with the opening factor as well, and indicates a fuel-controlled fire will have a shorter duration of intense burning. The data however, does not include the experiments that underwent second flashovers due to failing protection or delamination and char fall-off. Regarding exposed timber, there is a very low correlation with the % of exposed walls which contradicts observations made by many of the tests. There is also a low correlation with exposed ceilings. On the exposed ceiling plot, a large variation exists where the shortest and longest durations of intense burning both had 100% exposed CLT ceilings. That said, there is still tendency to a low positive correlation. Meaning, the more exposed CLT on the ceiling, the longer the intense burning period. This agrees with the positive correlation between fuel load density and burning duration.

Regarding maximum fire temperature, there is a low negative correlation with ceiling height. Therefore, the lower the ceiling, the more likely the compartment will reach higher temperatures. This is true for floor area and volume as well where the smaller the volume, the more likely the compartment will reach higher temperatures. There is a positive correlation with fuel load density as well (R=0.7). The more fuel, the hotter the fire burns. Interestingly, however, there is little to no correlation between % of combustible wall finishes and maximum temperature, indicating that exposed CLT has little to no effect on the maximum temperatures reached.

Maximum HRR has a very strong positive correlation with the floor area and volume of a space. The greater the floor area, the greater the HRR. The increased HRR makes sense since larger spaces will have larger fires. There is almost no correlation between %combustible (exposed timber) wall finishes and maximum HRR but there is a low positive correlation with %exposed ceiling. The more exposure of CLT on the ceiling, the higher the HRR. Fuel load density has a low negative correlation (R=-0.45) with maximum HRR. This negative correlation is surprising and warrants further research.

Overall, the plots in Figure 4-3 suggest that changing the ceiling height is likely to impact time to flashover, maximum temperatures reached, and the maximum HRR. Changing the floor area will likely impact all fire dynamic factors, but especially the maximum HRR. The data in Figure 4-3 suggests that changing the amount of exposed wall surface is not likely to affect time to flashover, intense burning duration, temperatures, or HRR but this contradicts observations seen in the study. The contradiction may be because exposed walls have a greater impact or correlation on the overall duration of a fire or time to self-extinguishment, and/or other factors for which there was not enough data for this study. Therefore, it is paramount that more studies with exposed CLT walls are performed where data on burn-out and smouldering is obtained. A stronger correlation exists between % exposed ceiling and the duration of intense burning and maximum HRR. If occupancy changes are made, thereby changing the fuel load density, it is likely that the duration of intense burning, maximum temperatures and HRRs will change as well.

Structural Fire Engineers can use data such as duration of fully-developed (intense burning) stage, time to flashover, and maximum temperatures or HRRs to apply dynamic temperature changes to the structural elements and ensure the prevention of collapse. Fire Safety Engineers also need to determine that there is enough time for occupants to escape which is why the metric ‘Time to Flashover’ is so important.

4.5.2 Limitations and Future Research

The complex nature of fires makes the data collection and analysis subjective and susceptible to human error. An example is of this subjectivity is how the authors determined duration of a fire’s fully developed stage from time temperature graphs, or how other researchers determined duration of intense burning in their respective studies. Additionally, external factors such as wind, moisture, types of glue, etc., influence the fire dynamics, altering the outcome of the tests analyzed in this study, and explains the variability. Currently large-scale testing facilities are unable to consistently reproduce realistic fires [146]. The relatively low number of published full-scale tests results in low correlations.

To improve the accuracy of the correlations in Figure 4-3, it is necessary to gather more data. Areas that require more data include where gaps in plotted points can be seen such as more variation in larger compartment floor areas and more variation in % Combustible (exposed CLT) ceilings. Other fire dynamic metrics which did not have enough data for this study, thereby inferring a need for further research, are ‘Time to Burnout’, ‘Time to End of Smouldering’, ‘Max. Heat Flux Above Openings’, and ‘Max Flame Height Above Openings’. The research gaps in these areas indicate a lack of consensus among researchers as to which information should be collected from full-scale tests, how full-scale tests should be instrumented, and the fire performance metrics recorded. Full-scale compartment tests in the future should have standard instrumentation procedures in order to collect comparable outcomes for fire dynamics regardless of the architectural composition. Other fire dynamic metrics such as heat fluxes above openings, flame heights, smoke development rates, etc., could also be determined. Eventually, with enough data, it could be possible that probabilistic models could be formed.

This study could be improved by including the time it takes to reach certain life safety limits such as the point at which a human would not survive smoke or heat. It could also be improved by undergoing a deeper statistical analysis and include calculating the relationship (area of the graph) in which 90% of the data falls.

4.6 CONCEPT: A BIM-BASED VISUAL ALERT TO AID PARAMETRIC DESIGN AND DECISION-MAKING

Table 4-2 below summarizes everything learned in the chapter thus far. These learnings serve as the requirements and limitations for the desired solution to be successful. Based on these rules, the concept for a visual decision aid alert emerges.

Table 4-2: Chapter Summary Indicating Design Rules for Conceptual Solution

The Problem	Design decisions/changes causes expensive redesign of fire engineering
The Goal	Ensure decision makers are well-informed on the impacts of the design change
The Scope	How architectural changes effect the fire dynamics of modern CLT compartments
Known Information (Rules)	• **Understanding the nature of the problem, or the true impact of decisions without technical knowledge is problematic** • **Need a visual representation** of the design parameters before and after the potential change/iteration. • The **appropriate necessary information supported by technical knowledge** needs to be provided to the decision maker in a **representation that the decision maker can accurately interpret** • Communicate effectively to the decision-maker what kind of **uncertainty, risk, or conflict may be associated with the impacts** of design decisions and changes • **Data-driven statistical approach is acceptable for forecasting magnitude of impact** but not for accurately predicting outcome (based on current knowledge) • **BIM is a suitable interface** for cross-disciplinary coordination applications and data-informatics in AEC • **R-values indicate degree of certainty** regarding whether an architectural factor affects the fire dynamic outcomes
Unknown Information	• How exactly an architectural change impacts fire dynamics (FSE) of a CLT compartment • How much risk/uncertainty is associated with such changes • How effective would a visual decision-making aid be?

With the goal in mind, and what is known about BIM and decision-making in the AEC industry, the following solution is proposed: When design options are being generated, or a design change is being suggested, the Architect, Project Manager, or Owner is able to compare the effects of the changes on various performance parameters against the backdrop of the visual model itself. In a fully developed project, performance parameters would include things such as cost, time to completion, carbon footprint, operating cost, structural integrity, mechanical equipment, fire safety, etc. For this research, the focus is on architectural changes and how they affect the fire dynamics of a CLT compartment fire to inform fire safety. The results are especially useful in early stages of generative design when FSE is often excluded from the process. For the purpose of this study, the Initial Design will have met the design criteria. If the change in fire dynamics due to the proposed design change can be predicted, then the application can indicate to the user whether a re-design is necessary, or if more research is required, which can incur additional costs that the decision-maker did not initially realize.

A visual representation of the effects of the architectural change can be done by showing a bar graph, where the height of the bar indicates how improved/reduced a parameter (FSE) is compared to the performance target. The colour of the bars can indicate the degree of uncertainty, risk, and/or conflict. Upon clicking the bar for more information, the user can learn in detail, the justification for such a colour code. The justification is essential for the non-technically fire educated decision-maker. A representation of this concept can be seen in Figure 4-4 below.

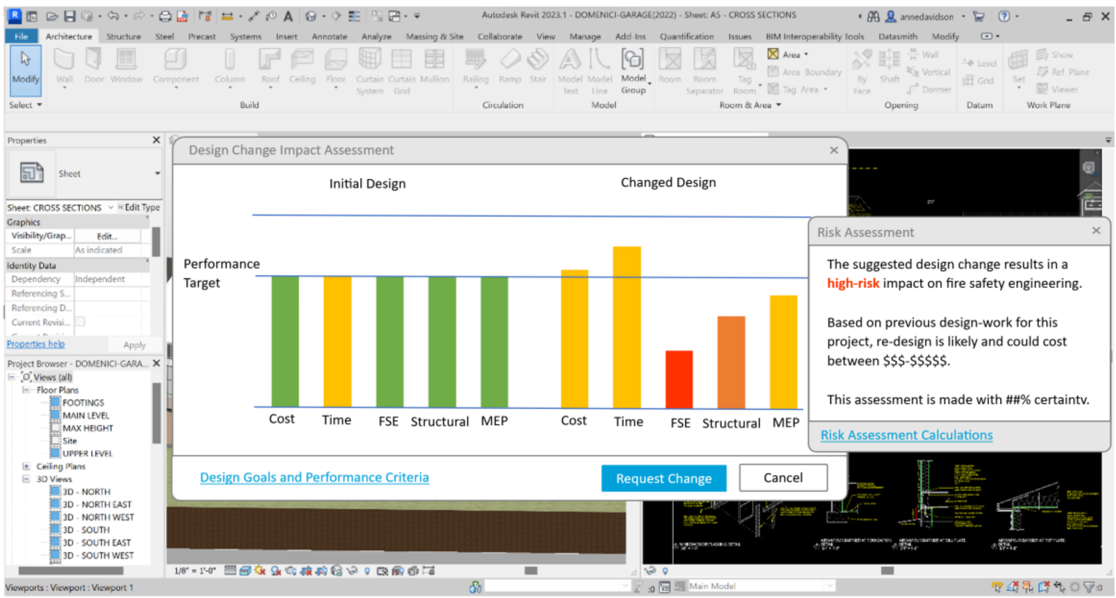


Figure 4-4: Conceptual BIM-based Alert to Aid Parametric Design Decision Making

However, to build this application, an input is first needed. The inputs for this study are architectural building parameters and statistical analysis on the performance of different CLT compartments in real fires. To further develop this concept, the next steps are:

1. Propose and test a protocol for design teams to decide on performance targets and acceptable limits to uncertainty and risk.
2. Propose and test a protocol for CLT compartment fire test database that would support application.
3. Build and test protype for usefulness.

4.7 CONCLUSION

In concluding this study, the most significant finding is the lack of data available on the real fire outcomes of mass CLT compartment fires. The second most significant finding is the lack of consensus on the method with which researchers have been obtaining fire dynamic metrics from full-scale fire tests as well as lacking consensus on what kinds of metrics are obtained. Since fire is complex, it is unlikely that practitioners will ever be in full consensus, however, the industry would greatly benefit from a standardized guideline on instrumenting large scale CLT tests and recommendations as to which fire performance metrics should be measured/studied. A surprising finding was that according to the analysis, there is a very low correlation between CLT wall exposure and fire dynamic outcomes despite qualitative observations indicating otherwise. The results indicate an overall need for more testing and improved understanding regarding the fire performance of CLT compartments.

This study is a first step in a numerical approach to quantifying the effects of design changes on fire dynamics in CLT compartments. The concept of a BIM-based alert for parametric design decisions illustrates how fire testing research can be used in the future and further highlights the importance for more data from future research.

CHAPTER 5

Benchmarking and Automating FRR Calculations with BIM

Rather than wringing our hands about robots taking over the world, smart organizations will embrace strategic automation use cases. Strategic decisions will be based on how the technology will free up time to do the types of tasks that humans are uniquely positioned to perform.

-Clara Shih

5.1 INTRODUCTION

In many cases a fire engineer must evaluate existing buildings, assess various fire scenarios, and design a fire protection plan that will ensure life safety. In Canada, CSA 086 design standard for wood uses a reduced cross-section method to evaluate the fire resistance of a structural member. The reduced cross-section method assumes a linear charring rate of 0.65 mm/min for all wood species. The US Department of Agriculture expands by providing charring rates for different species, although limited. Western Red Cedar for example, has a linear char rate of 0.82 mm/min [21]. A char rate of 0.82 mm/min is more severe than the one suggested for use in the Canadian code. Among the literature available however, some species lack any data at all. Among these is Eastern Hemlock, a wood found in southeastern Canada, stretching from Nova Scotia to southwestern Ontario.

In Ontario, many barns were built with Eastern Hemlock due to its strength properties and availability. Most of these barns are over a hundred years old, sometimes 200. Currently, the use of Hemlock is less common after land development and Hemlock Woolly Adelgids wiped out many of the species. To save a part of Canadian history, it is imperitive that these barns are rehabilitated. Fortunately, the large open space interior is easily adapted as a public gathering space. Many have been repurposed as restaurants, breweries, museums, and wedding venues. However, not without challenges. To ensure the public's safety, the re-purposed timber-frame must be able to withstand various loads and guarantee occupant safety, even in the event of a fire.

There exists a common belief that the cost to rehabilitate heritage buildings is more than it would be to demolish the structure and start anew which is not accurate. Publications such as *Barn Again! A Guide to the Rehabilitation of Older Farm Buildings* suggest that on average, the cost to build anew is almost double than that to rehabilitate [147]. That said however, there are always ways to make things more efficient and affordable. From an engineering perspective, the prescriptive reduced cross-section method of evaluating fire resistance is favorable to automations within a BIM environment using an internal integration approach.

For internal integration, for the automated calculation of a member's Fire Resistance Rating (FRR) using the reduced cross-section method outlined in CSA 086 Annex B, the structural members will need to be smart BIM objects. The BIMsmart structural element needs to contain geometrical information as well as structural and thermal material properties. Specifically, information on the charring rate of that material.

In this chapter, a demonstration of a FRR calculation according to the CSA 086 Annex B standard within the BIM environment is carried out. The scope will focus on a theoretical Eastern Hemlock barn beam. This chapter therefore is comprised of two parts: (1) Obtaining charring rate data through testing, and (2) FRR calculation demonstration within BIM. With the successful automation of FRR calculations for historic timbers, the prescriptive approach to FSE will be improved and hopefully entice a more affordable rehabilitation, ultimately encouraging the rehabilitation and continued life of Ontario's historic barns.

5.2 BACKGROUND

5.2.1 Eastern Hemlock

5.2.1.1 Physical and mechanical properties

Figure 5-1:Eastern Hemlock. Fig. A shows ring shake. Fig. B cross-grain

Eastern Hemlock (Tsuga canadensis) is a reddish-brown tinged wood with a light weight of 465 kg/m^3 [12]. Eastern Hemlock is prone to ring shake (Figure 5-1 A) and cross grain during seasoning and tends to split when nailed [12]. These kinds of defects affect structural performance goes, but most codes account for this with some fairly serious reduction factors assigned according to the visual grade of the lumber. The cross-grain image in Figure 5-1 B shows properties unique to Eastern Hemlock which help with identification. The absence of pores and resin ducts, abrupt transitions between earlywood and late wood (the rings), and a reddish-brown tinge with the absence of an odour all indicate that the wood species is Eastern Hemlock [12].

Table 5-1: Average clear-wood strength values for Eastern Hemlock in air-dry condition [12]

Mechanical Properties	Strength (MPa)
Modulus of rupture	67.1
Modulus of elasticity	9720
Compression parallel to grain, crushing strength max.	41.0
Shear strength	8.75
Compression perpendicular to grain, fibre stress at proportional limit	4.28
Tension perpendicular to grain	2.06

Table 5-1 shows the Canadian Forestry Service and Environment Canada's recorded strengths for Eastern Hemlock. It is worth noting that these properties are not presented in CSA 086. Most studies agree that the age of the wood in service, if kept in dry conditions, has virtually no effect on the wood's strength properties [12]. However, a more recent literature review by Cavalli et al. indicates that ageing has different impacts on different species, and though the strength properties are usually not affected, some species gain strength over time while others showed a reduced modulus of rupture (MOR) by up to 60% [148]. The reduced MOR, however, has been mostly attributed to the service conditions such as duration of load [148]. More research in this area needs to be done, especially for shear strength, but is out of the scope of this chapter.

Strength also depends on material defects, the angle at which the wood is cut, or the angle of the grain, Moisture Content (MC), and temperature. Perpendicular to grain, the strength is dramatically reduced, the dryer the wood, the stronger it becomes, and the more elevated the temperature of the wood, the weaker it becomes. More details on the effects of MC can be found in Chapter 2.

Since Moisture Content effects the thermal and mechanical properties of wood, it is worth noting that a MC of 12% is typically assumed for structural members since it is the MC factored into the structural properties by Canadian standards. However, Table 11.20a in the CWC Wood Design Manual provides a standardized way to predict the equilibrium moisture content (EMC) of wood based on temperature and relative humidity. In a conditioned space, where the wood has had sufficient time to reach equilibrium, in a country like Canada, where it can become quite dry in the winter, it is possible that wood may reach a MC of 4%.

5.2.1.2 Thermal properties and char rate

Thermal properties are not typically listed by species, but rather calculated theoretically using numerical models based on the density, Moisture Content (MC), and temperature of the wood. With increased temperature, the wood loses strength, and the cooler the wood, the more strength it has [148]. Up until 150°C, the relationship between strength and temperature is linear [148]. Up until 100°C, the effects are reversible when the wood returns to room temperature [148]. In general, the higher the temperature the wood is being heated at, the faster it loses strength.

While these thermal properties are useful for thermodynamic analysis, they do not provide the charring rate data required for the reduced cross-section method of calculating FRR. For that, charring rates need to be obtained. Charring rates vary for different species and vary over time. When the wood reaches about 288°C (accepted temperature criterion), it begins to char [21]. The charring rate at the beginning stages are considerably faster and gradually decrease over time due to the thermal insulating properties of char. So as the char layer increases, the wood beneath becomes more protected.

Natural aging of wood does influence char rate. In a study by Asseva, Serkov, and Sivenkov, a linear relationship was found between age and char rate, where pine that had been naturally aged for 150 years had a charring rate of about 150% of the original char rate [28].

The Heat Release Rate (HRR) of a material can also be calculated theoretically, but due to the organic cellular structure and properties, this is more difficult to accomplish accurately with wood. Therefore, testing is a good method for determining HRR. *The Encyclopedia of Wood*, published by the U.S. Department of Agriculture lists peak HRR, and average HRRs at 60, 180, and 300 seconds, as well as average effective heat of combustion and ignition times for a given 50 kW/m^2 heat flux during a cone calorimeter test. The species listed, however, do not include Eastern Hemlock. In Canadian resources, no such reference exists (to the author's knowledge).

5.2.2 Determining Char Rate from Experimental Testing

Currently, codes use linear char rates, which have been taken as the average char rate of wood exposed to a standard fire-resistance test [21]. However, the U.S. has accepted a non-linear char rate model developed by White and Nordheim discussed in Chapter 2 and other researchers have used the Cone Calorimeter for calculating linear char rate as well [27]. The White and Nordheim model involves calculations based on char contraction factors which can be calculated from experimental testing using a Cone Calorimeter.

5.2.3 Developing Fire Smart BIM Objects

Objects within BIM are associated with a multitude of information. An object could be anything from a floor to a window or door, to a beam or column. Anything considered on object in reality can be an object in the virtual BIM. The benefit of having highly developed BIM objects is that the information stored in the object can help save a lot of time, especially for code compliance. In a study by Doukari et al, a compliance checking algorithm was employed to the BIM objects, saving 125 minutes of manual labour per object [64]. The Doukari results are very impressive and a much-needed improvement in the design industry, especially when it comes to life safety.

For a timber member to comply to fire codes, it needs to meet the required FRR. In Canada, this is calculated using a reduced cross-section method in CSA 086 -Annex B. The smart object already contains the parameters required to carry out the calculation – with the exception of char rate. Once the timber member object is further developed to contain FSE requirements, such as char rate, FSE code compliance can be carried out, saving time. The prescriptive approach is suitable to "internal integration".

As discussed in Chapter 3, a literature review revealed that Revit by Autodesk was the most commonly used platform for BIM and that Dynamo was the most commonly used VBA for manipulating data and performing calculations. Python is the most used programing language within Dynamo and often used to build smart BIM objects. Therefore, the conceptual framework presented in this chapter will also indicate where these commonly used applications fit.

5.2.4 OpenBIM Material Performance Databases

When searching for the terms "open material database", literature regarding data mining, machine learning, and material-mechanical responses comes up. In the material science sector, the advantages of data-analytics are well recognized. However, there was little evidence of engineers and scientists beyond this sphere, especially for fire and thermal mechanics. What was provided was a small understanding and framework for what is required to harness data-analytics regarding the performance of materials. It was found that Python is the most popular coding language [149] [69]. Python is built in to popularly used tools such as Revit making it more accessible for engineering use. A number of open-source algorithms and libraries also exist for various material properties research [69] [150]. The benefit of these open-source resources is that non-professional programmers, such as material researchers or engineers, can use the data and algorithms more easily [69]. Talirz et al. agree with this and developed a web-hosted open-science platform for material science called "Materials Cloud" [151]. Although the database does not hold useful information for FSE or structural engineers, it provides exemplary protocol for the creation of such a database. In the field of FSE, an open-source material library can have a similar beneficial effect. There are many structural engineers who do not have training in FSE research and instead need more accurate data on the fire performance of different wood species and members.

5.3 CONE CALORIMETER TESTING

5.3.1 Methodology

5.3.1.1 Procurement

Parks Canada owns numerous properties whose old barns fall into disrepair. One such barn can be seen in Figure 5-2 below. At this level of dilapidation, the barn is considered unsafe and often carefully dismantled so that members can be re-used or utilized for research purposes. Parks Canada generously provided York University fire lab with a choosing of old members. The wood was brought back to the lab and identified using Environment Canada's "Key for Microscopic Identification of Woods Commonly Used in Canada". It was identified as Eastern Hemlock. Within the members collected, there were two identical connections.

Figure 5-2: Parks Canada Ontario timber-frame barn

5.3.1.2 Sample Preparation

Material from a salvaged beam of a timber frame barn dating to 1888, was cut into 30 100mm x 100mm Eastern Hemlock samples with a 45mm thickness. Most were cut with the face parallel to the grain. Some were cut perpendicular to grain. Each sample was labeled with its sample name which indicates heat and time exposures and sample number. All samples had been conditioned in a room at 21°C and 12%RH.

Before testing, the samples were weighed, measured, photographed, and wrapped in tinfoil, shiny side out, leaving the top 100mm x 100mm face exposed.

5.3.1.3 Measuring Moisture Content

A representative sample (not to be used in cone calorimeter testing but has been conditioned with all other samples) was placed into the oven for a period of time to evaporate any moisture. Once the sample is no longer changing in weight, it can be assumed that all the moisture has evaporated. Using the initial weight and the final "dry weight" in the below equation, the moisture content can be determined. By calculating the Moisture Content (MC) this way, it was found that on February 22nd,2023, the samples had a 9.8%MC, while on March 20th and March 27th, the samples had a 7.5%MC.

Equation 5-1: Moisture Content (MC)

$$moisture\ content\ [\%] = \frac{initial\ weight - dry\ weight}{dry\ weight} \times 100$$

5.3.1.4 Experiment Set-up

In Figure 5-2 below, the experimental set-up at the University of Waterloo Fire Lab is shown. On the left is the computer and Data Acquisition Unit (DAU). The Gas Analyzers and Cone Calorimeter are the large light grey units behind it. To the right of the units is a camera for recording the tests.

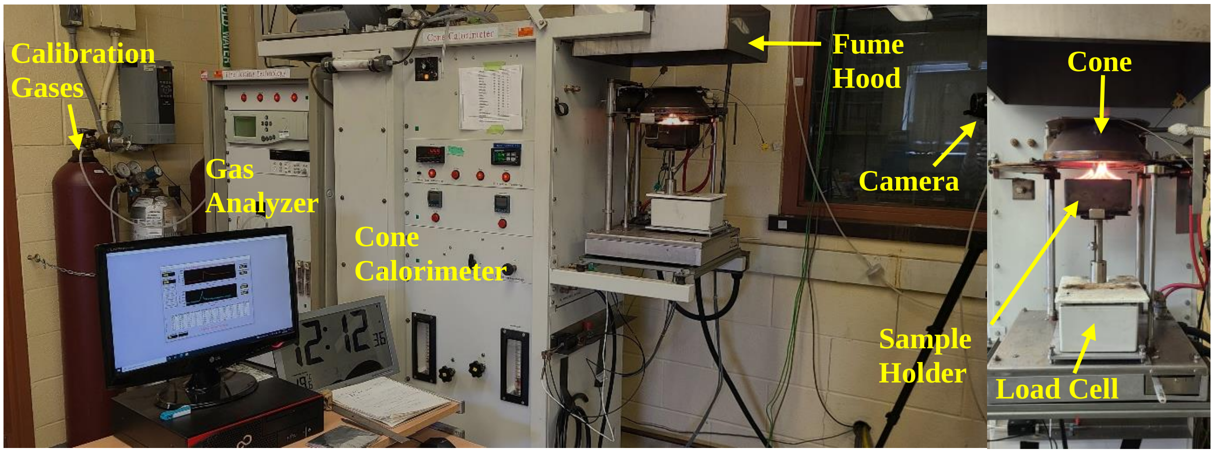


Figure 5-2: Cone Calorimeter experimentation set-up

5.3.1.5 Cone Calorimeter Testing

Once the sample is prepared and the Cone Calorimeter was calibrated and reaches the required Incident Heat Flux, a modified ASTM E1354 procedure can be carried out. The ASTM E1354 testing procedure was modified so that no igniter was used and that once the desired time was up, the sample was removed and cooled down with a light spray of cold water. A total of 30 tests were carried out with three samples (1 cut perpendicular to grain) exposed for 3,6,10,15, and 30 minutes at 30 kW/m^2 and 50 kW/m^2 exposures. These heat and time exposures were chosen for two reasons: (1) To provide a granular view of charring rates over time for different heat exposures, and (2) To mimic previously carried out research done by York University (Ontario, Canada), so that direct comparisons with other wood species may be made in the future.

5.3.1.6 Measuring Char Depth

To measure the char depth, the samples were cut in half. The char depth was then measured at the centre of the sample. Final thickness (t_f) was measured from the uncharred side up to the point at which there is char. The char depth measurement includes the discoloured pyrolysis zone as seen in Figure 5-3 below. Char thickness was also measured (t_c).

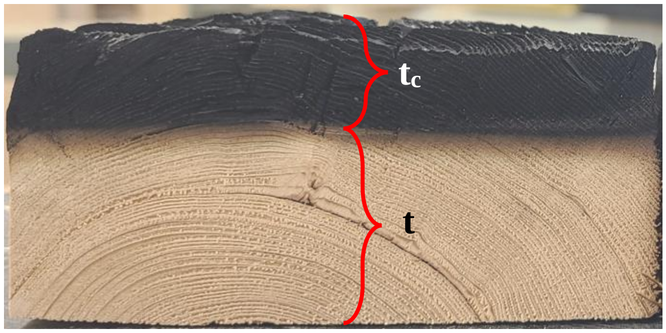


Figure 5-3: Measuring final thickness and char depth

5.3.2 Results

5.3.2.1 Cone calorimeter testing

From the cone calorimeter tests, the average of the results obtained for each heat exposure that can be directly compared against the U.S. Department of Agriculture database can be seen in Table 5-2 below. Taking all the tests into consideration, a maximum HRR and the average HRR were plotted over time for both 30 and 50 kW/m^2 exposures, as seen in Figure 5-4. It should be noted that only three tests for each exposure ran the full 1800 seconds, which is why there may be a jog in the data at around 900 seconds. It is for this reason as well that the average HRR lines are more accurate within the first 300 seconds and have more variation further on (because there are less tests from which to sample).

Table 5-2: Heat release data for Hemlock

Exposure (kW/m^2)	Heat release rate (kW/m^2) Peak	60-s avg	180-s avg	300-s avg	**Average effective heat of combustion (MJ/kg)**	**Ignition time (s)**
30	27	4	10	14	6.0	N/A
50	177	121	88.3	78	13.3	23

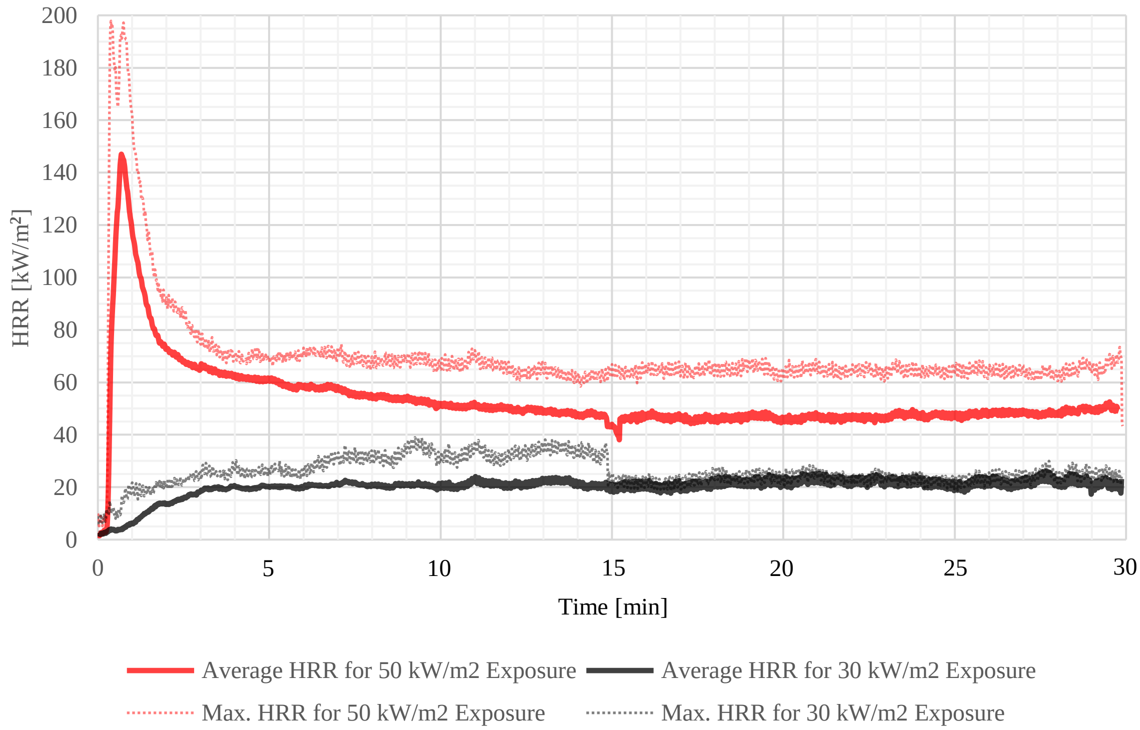


Figure 5-4: Average Heat Release Rate (HRR) over time for Eastern Hemlock

Another interesting metric is the specific Mass Loss Rate (MLR) ($g/s \cdot m^2$) which was obtained from the cone calorimeter. MLR represents how much mass is lost per second per surface area. Although it can be a very useful metric, it is not needed for calculating char rates or for reduced cross section method since the mass lost in experimentation does not include the mass of the char still present on the surface of the wood (which has no structural strength). Therefore, the plotted data for the average specific MLR of the tests can be found in Appendix A.

5.3.2.2 Char rates

The char rates obtained from the samples can be seen in the box and whisker chart (Figure 5-5). Each box contains at least three data points. Figure 5-5 shows that the greatest variation in char depths between samples occurs for 15-minute tests while 3-minute tests have relatively low variability in char depths. The average linear char rate for each constant heat flux exposure was calculated and is summarized in Table 5-3 along with the average mass loss rate and char contraction factors. This is then illustrated in Figure 5-6, which shows the average of experimental results vs. the White and Nordheim non-linear model (calculated from char contraction factors) for predicting char rates under ASTM E119 exposures. For this, the average sample MC of 8.2% was used.

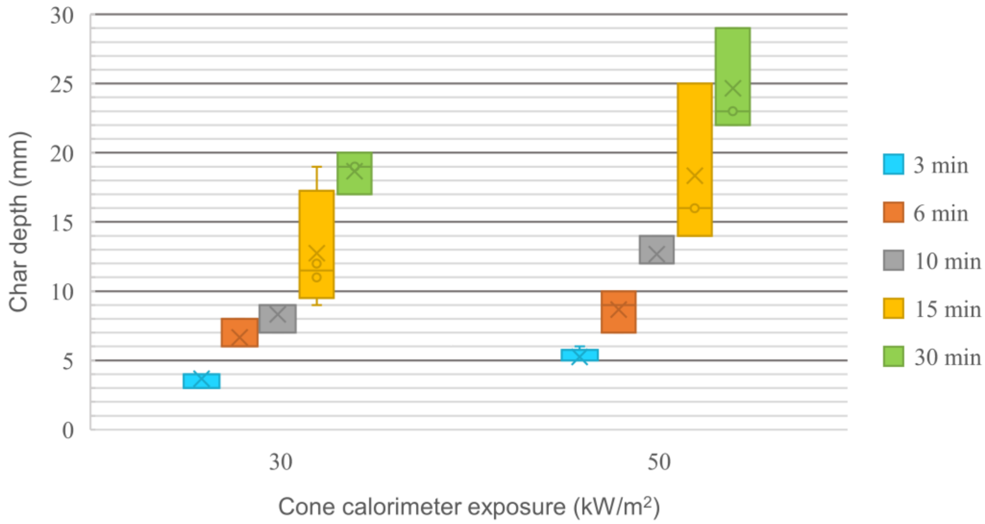


Figure 5-5: Char depths after different durations for different heat exposures

Table 5-3: Eastern Hemlock exposed to constant heat flux

Heat Flux Exposure (kW/m^2)	Char contraction factor	Linear charring rate (mm/min)	Average mass loss rate ($g/s{\cdot}m^2$)
30	0.89	1.00	5.05
50	0.88	1.42	8.35

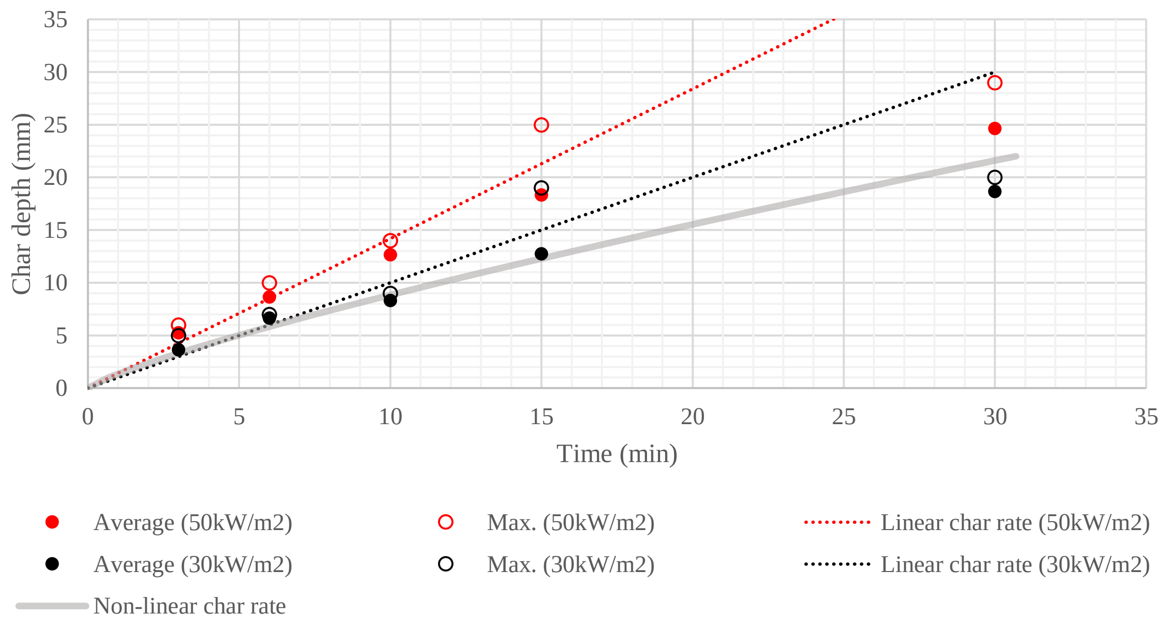


Figure 5-6: Char depth over time for constant heat flux exposure

5.3.2.3 Observations

When measuring the char depths of the various samples, the sides of the sample that were not fresh cuts but rather wood that has been exposed to air for 100+ years, had deeper charring than other portions of the sample that did not have the same air exposure durations. An example of this can be seen in the Figure 5-7 A below where the aged side is considerably darker. Another interesting observation was that if a knot was exposed to the heat flux, it would remain raised while the wood around it would reduce. When cutting the sample in half, through the knot, the ultimate char depth remained fairly consistent despite the presence of the knot (Figure 5-7 B).

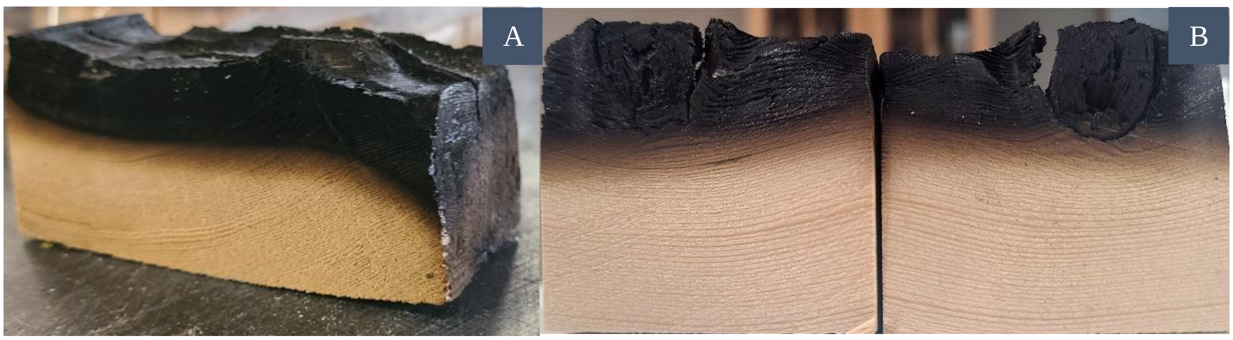


Figure 5-7: Charring behaviour observations

Additional observations include time to off-gassing and ignition time. None of the samples exposed to 30 kW/m^2 heat flux ignited but perhaps they would have if there was a spark since off-gassing was observed. A typical 50 kW/m^2 sample burn test, all of which ignited, had the following sequence of observations as seen in Figure 5-8, which illustrate the insulating qualities of the char, and explains the initial high HRR and char rates.

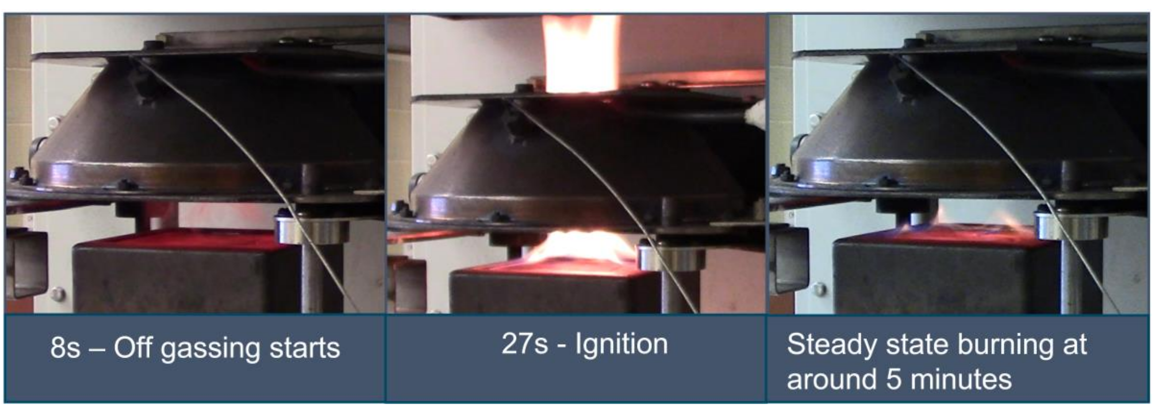


Figure 5-8: Cone calorimeter sequence of observations

5.3.3 Discussion

When comparing the results for the moving average HRR of samples exposed to a constant heat flux of 50 kW/m^2 summarized in Table 5-3 to those published by the U.S. Department of Agriculture for Red Pine, White Pine, Eastern Redcedar, and Redwood, in Table 17-3 of [21] the aged Eastern Hemlock fairs well. The 60-s average HRR of 121 kW/m^2 is the median value when comparing these species. The 300-s average of 78 kW/m^2 is lower than any other species which indicates that Eastern Hemlock may contribute less heat to the overall growth of a fire compared to other species of wood. The low contribution of heat is useful to know since in Chapter 4, it was discovered that current research lacks the ability to accurately predict time-temperature curves of wooden compartments. Knowing that the Eastern Hemlock contributes less energy to a fire than a typical wood adds some conservativeness to the assessment.

The charring rates in Figure 5-5 show the greatest variation for 15-minute tests for both heat exposures while the shorter 3-minute tests have less variation. The difference coincides with the HRR, where the initial stages of heating and burning tends to have less variability. Since most of the samples had the same MC, the variability could likely be due to physical defects such as knots and ring shake. However, this is unlikely to affect the char rate in a significant way since previous research by Harun et al. found that checking (cracks) did not significantly affect the propagation of char. The observations of this chapter's testing series observations reinforce those made by Harun et al., where many of the samples if they had cracks, did not seem to affect the propagation of char. The sample in Figure 5-8 shows the char rate through a knot, and although the surface of the knot did not burn away as quickly as the wood around it, the char front within the sample is even all the way across. Therefore, the defects do not significantly impact the reduced cross section, which makes it easier for FSE to predict the outcome of the structural performance of wood members during and after a fire.

The charring rates can be seen better in Figure 5-6 where samples at both 30 and 50 kW/m^2 heat flux exposures show a logarithmic trend. The non-linear model by White and Nordheim fit the 30 kW/m^2 exposure well, better than the linear model, but does not fit the 50 kW/m^2 exposure. This is likely because the non-linear model was designed for the char rate of a member exposed to a standard fire curve rather than a constant heat flux. For the 50 kW/m^2 exposure, the linear char rate model overestimates char depth beyond 25 minutes. This is fairly irrelevant for smaller members that, in a real fire, would completely burn up. However, for mass timber members such as 12"x12" columns often found in barns, the linear char model could be a gross over-estimate for a 60-minute fire.

The char contraction fire is an interesting metric because it quantifies the relationship between the total depth of the char with the thickness of the char. The char contraction factor at the knot for example is greater

(1 as opposed to 0.89) than char for clear wood. However from these experiments, there was almost no difference in the char contraction value between 30 and 50 kW/m^2 heat exposures. The char contraction factor of 0.88 does differ to the published char contraction factor of Southern Pine (0.60) [21]. The differences suggest that the char contraction factor is dependent on species but not necessarily heat exposure.

5.3.3.1 Limitations and Sources of Error

The limitation of this research is that char rate is dynamic and not necessarily linear. It depends on heat exposure, not just time exposed. In a real fire the incident heat flux on the member changes over the course of a fire and changes the char rates.

There is an aspect of human error associated with this research. For example, measuring the char depths with a ruler by eye.

Instrumental error is also possible. A few tests had to be redone because the software for the cone calorimeter froze and stopped collecting data mid-way through the test. There was one day that the load cell could not fully calibrate and was showing mass loss even without a fire. It had to be recalibrated to a larger mass, then back to the mass used for these samples to ensure accurate results.

5.3.3.2 Recommendations and Future Research

I would be useful to do more cone calorimeter tests at 17 minutes and also at 45 and 60 minutes to see if the char rate continues to slow down further into the test. The longer tests times would also be useful for calculating more accurately the char rate over longer periods of time and the char contraction factor. More cone tests should also be done at various heat fluxes, not just 30 and 50 kW/m^2, since heat flux significantly affects the char depth.

Additionally, more tests should be done where the aged wood is exposed to the cone calorimeter rather than being on the side of the sample. Tests in this way could quantify how much the aged surface affects the char rate. Because char rates are influenced by species, to determine the full effect of aging on the char rate of Eastern Hemlock, more testing needs to be done on various degrees of aging. In this experiment all the samples were cut from the same member.

It would be interesting to see if the non-linear char rate model could be adjusted to account for different heat flux exposures. This, however, would require many more tests so that the variables could be derived statistically, complimenting how the model was initially developed.

5.4 CONCEPT: BIM-SMART OBJECT - AUTOMATED FRR FOR TIMBER

5.4.1 Motivation

The parameters required to calculate the reduced cross section after fire, according to CSA086 – Annex B, are the dimensions of the member, the member's side exposures, the mechanical properties of the wood species, the one-dimensional charring rate, and the fire design load. Annex B offers a simple analytical equation for calculating the reduced cross-section leading to the FRR which is favourable to automation. By automating the FRR of structural timber members, FSE becomes more accessible to individual owners who might want to save their barn. For new builds, and automated FRR of timber structural elements can improve cross-disciplinary collaboration and understanding since the architect or structural engineer can easily and quickly see how the FRR might be affected by changing the dimensions of the timber or the placement. An automated approach would also lay the groundwork to allow for parametric design during the early stages, when FSE is often excluded from the conversation.

5.4.2 Proposed Framework

By way of the schematic shown in Figure 5-9 below, the reduced cross section can be calculated by one of three ways:

Option 1: Calculate FRR within the BIM platform (Revit in this example). This is done by using the Dynamo plugin to extract the required FSE parameters from the model. A python script can then run the desired calculations and change/update the BIM (IFC model and Revit).

Option 2: Export FSE required parameters for each timber element into excel where the fire engineer can easily check the data and run the calculations. After which, the results are imported back into BIM and FRR requirements are updated.

Option 3: Option 1 and/or 2 with the added synchronicity to the cone calorimeter data base. As more research is being done, the database is updating, and a more accurate char rate can be obtained.

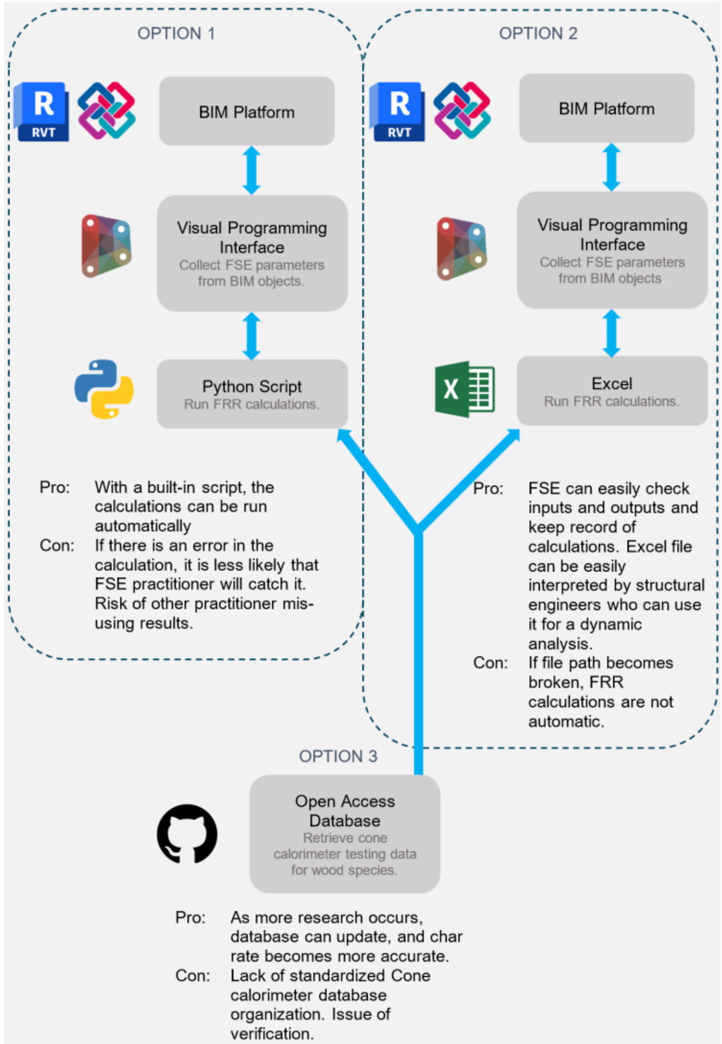


Figure 5-9: Framework for automating FRR calculations by utilizing BIM

5.4.3 Challenges and Future Research

It is difficult to modify IFC files and object parameters in many proprietary BIM platforms, such as Revit. There is an added difficulty that many of the FSE parameters are not included in IFC. With lack of standardized data structures for IFC, the framework above needs to be built and used by each stakeholder individually for the specified parameter names of reduced cross section, especially if the information is to be shared with a structural engineer.

Lack of education on BIM and lack of open access code and data sets, make it very difficult for individuals to take advantage of the full benefits of BIM. Instead of having literature, tutorials, or course work to train an individual on automating calculations in a BIM environment, each individual must learn by trial and error. The trial and error approach is likely because most of the instances where FRR automation has been applied, are proprietary.

The benefit of building in an automated FRR function like the one mentioned, is that this reduced cross section, could be used during the parametric design. As the architect or engineer changes column spacing for example, the size of the columns will be affected; they can automatically resize according to FRR (which typically governs the cross-sectional size for mass timber). This is a step towards the cross-disciplinary understanding that was discussed in Chapter 4.

5.5 CONCLUSION

Eastern Hemlock is the material used to construct many of the heritage timber framed barns of Ontario. There was no data on how this material performed in fire. To calculate the reduced cross section due to charring, the char rate data for Eastern Hemlock had to be collected. Thirty samples were tested with the Cone Calorimeter apparatus, at the constant heat flux exposures of 30 and 50 kW/m^2. None of the samples exposed to the 30 kW/m^2 heat flux ignited while all of the samples exposed to 50 kW/m^2 ignited at an average time of 23 seconds. Using the Cone Calorimeter allowed for the collection of data pertaining to the fire load of Eastern Hemlock, such as HRR. The samples exposed to 30 kW/m^2 heat flux, had a 300-s average HRR of 14 kW/m^2, and 78 kW/m^2 for 50 kW/m^2 exposure. At the point of steady burning, the samples exposed to 30 kW/m^2 had a fairly steady HRR of 23 kW/m^2, while the samples exposed to 50 kW/m^2 had a steady HRR of around 48 kW/m^2.

Because the tests were run for different durations (3,6,10,15, and 30 minutes), the samples could then be cut in half and the char measured. The study yielded average linear char rates of 1.0 mm/min for 30 kW/m^2 heat flux, and 1.42 mm/min for 50 kW/m^2 heat flux. These char rates compare well with that of other softwoods. During the testing, it was observed that material defects such as knots did not affect the char front. The side of the samples that had been exposed to air for over 100 years however, experienced deeper char penetration. The deeper char layer agrees with research on the relationship between natural aging of wood and char rates. How this effects Eastern Hemlock as a species requires more research.

The char rate for the 30 minutes tests suggests a non-linear char rate. However, more tests should be done at 15 minutes, and 40 minutes to evaluate this more closely. While the non-linear char rate model by White and Nordheim fit the char rates of the samples exposed to a 30 kW/m^2 heat flux, it did not fit the char rate for the 50 kW/m^2 heat flux. Heat exposure is evidently a parameter affecting char rate. Perhaps White and Nordheim’s non-linear model could be adapted for such a parameter rather than being purposed for a standard fire curve. As noted in Chapter 4, standard fire curves do not occur in real-life timber compartment fires.

The need for more research leads to the need for an open-access database of char rate testing for wood samples. The larger the database, the more statistical inferences can be made, and perhaps, in future research, a new char rate model could be proposed. The cone calorimeter testing data will be added to York University's fire research team's growing database. Before giving open-access to the database, more research and protocol on how to publish and manage such a database without compromising the integrity of the research needs to be carried out.

With the charring rate determined, the reduced cross section can be calculated. The calculation method (CSA 086 – Annex B) for determining the reduced cross section of a member is favourable to automated calculations, creating a Fire-smart BIM object. A Fire-smart BIM object can be developed in a number of ways, but without standardized data schema for FSE requirements and results, it is difficult to effectively construct and demonstrate. The framework options provided in this chapter offer the most likely accessible procedural approach, by today's standards, to attaining a Fire Smart BIM object. In the future, once an IFC data structure and MVD is developed for FSE, research demonstrating this concept will have a greater impact due to the universal structure of the outcome. More research on evaluating the usefulness of such a feature should be carried out before further developments.

CHAPTER 6

Fire Performance of Heritage Hemlock Connections

"If we don't care about our past, we cannot hope for the future… I care desperately about saving old buildings."

– Jaqueline Kennedy Onassis

6.1 INTRODUCTION

When thinking of Canada, vivid images of vast beautiful landscapes come to mind. Landing in Toronto, a visitor is first greeted by one of North America's densest modern cities, with soaring skyscrapers and a colossal network of freeways spanning up to 18 lanes of traffic. Driving a little further from the urban sprawl, one can begin to see the countryside the city was built on: rolling hills of rich soil, fields upon fields intertwined with hardwood forests, flowing creeks, and the splendidly diverse vernacular architecture. The most notable being the lofty wooden barns sprinkling the landscape with the remains of a pioneer's story. It is an amazing contrast to see how far civilization has come in a relatively short period of time and yet, it is easy to forget.

Despite their monumental presence and inherent multi-use potential, the old barns of Ontario are endangered. Unfortunately, these soaring cathedral-like structures have been slowly disappearing, falling to the ailments of wind, snow, rain, biota, fire, and neglect. The under utilized and neglected barn often falls into disrepair and demolished to make room for economic land development. This was the case of a 130-year-old barn at 247 Halls Mills Rd. in Byron, Ontario, where the owner demolished the barn two days after the city expressed interest in the barn's heritage significance [152]. The property is planned to be developed for housing in the future [152]. One of the arguments developers use to dispute a barns historical significance, is that the barn has been modified over the years, therefore it is not original, therefore it is not significant. Modifications and additions to vernacular architecture is common however, and intrinsic in their value. Timber framed barns especially, were built with alterations and future additions in mind. The very nature of a timber-framed barn, or bent construction, "allows for expansion bay by bay as required, in time with the development of the farmhouse and overall property. The timber frame explains the long history of wings, tails, and lean-tos, added on by increments, that distinguish so many of Ontario's houses and barns" [153]. The typical evolution of a timber frame barn in Ontario can be seen in Figure 6-2 where the change displays a farming family's progression and success over time.

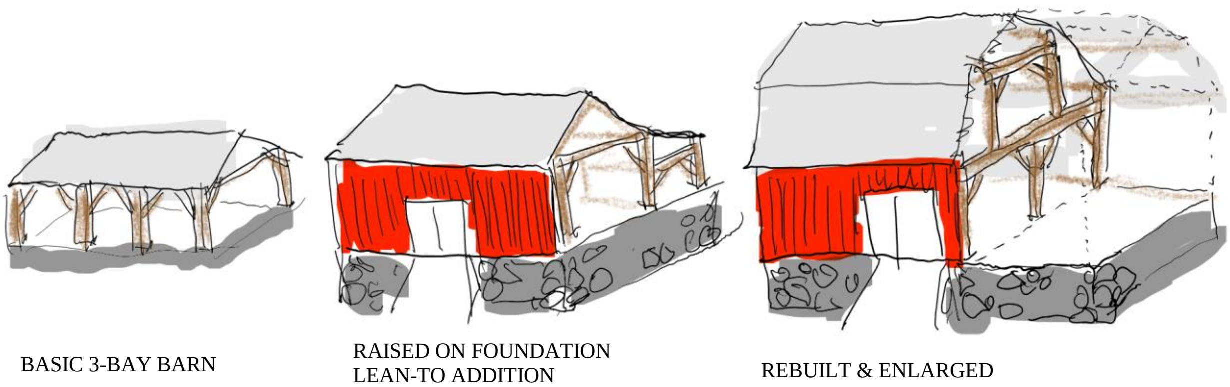


Figure 6-2: Evolution of the frame barn adapted from McIlwraith [121]

One of the character defining elements of a traditional mass-timber framed building is its pegged connections, often referred to as mortise and tenon connections where large beams and columns are carved to fit together and held in place with higher-strength wood pegs rather than screws/nails. This type of connection is visually described below in Figure 6-3. In the event of a fire, the connections of a structural frame are often the most vulnerable. Because they are a character defining element of a timber-frame, they should not be covered up as a method of protection. Research on the thermo-mechanical response of heritage timber connections (Eastern Hemlock) does not exist, nor does it exist for contemporary structures.

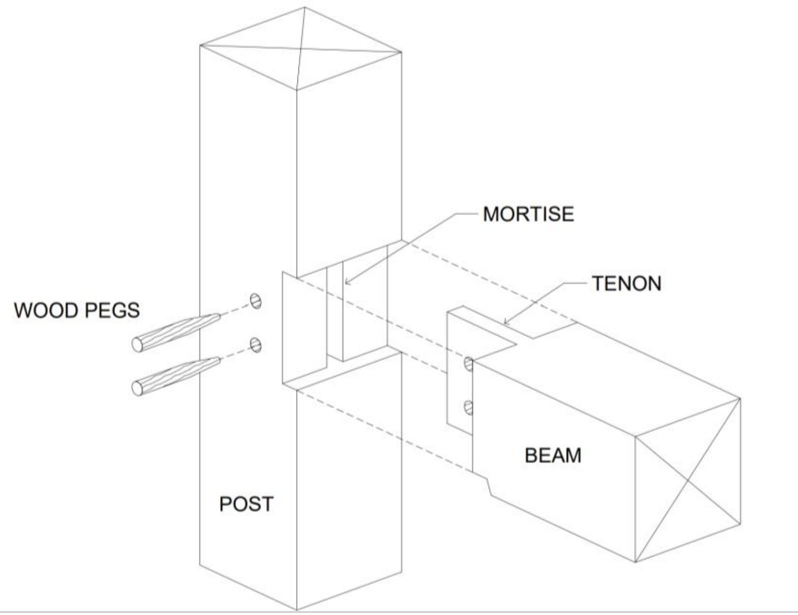


Figure 6-3: Mortise and tenon beam-column connection

The purpose of the research detailed in this chapter is to build on the last chapter and determine how a traditional timber-frame connection performs in fire. These are all of use towards a first-stage computational model to predict material degradation. Of the salvaged materials, there were two identical Eastern Hemlock column-to-beam connections. The connections were constructed using traditional methods employing a fully housed mortise and tenon (Figure 6-3). The Eastern Hemlock heritage connection underwent a full-scale burn test that utilizes state-of-the-art narrow spectrum illumination for better observation of thermal degradation. The damage due to charring is then presented and compared to the prescriptive calculation from Chapter 5. The Chapter concludes with key observations, findings, and suggestions for building a predictive model.

6.2 BACKGROUND

6.2.1 The Heritage Wood Connection

6.2.1.1 Description

The connection tested is an Eastern Hemlock fully housed mortise and tenon connection (Figure 6-4). Mortise and tenon connections are technically semi-rigid, but for structural analysis, is considered pinned by standard. The column member with the mortise is a hewn timber, meaning it was shaped and formed using an axe. The beam member with the tenon was rough sawn. The hewn finish indicates that the column member is likely older than the beam member and repurposed. This agrees with the un-used notches in the column member as seen in Figure 6-5. Due to the hewn characteristic and the vertically aligned 1-1/2” pins[2] it is likely that this member dates back to the early 1800’s [154]. The sawn beam and metal brace were likely added somewhere in the mid-late 1800’s because though the beam is sawn, the pins are large, and the metal brace seen in Figure 6-5 was for holding in place a wagon-rack-lifter (which was in storage beside the procured connection).

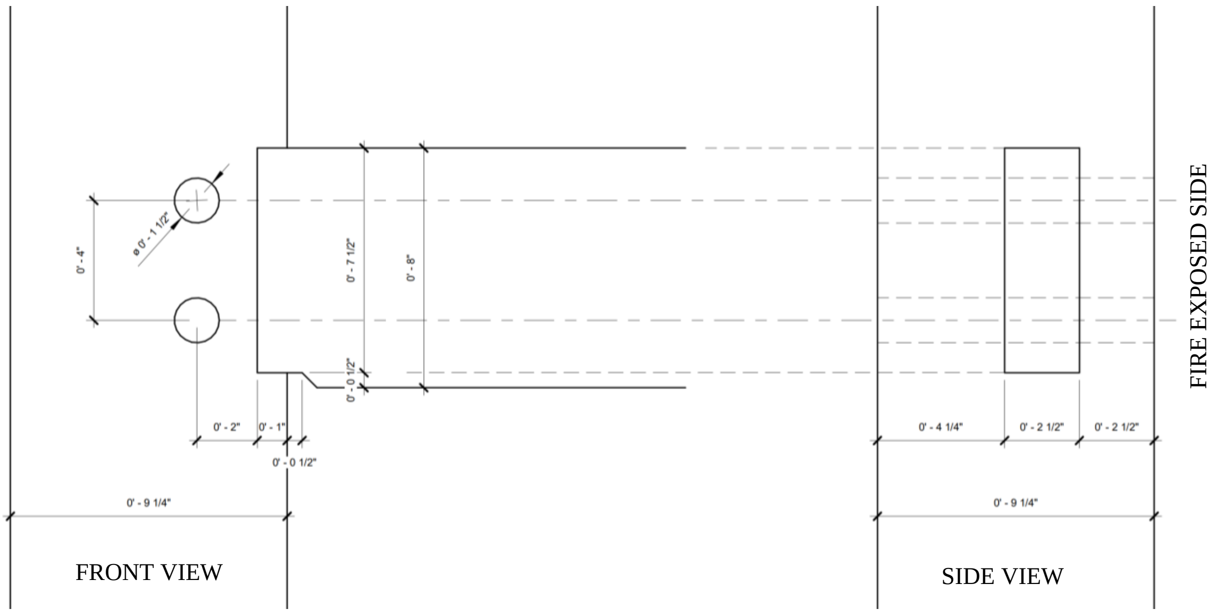


Figure 6-4: Dimensions of fully housed mortise and tenon heritage connection being tested

6.2.2 Wood Connections in Fire

What is known about the performance of wood connections in fire is described here. First, an overview of the prescribed approach will be offered, then a short summary of current research regarding wood connections and the testing methodologies.

6.2.2.1 Current code requirements

In the Canadian code for evaluating the FRR of connections, there is little information save a reference to both the *American Wood Council’s Technical Report 10* and *Eurocode 5-Part 2*.

The *American Wood Council’s Technical Report 10* gives an equation for calculating sufficient wood cover (protection) of the connection [155]. In a worst-case scenario, the wood coverage (plug) would burn through, the depth of which is determined by the char rate and required FRR, but this example describes a steel connection protected by wood. For traditional timber framing, there is no steel. The “bolt” is actually a wooden peg, so when the peg starts to burn, the capacity of the peg will be reduced. As the beam and

[2] Ontario barns in the early 18^{th} century used pins that where between 1-1/4” and 2” in diameter [154]

column cross-sections decrease, the higher the stress distribution in the members, and the higher the concentration of stresses on the connection (and pegs).

The *Eurocode 5-Part 2* also does not consider traditional timber-frame connections in their approach to fire design for wood connections. They do however offer a simplified FRR of 20 minutes for dowel (i.e. peg) connections. Although, the dowels considered in *Eurocode 5* are steel.

6.2.2.2 Current research

Most research on the fire performance of connections for mass timber construction focus on steel-to-timber joints for engineered glulam. Zhang et al. develop a numerical model to assess the thermos-mechanical response of dovetail connections and validate it with full scale tests under ISO 834 fire conditions [156]. The wood used in this experiment, though, was engineered glulam rather than a solid and/or aged timber.

Even research on the mechanical performance of wood-wood connections using wooden dowels, such as the mortise and tenon, are lacking [157]. Brandon compared a wood dowel connection to a metallic dowel connection and found that when the connection was cut in half, the wood dowel did not allow for char to propagate into the connection, whereas the wood surrounding the metal dowel experienced charring [157]. Brandon also tested for creep of wood doweled connections for which there is very little literature. All of the experiments in Brandon's PhD dissertation, however, did not include traditional timber samples, and were also glue-laminates.

From what the author could find, the only published literature on traditional timber framed connections with aged timber were not mortise and tenon connections. Therefore, there is no current literature on the fire performance of heritage mortise and tenon connections for aged timber, especially Eastern Hemlock, as far as the author is aware. The complexity of fire dynamics brings to question if there are any special differences when burning heritage timber and how it contributes to the fire. For example, does aged solid wood produce a lot of embers when it is burning, which would contribute to a faster spread of the fire? How severe is corner rounding at the connection? These are just some of the questions the author aims to address in this chapter.

6.3 METHODOLOGY

6.3.1 Sample Preparation

Before any preparations, the connection was completely recorded using photography and hand measurements. The connection was prepared according to Figure 6-6 where the ends were wrapped in rockwool insulation so that the fire could be isolated to the connection only. As indicated in the figure, three thermocouples were placed into the connection: one in each peg, and one in the centre between the two members. Each thermocouple was placed approximately 1” into the cervices. However, thermocouple TC2 is placed closer to the surface than TC0 due to the tight fit between the peg and the peg hole.

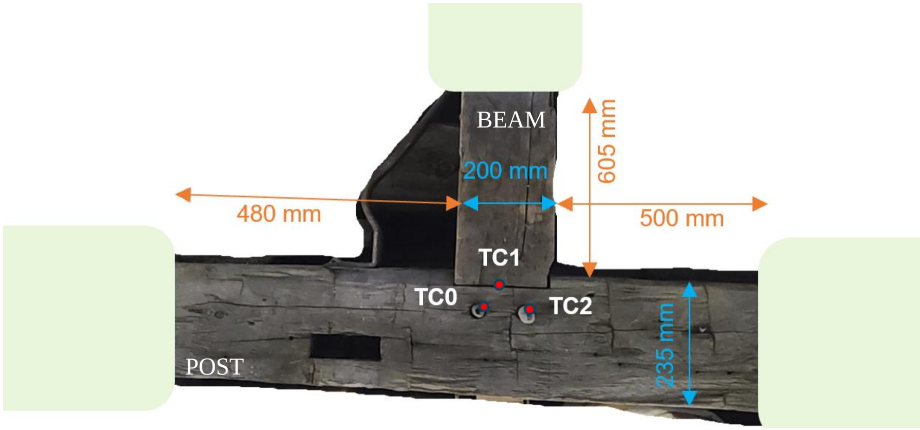


Figure 6-5: Connection sample preparation (top view)

6.3.2 Experimental Set-up

The fire research team, under Dr. John Gales’ supervision at York University, collected a baseline of data for temperatures above a methanol pool fire using fuel pans which are the same size as those at the Waterloo fire research facility. From this baseline data, it was found that at a distance of 200 mm above the fuel pan, a decently consistent exposure temperature of 700-750°C occurred. Therefore, it is specified that the bottom of the connection be placed 200 mm above the fuel pan to ensure quick ignition and to simulate exposure to a real fire. For a 30-minute burn, 8 L of Methanol was needed.

The cameras and blue lights were set-up in the configuration shown in Figure 6-6. The camera in the centre with direct view of the mortise and tenon had a blue light filter attached to it, generating the images seen in the results section. This method is called narrow spectrum illumination. By illuminating the sample with high intensity narrow-spectrum lights, researchers have successfully been able to filter out the light emitted from the flames, making the surface of the sample visible during the burn [158].

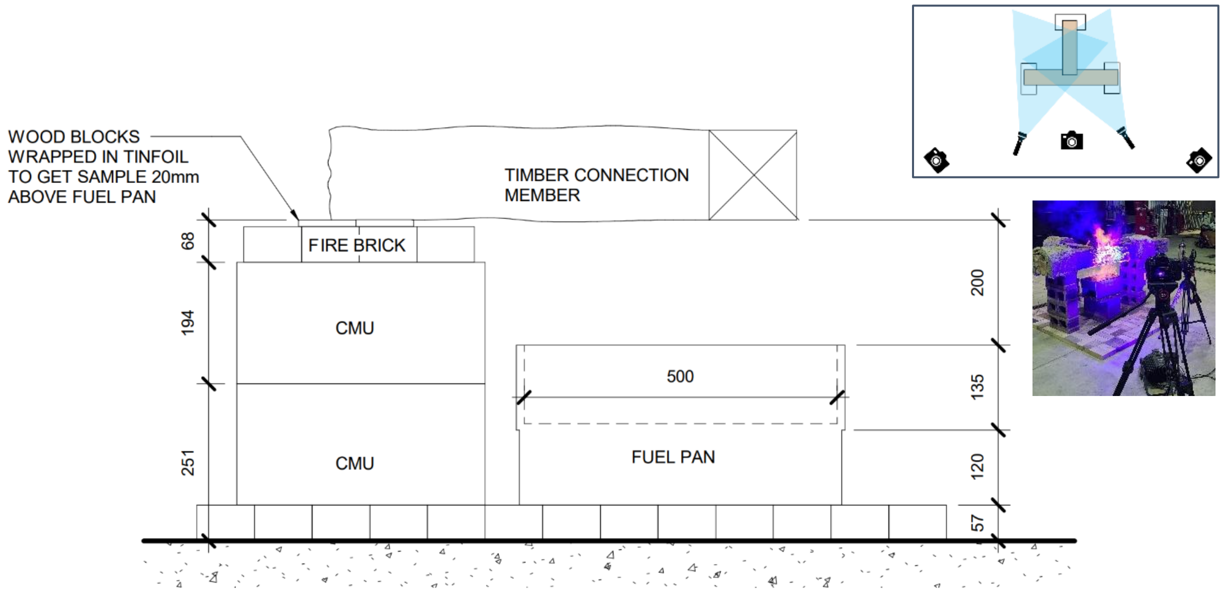


Figure 6-6: Cross-section of test set-up. Bottom of timber connection is 200 mm above top of fuel pan. Top right-hand corner is an areal view of test set-up showing blue light and camera positions.

6.3.3 Fire Testing Procedure

The two cameras of the far left and far right were set to record video. The camera in the front-centre was set to automatically take a photo every 5 seconds. Once the thermocouples had achieved 10 minutes of baseline data, 8 L of Methanol fuel was added to the fuel pan and ignited. At 28 minutes, the fire was put out and the connection was doused with water by gently pouring rather than spraying to avoid damage to the char.

Figure 6-7: Cooling down burnt connection.

6.3.4 Char Removal Procedure

Once the connection was back at York University's lab and photographed, the char was carefully removed. The char was removed by using palm sanders. To remove the bulk of char, 80 grit sandpaper was used initially and then changes to 120 grit. For tighter spaces, the char was sanded off by hand rather than using a palm sander. Sanding was discontinued once the wood grain was visible. The result is the reduced cross section after the burn. Sanding inside the mortise and any other voids was evaded.

Figure 6-8: Connection with removed char

6.4 RESULTS

Although the originally planned test duration was for 30 minutes, the fear of the member failing prompted an early end to the test. The fuel pan was covered (smothering the fire) at 26:17 minutes. The fire was extinguished from the connection at 28:22 minutes.

6.4.1 Thermocouples

The thermocouples placed within the connection are shown below in Figure 6-9. The time in minutes shown below has been adjusted so that the point at which the fuel was ignited is time=0. Interestingly, Figure 6-10 shows that the thermocouple placed in the crevasse between the two connecting members starts experiencing higher temperatures relatively quickly, then slowly increases at a rate of just over 1°C/min. The thermocouples in the left and right pins increase at a steadier rate with no initial jump in temperature, suggesting that the interface between the pins and the members is a fairly tight connection as opposed to the interface between the two members that is not as snug, thereby allowing more heat to infiltrate. The likely reason why the right pin experiences greater temperatures is because the pin was placed at a shallower depth than the one on the left, thereby being more exposed to the heat.

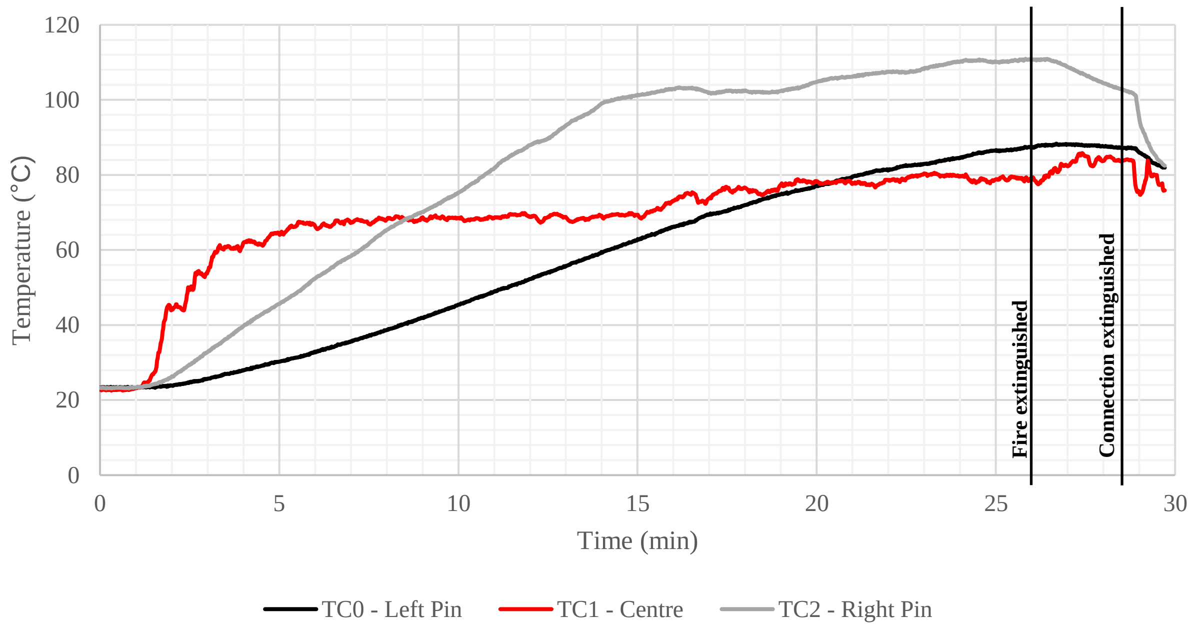


Figure 6-9: Thermocouple temperatures during the connection burn

6.4.2 Narrow Spectrum Illumination Observations

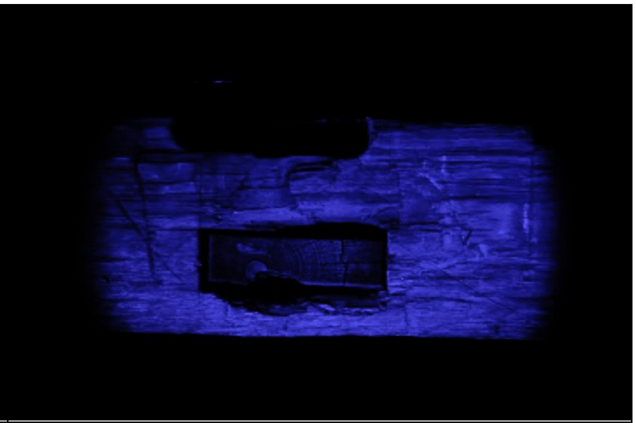
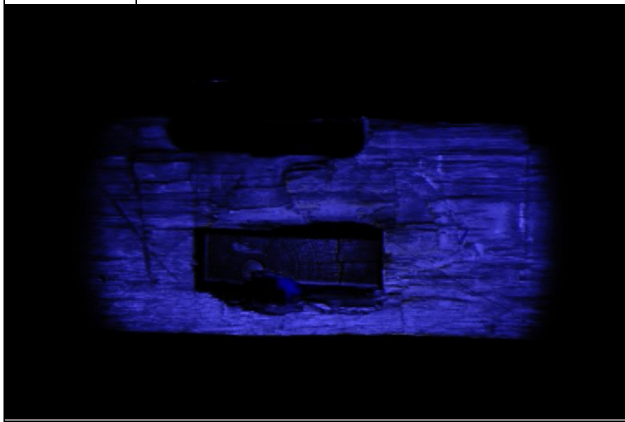
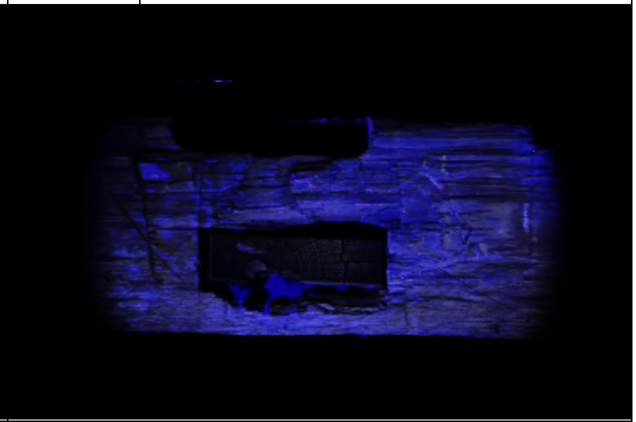
What is shown in Table 6-1 are the blue light images overlayed on top of the first image. This way the blue-light image showing charring can be directly compared against the connection's original state. From beginning to end, the positioning of the tenon inside the mortice remains relatively unchanged (suggests that the member is not deflecting).

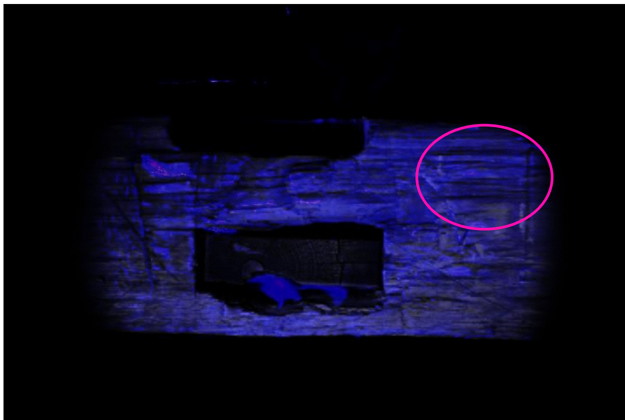
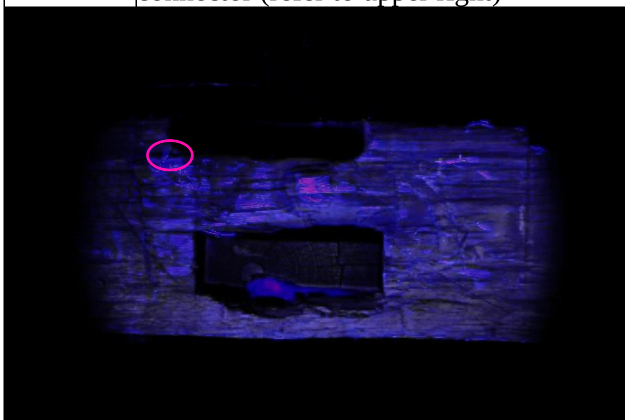
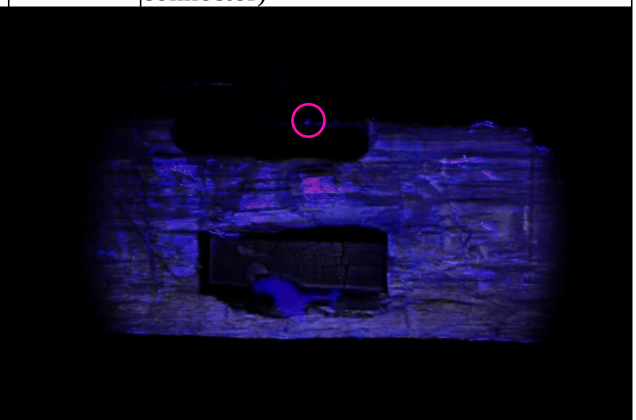
The progression of photos shows the charring phenomena well. Relatively soon (2.42 min), the connection is fully involved in charring. As the wood fibres become dehydrated, they contract. At 3.50 minutes, the wood fibres are still intact. In the next photo, at 4.92 minutes, small fissures have occurred across the grain. As the wood dehydrates more, more stress is created, and the larger the "cracks" or char mounds become.

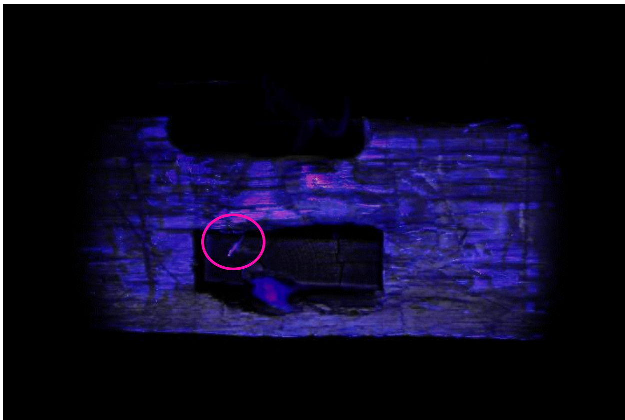
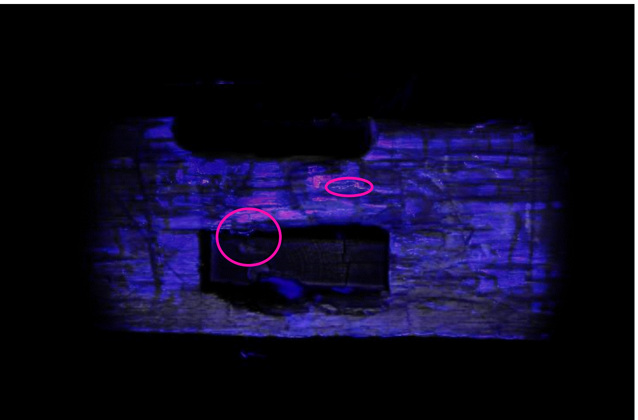
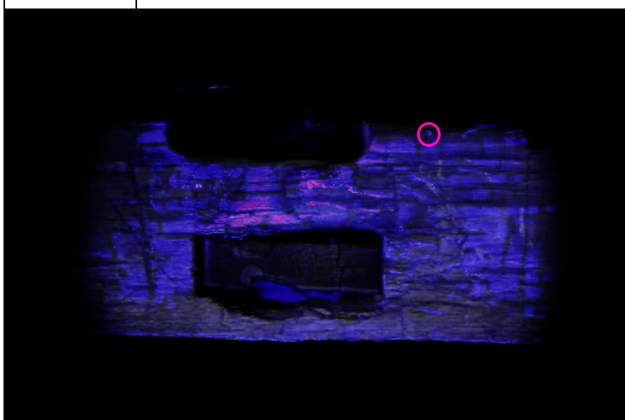
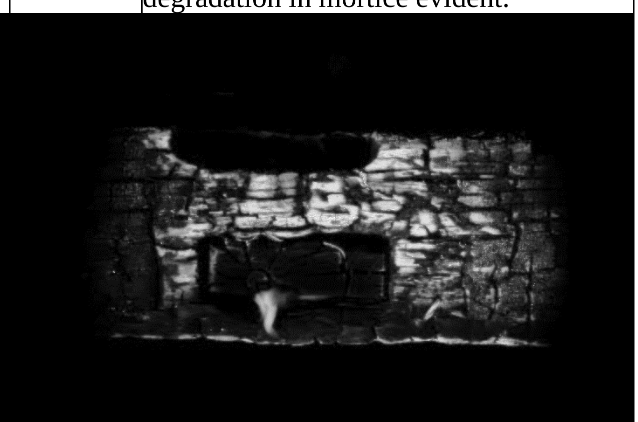
Early on, smouldering is captured in the connection (1 min). Throughout the entire test, it seems as though heat gets captured in the mortise, creating a kind of oven. This observation is supported by continued smouldering in the same location after the connection is no longer burning, which is likely to cause significant damage to the tenon. In under 3 minutes, the connection is completely charred.

The progression of photos also illustrates the behaviour of embers as the wood burns. Almost instantaneously, embers are seen leaving the surface of the wood (0.67 minutes). Mostly larger embers were observed at first. As the connection started burning at steadier rate, the embers became smaller. Throughout the test, some pieces of char would dislodge, but usually it would fall to the ground rather than be carried away into the air as an ember.

Table 6-1: Narrow Light Spectrum Illumination of the connection throughout the burn test with observations

			
0 min	Ignition	0.67 min	Ember seen
			
1.00 min	Smoke emerges from connector	1.33 min	Char front begins around connector
			
1.58 min	propagation of char front elliptically away from connector	2.42 min	Connector is fully charred

			
3.50 min	Cleave marks begin to open on face of connector (refer to upper right)	4.92 min	Cleave Marks open (refer to above the connector)
			
5.08 min	Ember loosens	5.17 min	Ember releases
			
7.58 min	Ember loosens	7.66min	Ember releases

			
8.33 min	Ember falls down in mortise	9.83 min	Ember in mortise releases. Another ember loosens.
			
10.08 min	Ember releases	17.58 min	Large ember releases. Further degradation in mortice evident.
			
23.42 min	Little embers continuously releasing	26 min	Fire put out. Connection still burning.

6.4.3 Charring

Figure 6-10 shows an enlarged photo of the connection at the end of the test. The faint red line is the outline of the connection before the burn. An image of the connection after the burn is overlayed, showing the extent to which the char has retreated from the original dimensions. On top of the charred connection image is an overlay of the connection after the char was removed. As shown in the figure, despite the char remaining close to the original dimensions, once removed, the reduced cross section is apparent.

Figure 6-10: Overlay of connection before burning, after burning, and after char removal

Scaling the photograph above, confirmed by measurements made on site before and after removing char, the cross-sectional dimension shown reduces from 235mm to 224mm, to 184mm with the char removed. The resulting charring rate is about 0.85 mm/min on the top face and 1.11 mm/min on the bottom.

The mortise and tenon shown in Figure 6-11 A. did not have the char removed from it, but here it can be seen that the mortise has become larger due to charring within it. The tenon, although still intact, also appears significantly charred. The original pegs in Figure 6-11 B, were cut to be level with the surface for testing since it was the side exposed to fire. During char removal, the mortise, tenon, and pegs were avoided, but once the char was removed surrounding the pegs, the pegs crumbled away with the char, leaving what is shown in Figure 6-11 C-D. In Figure 6-11 D, shows the extent of damage to the left peg, which had loose char falling out at an additional depth of about 25 mm. What is interesting about these photos is that the old nails in the member are shown protruding now that the char has been removed, whereas before the burn (Figure 6-11 B) the nails were slightly inset. So, the nails themselves, provide a useful way to measure the various char depths across the member however, they also contribute to heat transfer into the member.

Corner rounding is apparent in the below photos; however, it is more significant at the corners where the two members connect (Figure 6-12 C & D). Despite the greater than anticipated corner rounding damage, the connection remained rigid while handling.

Figure 6-11: Connection after char removal. B) the same connection before burn

6.5 DISCUSSION

The dynamic behaviour revealed by the narrow-spectrum illumination shows smoke and heat getting trapped in the connection early on. The trapped smoke paired with the continual presence of smoke and flame at the same location, and the continued smouldering after the test, indicate that the mortise captures and retains heat more than the surface-level wood of the members. When putting out a structural fire for a barn with these kinds of connections, the fire fighters should take special care to check the mortise of these traditional connections for smouldering as they could continue to decay for hours and provide a possibility of reignition if not properly delt with.

The narrow-spectrum illumination also revealed the behaviour of embers. Early in the fire, larger embers were released into the air. Later in the fire as chunks of char released, they typically fell to the ground, and while there was consistent burning, a continuous release of small embers occurred but did not visibly travel far from observations. These observations could be attributed to a number of factors. The first one being, that at the beginning of the fire, the aged wood burns quickly, releasing fumes and particles with more vigour than later in the fire. This coincides with the cone calorimeter testing discussed in Chapter 5.

The narrow-spectrum illumination shows that the entire connection is undergoing the beginning stages of charring in under three minutes. By comparing the reduced cross section to the original cross section, the char rates of 0.85 mm/min on the bottom face and 1.11 mm/min on the top are calculated. The result is an interesting observation because the bottom was the side exposed to the fire. However, the upper portions of the connection would have received heat from the pool fire and additional heat from the lower parts of the connection burning.

By removing the char, additional observations regarding the fires behaviour and charring are possible. The photos reveal that the corner rounding at the interface of the two members is more severe than the corner rounding located elsewhere on the member. The mortise is larger due to the charring and the tenon will have been damaged as well. Despite the damages to the key features of the connection, the connection maintained its integrity during testing and remained rigid while handling. The outcome could be due to the "tight fit" between the two members; a hypothesis supported by the lower temperatures of the centre-located thermocouple.

The pegs underwent the same charring, if not slightly more, than the rest of the members. When calculating the reduced strength of the connection after a fire/charring, it is important to consider the reduced length of the wooden dowels. The wooden dowel/peg on the left, showed more char damage than the dowel on the right. The damaged pegs would have a significant effect on the shear capacity of the pegs. Since the wood dowels of a timber frame connection are often a hardwood such as oak, and the wood dowels were not removed or had their species of wood identified, it is hard to draw conclusions as to why, exactly, the wooden dowels in this scenario underwent sever charring.

6.5.1 Limitations and Sources of Error

Since the “column” member and “beam” member likely have different ages, as well as different finishes (hewn vs. sawn), there is an added variability to the analysis. Charring rates may differ slightly depending on aging for example. Currently, there is no data or existing knowledge to calibrate for this effect with Eastern Hemlock.

This fire test was performed by laying the connection on its side over the pool fire rather than being placed in its intended original position. The unconventional position could change aspects of the fire dynamics within the mortise and tenon and certainly affect the wooden dowels since, in a real scenario, the wooden dowels would not typically be suspended over a fire. This test-setup, though, does provide an aspect of worst-case-scenario. There was 2 in. (50mm) of wood holding the tendon in place, and after 26 minutes, the thin aspect of the mortice did not fail.

A source of error, or limitation, is the test end time. Rather than allowing the fuel to burn out as intended, the test was ended early (although with difficulty). The consequence was time between the end of the test and the moment when the connection could be carried away to be watered down to effectively stop charring.

As far as the thermocouples go, they were not placed at systematic equal depths, but placed to the point in which friction would not allow deeper placement. It is difficult to compare the performance of the connection interface between members and dowels.

6.5.2 Recommendations and Future Research

When considering the fire design of a traditional mortise and tenon timber frame connection, the following should be considered:

- Reduced cross section of the column will reduce the beam’s bearing.
- The corner rounding effect is more severe at interior interfaces (90° angles). The result is a further reduction in the bearing for the beam and the beam’s cross sectional area. It would be suggested that a more severe reduced cross section be used at connection locations to account for this effect. Quantifying the severity of this effect is an area for future research.
- The expanded mortise and reduced tenon results in a “loose” connection that is likely to result in lateral instability of the beam. The reduced cross section of the column at this point also experiences double the char than typical, which should be considered.
- More research needs to be done on the char rate of the wooden dowel/pegs in a connection.

Future research should remove the char from the mortise and tenon, as well as the charred portion of the pegs to see how much of these integral parts of the connection have been compromised. In the future, this connection will be tested mechanically and compared to design values for a 26-minute fire.

Future research should also look at the wooden dowels/pegs. Orienting the connection in its intended fashion could reduce the heat to which the dowels are exposed. Additionally, not cutting the dowels to the surface of the connection could reveal that the dowels are more protected. In the future, the connection could be cut through the location of the pegs to evaluate how char might have impacted the interior.

Future research could also use narrow-spectrum illumination at an interior angle of the connection to capture the more severe corner rounding. And, future research should record, in more detail, the extent to which the corner rounding becomes more severe. Perhaps members connected at different angles have different corner rounding effects.

6.6 CONCLUSION

There are many barns in Ontario which need rehabilitation. Should a barn be repurposed as a public gathering space, the barn will need to be brought "up to code". From a review of the design codes (Canadian, American, and European), traditional timber frame connections using wood dowels are not considered. Current research also neglects wood-to-wood connections. The research that does look at wood-wood connections, neglects to consider heritage aged solid wood connections.

From the fire test of a heritage Eastern hemlock connection, the following was revealed:

- Embers start immediately. Large at first, and smaller throughout steady burning
- The connection is fully developed in char in under three minutes
- Heat gets trapped in the mortise causing continued smouldering
- The corner rounding effect is more severe at interior interfaces (90° angles)

These results highlight the point that current models for calculating FRR of traditional timber frame connections are unsuitable.

Future research should look further into how the interior of the connection might have become damaged due to fire as well as the mechanical performance resulting from the reduced cross-section.

CHAPTER 7

Conclusion

Scientists investigate that which already is; Engineers create that which has never been.

-Albert Einstein

7.1 SUMMARY

There are many advantages to building with wood in Canada as it has one of the most abundant and sustainable forestry programs in the world. The renewable aspect of wood, its workability, acoustic and structural properties, as well as its beauty render it a desirable construction material. The use of wood as a building product spans history from use by traditional Indigenous peoples to traditional mass timber frame construction. Today, with the advancement of engineered products such as glulam and CLT, high-rise structures built with wood are possible.

The number one safety concern regarding wood construction, is its fire performance. To ensure the safety of occupants for new high-rise construction, or for rehabilitated traditional buildings such as the disappearing heritage barns, fire performance must be considered. How wood performs in a fire is dependent on many factors such as wood species, wood product, room size and shape, HVAC, fenestrations, interior finishes, fire safety systems such as sprinklers and fire alarms, and much more. All of this information must be processed and evaluated by a Fire Safety Engineer (FSE).

Building Information Modelling (BIM) is used for many construction projects and is growing to be mandatory in many countries. BIM is a collection and organization of all information regarding the building throughout its life cycle, from conception to demolition. A fully developed BIM will contain all the necessary information for FSE to perform their analysis with the added advantage of increased project efficiency and collaboration that BIM is known to provide.

The compatibility between BIM and FSE for the design of mass timber structures seems obvious and inevitable, yet upon further investigation, there existed some large information gaps. Not only are the uses of BIM not fully understood, but the knowledge base on the performance of wood and fire is also not fully understood. Therefore, this thesis explores the gap between three themes: Fire, mass timber construction, and Building Information Modeling (BIM). The multi-faceted under-researched aspect of all three subjects has resulted in an holistic approach to the overall thesis; identifying where industry is currently and suggesting future directions.

Chapter two provides the technical background relating to wood as a construction material and principles of fire dynamics. The chapter is limited to provide just the information needed to better understand the subsequent chapters. It acts as an encyclopedia for the terms and phenomena referenced throughout the thesis.

Chapter three is an in-depth literature review regarding the integration of BIM and FSE for mass timber construction projects. Themes discovered and explored include BIM and FSE data management, fire smart BIM objects, automated code checking and model compliance, structural fire dynamic integration, emergency evacuation integration, BIM and construction fire safety, BIM and fire safety operations, BIM and fire rescue, and the use of extended reality technology. Each theme becomes more relevant at different stages of a building's full life cycle, starting with the beginning, where a BIM management plan is required. Popular approaches and software are analyzed. It was found that IFC is key to the future development of BIM and FSE. The current lack in FSE data structure within IFC is a major issue discouraging further development of BIM and FSE integration since each attempt is unique and will be difficult to apply universally without a standardized data structure.

Chapter four explores the impacts of architectural features on full-scale CLT compartment fire tests with the motivation of increasing cross-disciplinary understanding between architects and engineers via BIM. Thirty-six full-scale tests were analyzed for correlations between architectural features and fire performance metrics. A strong correlation will signify that changing that architectural feature will very likely change the fire dynamic performance outcome. It was found that only four fire dynamic metrics had enough data (25 points or more) to create a plot in order to consider correlations. These fire dynamic outcome metrics are closely related with the requirements for calculating a parametric fire curve. Many tests neglect some useful data such as heat flux above window openings. After plotting 7 architectural features against 4 fire dynamic outcomes, it became evident that some major research gaps exist as well as the low level of predictability that even FSE has. While it was clear that room volume had a very predictable effect on time to flashover or duration of a fully developed fire was less obvious. Some findings were surprising like the extremely low correlation (almost zero) between amount of exposed timber on walls and the fire dynamic outcomes that contradicted some testing observations. In summary, this chapter highlighted the fact that FSE are still developing the working knowledge regarding fire performance of CLT compartments and that more research must be done in this area. Additionally, future large-scale compartment tests need to measure more of the other fire dynamic outcomes possible with wood structures. There is need for a standardized testing outcome requirements regarding large scale CLT compartment testing. To communicate some of this developing knowledge to architects and owners, to increase cross disciplinary understanding, a BIM-based alert concept for aiding design decision-making is presented.

Chapter 5 identifies the charring rate for heritage Eastern Hemlock for the purpose of performing FRR calculations, specifically in a BIM environment. The motivation is that this new research will encourage the repurposing of heritage barns in Ontario. A Cone Calorimeter was used at constant heat flux exposures of 30 and 50 kW/m^2. The samples were all cut from a beam that had naturally aged for 100+ years and were tested for different burning durations of 3, 6, 10, 15, and 30 minutes. The results were then able to be used with CSA 086 for a reduced cross section calculation. A framework for integrating the char rate parameter within BIM for automatically calculating the FRR based on the CSA 086 Annex B reduced cross section method is presented. The re-occurring theme of developing FSE research regarding wood and different species is highlighted and the concept of utilizing an open access database is introduced. The concept of having a Fire-smart BIM object which automatically calculates FRR is limited again due to the lack of standardized FSE data structure within universally accepted IFC BIM data schema.

Chapter 6 builds on Chapter 5. The significance of Eastern Hemlock within an Ontario landscape is highlighted, motivating the need for better understanding how traditional timber frame connections of Eastern hemlock members perform in fire. A fully housed mortise and tenon connection is recorded in detail and placed on its side over a pool fire for a duration of 26 minutes. The char was then removed from the connection, revealing the reduced cross section and damages. A number of fire dynamic phenomena occurred. With narrow-spectrum light imaging (NSLI), the progression of char at the connection was observed. The connection was fully developed in char in under three minutes. The NSLI also revealed the dynamic behaviour of heat becoming trapped inside the mortise of the connection; An observation that is supported by the additional observation that the mortise continued to smoulder after efforts to extinguish and cool the connection. More sever corner rounding phenomena occurred at the interface of the two connecting members. Despite all the structural damage, the connection maintained rigidity/stability. This fire research on traditional timber frame connection is one of a kind and lays the foundation for future model validation.

There still lacks a FSE disciplinary understanding on how mass timber performs in fire, both in a traditional use, and in a modern CLT compartment use. Continued research needs to be done before predictive modelling can be used with a high level of confidence. FSE is also slow to adapt BIM concepts and applications. Slow adoption is mostly attributed to the complex nature of fire, and also from lack of education. FSE could benefit from using BIM, even while research is being developed, by taking advantage of data analytics. Due to the slow development of FSE-BIM integration, the BIM applications conceptualized in this thesis are likely 20 years out from implementation and regular use.

7.2 CONCLUSIONS

The following key conclusions were drawn on the basis on the literature review, experimental analysis, and experimental testing regimes in this thesis:

- The development of BIM for FSE is significantly lagging compared to other engineering disciplines. The open IFC standard needs to be developed to include IFC data structures and MVDs.
- Some ways in which the author suggests FSE can benefit from BIM is through data management of experimental testing, alerting other users on how their changes impact fire dynamics, and providing opportunity to be a part of early-stage parametric design, bringing the possibility of a more fire safe optimized design.
- FSE understanding of how CLT compartments perform in fire is lacking. There are many research gaps and more research needs to be done.
- Under a constant heat flux of 30 kW/m^2, the aged Eastern Hemlock samples had an average peak HRR of 27 kW/m^2, there was no ignition, char rate of 1.0 mm/min, and char contraction factor of 0.89. Under a constant heat flux of 50 kW/m^2, the samples had an average peak HRR of 177 kW/m^2, a time to ignition of 23 s, a char rate of 1.42 mm/min, and char contraction factor of 0.88.

- Open-access material databases are needed and encouraged to move FSE understanding along at a faster rate.
- There is no literature regarding traditional mortise and tenon connections. The mortise tends to trap heat during a burn and more significant corner rounding occurs at the connection interface than is predicted by current codes. The wooden dowels show no signs of failure. More research in the area is required before a BIM approach can be considered.
- Lack of education, standardization, and open-access materials have made the adoption of BIM within the FSE industry slow.

7.3 DESIGN RECOMMENDATIONS

BIM is now a mandated requirement for the construction of mass timber buildings in multiple developed countries. When considering the FSE of a mass timber structure, BIM also needs to be accounted for. The author makes the following recommendations to the fire safety engineer undergoing just such a project.

- **Establish FSE BIM data requirements and performance outputs** – At the very start of a project's conception, FSE should be included in the projects overall BIM management plan. Since there is no IFC data structure for FSE, output requirements from other stakeholders will have to be specified.
- **Educate FSE team on BIM applications** – A "golden thread" of information regarding FSE needs to be documented and understood. BIM is the most suitable way to create and maintain this kind of digital fingerprint.
- **CLT compartment fires lack consensus understanding** – When designing a new mass timber high-rise with CLT compartments, the engineer should be aware that there is a lack of data on full-scale compartment testing. Conservative approaches and more research should be taken and more research conducted.
- **Architectural design changes likely to cause re-design** – Due to the lack of CLT compartment fire understanding, it is likely that any design change could result in a re-design since there is so much variability.
- **Char rate for heritage Eastern Hemlcok** – Use a conservative char rate of 1.42 mm/min for Eastern Hemlock.
- **The corner rounding effect of traditional connections** – the corner rounding effect is more severe at the connection interface, further reducing the bearing for the beam and the beam's cross sectional area. It would be suggested that a more severe reduced cross section be used at connection locations to account for this effect.

- **Effects of fire on a Mortise and Tenon connection** – The expanded mortise and reduced tenon results in a "loose" connection, likely to result in lateral instability of the beam. The reduced cross section of the column, at this point, also experiences double the char than typical (in one dimension, char is occurring on four surfaces instead of two), which should be considered.

7.4 RESEARCH RECOMMENDATIONS

The following is a list of research recommendations which should be considered:

- **Model View Definition (MVD for FSE)** – An in-depth analysis should be done identifying all FSE data requirements. Among them, pre-defined IFC structures should be identified and proposed IFC structures for non-existing ones. Additionally, fire performance outcomes need IFC data structures. Everything needs to be summarized in a model view definition which considers fire safety.
- **Leveraging Open access experimental result databases** – More research should be done into how current open-access research databases are being leveraged in other disciplines and quantify how it can be leveraged in FSE.
- **Quantifiable metrics for architectural impacts on FSE** – The analysis of full-scale compartment fire tests can be taken a step further by analyzing how a change in the architectural variable influences the change in the fire dynamic outcome metric. Additionally, a 95% data inclusion method could be implied to create a "limit" for future buildings. Upon success, this could be applied across other discipline overlaps such as mechanical variables.
- **Large Scale CLT compartment fire testing** – More large-scale fire tests need to be performed to fully understand the fire dynamics of CLT compartments.
- **Cone calorimeter testing for various ages of Eastern Hemlock** – Future research would burn some samples for longer durations of time such as 17 minutes and 40 minutes as well as burn more variety in natural aging exposure. The aim would be to eventually develop a more accurate dynamic charring model that could be used for predicting outcomes of non-standard fires.
- **Traditional connection burn tests** – the burned connection could benefit from being cut in pieces to better understand how the fire might have damaged the internal mechanisms due to charring such as the total reduced cross section inside the mortise.
- **Experimental testing of thermo-mechanical responses of traditional timber frame connections** – The burned connection needs to be tested mechanically as well. Future studies should look at simultaneously testing the mechanics of the connection during a fire.

- **Evaluate frameworks for automated FRR compliance calculations** – The full usefulness of automated FRR calculations of wood members is not yet understood. Considering traditional timber framed barns are often evaluated by structural engineers with little FSE background, this could prove useful, but should be quantified/evaluated, nonetheless.
- **Developing an open-access materials fire performance database** – A better look at quantifying the advantages and how to set-up such a database without having the data jeopardized or mis-used needs to be explored.

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Appendix A: MLR Data