Fire Safety Research towards Enabling Timber Structures in Canada

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ABSTRACT: In Canada, practitioners are moving beyond the mid-rise timber framed structure and progressing to the design of hi-rises. Examples include the *Brock Commons* building at 18 storeys, *Terrace House* which is planned to have 19 storeys, and the 13 storey *Origine* building. Each building encompasses an integrated usage of (multiple) engineered timbers: Cross-Laminated Timber, Laminated Veneer Lumber, and Glulam timber for example. These designs are being supported by extensive research which examined the fire performance of these aforementioned engineered wood products. While practitioners have begun to build these hi-rise structures in Canada and abroad, there is still much we do not know about these materials and their behavior in fire, as identified by various global research collegiums. This paper will begin with an overview of past and recent published 'timber in fire' research conducted in Canada and its relation to global research conducted elsewhere. Emphasis is on the ongoing Canadian research as being conducted by the authors themselves, collaborators and their consultancy partners towards a stronger confidence in timber buildings and design. Differentiation will be made between solid and engineered timber through discussion of a real fire case study. Particular attention will be made to the performance of various adhesives utilized in these various engineered wood products as this has been identified to degrade beyond the char formed layer. This paper will aim to discuss the current research gaps in a Canadian context with relation to the international context. The paper will conclude if we, as a Canadian practice, have sufficient knowledge to undertake more of these innovative designs, or if there is additional need in Canada, and perhaps abroad, for further research attention in this area to support mid- to hi-rise timber design.

1 INTRODUCTION

On December 17th 2013, a 'light' timber construction site caught fire in downtown Kingston, Canada. The fire demonstrated a 'modern' conflagration in an urban centre. The resulting fire led to the closure of that city's downtown core for four days, and the relocation of the city residents within a two-block radius from the site of the fire. There was no life loss but there were injuries. Evacuation of the city core, both immediate and long term, was done for a number of reasons: the fire had spread to multiple city blocks in part due to a south-westerly wind, a crane structure which was used for the construction of the timber building project was compromised, and the fire occurred across the street from a gas station. The latter reason led to a fear of an explosion as the fire developed. Hence, the firefighting strategy was to protect the station from the onset and clearing the surrounding area. Complicating the evacuation of the city core, adjacent to the construction site was a senior's home which necessitated relocation of these people during the fire – which was compounded by the difficulties of evacuating vulnerable people in a harsh Canadian winter where the temperature was near minus twenty degrees Celsius.

After the fire, Canadian construction industry began focusing attention to discussing the merits and pitfalls of using timber in general construction with emphasis given to timber's inherent risks of fire during construction (independent on the differences between light and mass timber). A photo of the site taken by the corresponding author during an investigation visit on December 18th 2013 is provided in Figure 1. This fire began a debate on recent changes in the Canadian building code that were recently promoting mid-rise timber construction.

Figure 1. Kingston, Ontario Conflagration of 2013 resulted in closure of the downtown core (authors' photos modified to remove business names).

A recent amendment to the National Building Code of Canada (NBCC) was to facilitate the use of engineered timber in construction to enable mid-rise construction of six stories (see Otto et al., 2017, Taber et al., 2015) and to support expansion of CSA O86-14 timber guidance for engineered timber construction (at the time of writing, it has been proposed to extend the code to 12 storeys with certain restrictions). All of these initiatives reflected government-supported research in the past two decades (see Su et al., 2014, 2015 for background information on these tests). Substantial tests and experiments led by a consortium from the National Research Council of Canada (NRCC), timber industry partners and various supporting universities in Canada were done over the better part of the last decade by performing demonstration large scale, standardized medium / full-scale, and material fire tests that have attempted to provide confidence in timber construction with prescriptive rules within an objective-based framework (NBCC) which could facilitate timber construction in Canada (*some of these tests and experiments are too numerous to describe herein, and many are proprietary and unavailable in the public domain. The reader is encouraged to consult the NRCC Publications Archive for available publications where applicable for original data*). The goal of the objective-based framework of the NBCC is to not be a performance based code. The NBCC does not completely express or even establish an explicit performance level regarding fire safety that needs to be achieved. The NBCC provides objectives that explain the intent behind the prescriptive code provisions. Under the NBCC framework, the acceptable solutions establish the minimum acceptable level of performance for the specific objectives that relate to the acceptable solutions (see FPInnovations, 2014). This code momentum led to one of Canada's first modern mid-rise timber constructions over four storeys. The building, at six storeys, was built in Prince George, British Columbia, and is called the *Wood Innovation and Design Centre*. It was built using engineered Cross-Laminated Timber (CLT) and Glulam structural members. Those engineered timber products are built from plies of various sizes that utilize an engineered adhesive to connect and build up a larger section. Each of these systems have shown satisfactory testing in a variety of standardized fire and demonstration style tests in Canada (see Su et al., 2014, 2015).

Building on the mid-rise momentum and advancements, Canadian and international practitioners are moving beyond the mid-rise timber framed structure and progressing to the design of the hi-rise construction. Canadian examples include the *Brock Commons* building at 18 storeys (see Figure 2), and the 13 storey *Origine* building in Quebec. More recently *Terrace House* has been proposed at 19 storeys, though that will include concrete floors. Each building encompasses an integrated usage of (multiple) engineered timbers: Cross-Laminated Timber (CLT), Laminated Veneer Lumber (LVL), and Glulam timber for example. These designs are being supported by extensive research which examined the fire performance of these aforementioned engineered wood products. In Canada, their facilitation is also being promoted with the flexibility afforded to the alternative solution clauses within the objective-based building code. These structures are all subjected to very significant control during construction to ensure their safety. The Kingston Conflagration, which was of 'light' timber – not engineered – resulted in 22 charges being laid for construction practices, including 12 related to fire safety. Heavier timber elements are known to perform better in fire than their 'light' counterparts. While they can still ignite with heat, because of their remaining cross section after fire they have larger reserve strength. That aspect was prevalent knowledge during the late 19th century in mill construction (see Otto et al., 2017). Engineers intentionally scaled up timber elements for business continuity in the event of a fire. Nevertheless, the distinction between light and heavy timber is significant and is a focus of the developments of research for timber construction in Canada. Proposed contemporary hi-rises are typically of mass engineered timber and not of light weight construction. Even so, information on the fire resiliency of mass engineered timber is scarce.

Figure 2. Brock Commons exterior and interior (authors' photos). Multiple layers of gypsum were used on timber columns and slabs in order to facilitate acceptance by building authorities.

While practitioners have begun to build these hi-rise structures in Canada, and even abroad, there is still much we do not know about timber's behavior in fire, as identified by various global research collegiums. For example, international momentum to hi-rise timber construction was helped with the publishing of the Skidmore Owings and Merrill's (SOM, 2013) feasibility study for a 42-story timber building called *The Timber Tower Research Project*. Reviewed within NIST 1188, the report declared that there was a lack of information pertaining to fire safety, particularly in the event that sprinklers did not work for any reason (Yang et al., 2015). The NIST 1188 report, more broadly known as the *Roadmap for Fire Resistance of Structures CIB workshop on Research and Development*, tabulates a variety of research needs that could help support these and other timber structures. There is necessity to provide an overview of past timber fire research with emphasis to ongoing and in-progress Canadian research. Herein, this is addressed by compiling work as being conducted by the authors themselves, their collaborators, their consultancy partners and their academic partners. Particular attention will be made to the performance of various adhesives utilized in these various engineered wood products as it has been identified in the past to degrade beyond the char formed layer (see Figure 3), as well as what projects relate to the research needs identified within the international research needs document NIST 1188 which seeks to enable this type of construction.

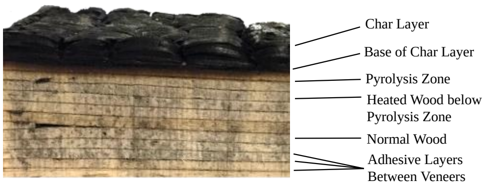

Figure 3. Timber breakdown (Laminated Veneer Lumber shown)

This paper will aim to discuss the current research gaps that are needed to instill further confidence in timber construction in a Canadian context. This paper's purpose is for the reader outside Canada to understand the motivations and limitations of tests and experiments within the Canadian industry; it is not to provide a holistic overview of all research done in Canada as much of this remains proprietary and that would be better tailored to a comprehensive manual (as planned by the authors). This paper concludes with the authors' opinion of the future of Canadian timber practice, in light of new tall and complex timber designs such as *Brock Commons* and *Terrace House*.

2 RESEARCH ENDEAVOURS IN CANADA

In the last ten years, there has been momentum regarding timber fire research in Canada. The work, available in the public domain or privy to the authors for discussion, primarily involves tests and experiments that helps promote timber within the regulatory framework in Canada. The research performed and subsequent analysis is aimed at demonstrating or meeting approval to enable timber construction – it is rarely exploratory. While this research is very useful for international practitioners, it does not meet all objectives as shown in Table 1, which was adapted from topics 10 through 16 from the CIB workshop as aforementioned.

Table 1. International Research and Development Roadmap for Timber Structures and Research Progress in Canada (adapted from NIST 1188; Yang et al., 2015)

Topic	Milestone	In progress in Canada
1. Predict the reliability of fire compartmentation	a. Perform medium-scale furnace tests.	✓
	b. Perform large-scale verification of tests.	✓
	c. Model material properties.	✗
	d. Publish guidelines	✗
2. Specific acceptable performance criteria	a. Determining scope and nature of occupancies and structures.	✓
	b. Obtain acceptance of the performance-based standards by stakeholders in the industry (code making and builders).	✗
	c. Define/identify fire experience in related structures and occupancies	✗
3. Development of structural models for timber fire resistance	a. Complete assembly of experimental library and existing software.	✓
	b. Develop new testing of models.	✗
	c. Complete validation of system modeling against experimental and actual experience.	✗
4. Calculating the strength of structural timber exposed to fire	a. Finish small-scale testing of a wide range of products.	✓
	b. Develop heat transfer and charring model.	✓
	c. Perform medium-scale testing and modeling of protected wood.	✓
	d. Perform large-scale verification test.	✗
	e. Publish design guide.	✗
5. Compartment burnout encapsulation	a. Quantify heat flux using small-scale tests.	✓
	b. Define the range of Time Temperature exposures to be used.	✓
	c. Perform fire-resistance tests of walls and floors with different time temperature curves using various encapsulation strategies.	✓
	d. Create and validate a heat transfer model for wood.	✗
	e. Validate the model with full-scale burns.	✗
6. Reliability-based analysis of fire testing	a. Reach a defined number of participating laboratories.	✗
	b. Identify organizations to coordinate participation.	✗
	c. Develop and gain acceptance of the method	✗
7. Design fires based on use and occupancy	a. Draft the proposed fire design curves	✓
	b. Agree on the first version of design fires	✗

The themes in this paper include material testing (strength and flame spread), and fire resistance (connections). Fire robustness, fragility and resilience could all be suitable themes to discuss (*and should be*), however the regulatory framework within Canada, and abroad, necessitates that timber is assessed on equivalency (*correct or perhaps wrong*) to the standard fire in the NBCC, which in some cases negates the implications of heat flux and its effect on charring. It should be noted that this research area is very important and is currently being explored by international practitioners (see Bartlett et al., 2015). Compartmentation and realistic sized fire exposure could also be discussed at length; however, these studies are under progress by various researchers as highlighted in Table 1 and are beyond the scope of the current paper. Finally, it should be noted that while there are a wide variety of timber species and engineered wood products available, attention herein focuses on three of the more commonly used systems which are often used in mid-rise and hi-rise construction.

2.1 Material Testing

The importance of material testing is that it provides requisite data that can enable a predictive model for how a structural system will perform in a real fire, or why it did perform a certain way in a previous fire. This material knowledge enables predictions for full scale performance of structural systems, as well as more complicated and unexpected behaviour of a structural system in a real fire. Material performance also allows the observation of unexpected behaviours that can be made apparent in real building configurations, some of which may require further study. Significant efforts have been underway in this area by the authors for the past two years. Their focus, in a study financed by the Government of Canada and independent of industry, is to study the performance of unusual shapes, which are akin to proprietary timber systems such as Post-Tensioned Timber (a system yet to be utilised in Canada to the knowledge of the authors- but being used in the United States), and the performance of adhesives, namely PUR (polyurethane), and PRF (Phenol Resorcinol Formaldehyde), which are commonly utilised in CLT, Glulam and LVL.

Quiquero et al., (2016) report the experiment data of four Glulam beams tested under two applied point loads, equally spaced, two of which were tested after fire exposure. In total, the experiment series included four solid beams (two burnt, one unburnt and one carved) and ten box beams (five burnt, four unburnt and one carved). Although the beams were short in length (< 1m), they highlight unique failure mechanisms which were induced through the degradation of both the timber and the adhesive. To do this, the authors physically carved a reduced cross section, based on char depth measurements of the burnt specimens, to allow the effect of adhesive degradation to be compared to the charred section. The burnt beams were exposed to high temperature with exposure equivalent to one hour of standard fire and one hour of natural cooling to flame out. Minimal to no water was utilised on the specimens to extinguish smouldering, and any water produced evaporated. Each beam that was exposed to fire was then tested in its altered condition. Figure 4 demonstrates the effect of heating from the load and displacement of a glulam box beam. Note the substantial drop in load capacity after heating exposure, with only 13% of the strength remaining in the burned member compared to 64% in the carved member. This led the authors to create a subsequent study to consider the effects of high temperature on the degradation of adhesive strength.

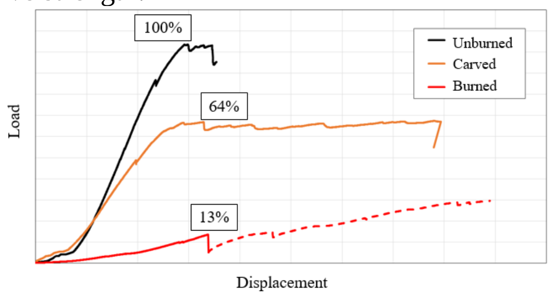

Figure 4. Glulam Box Beam Tests (Quiquero et al, 2016)

Quiquero and Gales (2017) considered the performance of two different types of adhesives utilised in engineered timber, PUR and PRF. The series of experiments were performed using a cone calorimeter at constant heat exposure of incident flux of 30 and 50 kW/m^2. The samples were exposed to various times of heating (3, 6, 10 and 15 minutes). There were two samples with PUR adhesive tested for each heat flux and duration combination. Two samples with PRF adhesive were tested for each duration at 50 kW/m^2 and one sample for each duration at 30 kW/m^2. The samples were then mechanically tested using an innovative shear apparatus, where load was applied through the damaged adhesive line at the specimen's centre as shown in Figure 5. These test results provided valuable requisite material data including measured char depth (Figure 6) under short term exposure and a clear degradation of adhesive (Figure 7) after results were compensated for a reduced cross-sectional capacity. Char was shown to be accelerated for short time exposure, though after 15 minutes of exposure for both levels of incident heat flux, charring rates began to plateau. This is a very important distinction, as conservatively we aim to provide a standardized charring rate for all timber (see FPInnovations, 2014) no matter the time of exposure (such as a standard fire time curve) and we typically only utilise one heat exposure in Canada, which is done in order to simplify our analytical models. Charring rates of LVL and solid timber were also quantified in subsequent studies connected to research presented in Section 2.2 (see Otto et al., 2017). The adhesive breakdown is significant, as demonstrated, however it is critical to know that the severity shown is a function of the size of the sample. The effect of adhesive degradation is likely magnified due to the small physical size of the samples. The tests meet Objective 4 in Table 1, and would naturally see a progression to a large-scale test to verify the results which will also connect to Objectives 1 and 3, as planned in the long-term by the authors. There are ample studies in public domain about delamination and that is beyond the scope of this paper to discuss.

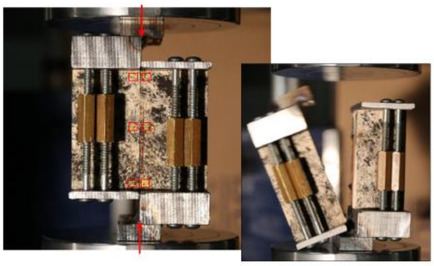

Figure 5. Glue line shear tests (Quiquero and Gales, 2017)

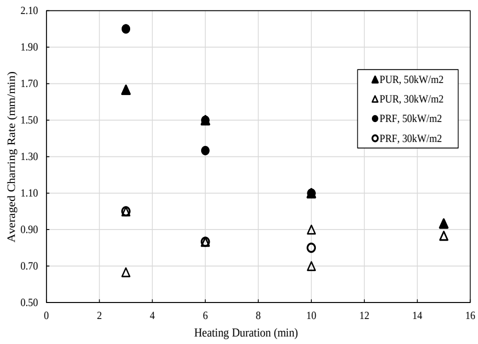

Figure 6. Charring behavior versus exposure time (Quiquero and Gales, 2017)

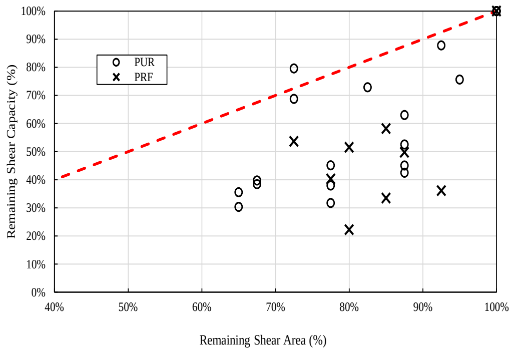

Figure 7. Adhesive breakdown after fire exposure (Quiquero and Gales, 2017)

Flame spread is a significant factor, particularity in the realm of architecture of timber buildings, where there is a trend to keep timber exposed and showcase it as an architectural feature to exploit biophilia tendencies. Naturally, this requires an understanding of pyrolysis and flame spread on timber to adequately quantify the performance of this exposed timber in a fire, and the reparability after fire for business continuity considerations. There is limited data pertaining to pyrolysis (see Hopkin, 2015). Material studies are useful for this, though small scale experiments can enable a richer comprehension of these effects. To enable this type of model to support this type of design, it is necessary that experiments be performed where flame spread can be adequately quantified and understood. Recent research by Otto et al. (2017) showed that it was possible to utilize selective flame filtration, a technology developed at NIST, to separate the pyrolysis front and the flame front to rationally quantify this difference, under a quantifiable exposed heat flux. These experiments were performed on two samples of each types of timber species (Laminated Veneer Lumber, Glulam, and solid timber) utilizing a Lateral Ignition and Flame Spread Test apparatus. This experiment series also included at total of twelve Laminated Veneer Lumber samples. This invaluable data then enables a researcher, in junction with other materials tests, to begin the rational modelling of this effect. See Figures 8 and 9.

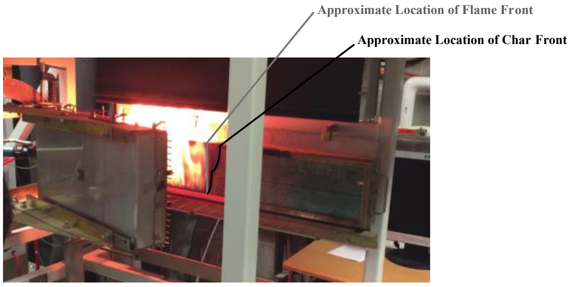

Figure 8. Pyrolysis Mechanisms for exposed timber

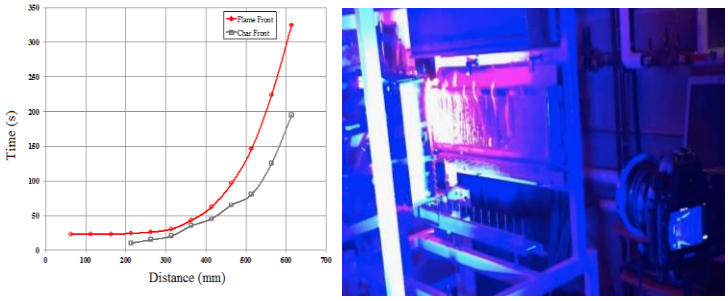

Figure 9. Measured Flame spread versus Char formation of Solid Timber using Selective Filtration

Unique in these material experiments of flame spread was a phenomenon observed in less than 25% of the LVL panel tests. What occurred was, at incision points, a bleeding effect of adhesive appeared to propagate flame spread along the surface of the specimen. Measured charring depths illustrated very little effect from this behavior (see Figure 10).

Figure 10. Adhesive bleeding effect in LVL (Otto et al., 2017)

2.2 Fire Resistance

Objective 5 in Table 1, which aims to develop compartmentation guidance, relies heavily on the concept of fire resistance. Walls, floors, and connections are an intricate focus here. Calculation methods (analytical and numerical) are used to determine fire-resistance rating of timber members and assemblies in Canadian design standards and they are intended to predict the structural fire resistance as determined using the standard fire-resistance test methods seen in CAN/ULC-S101-14. In Canada, the design standard CSA O86-14 is utilized, and this can be used to determine the fire resistance of CLT assemblies when left exposed or when protected by fire-rated gypsum board directly applied. The basis for these methods were developed from a series of 12 standard fire (full-scale) tests available in the public domain (see Craft and VanZeeland, 2017).

The tests were performed at the National Research Council of Canada (NRCC) within their furnace and financially supported by the timber industry (see Figure 11).

Figure 11. CLT Standard fire floor test conducted in 2014 (authors' photo; see Su et al., 2014).

Tests for fire-resistance were performed on CLT wall and floor assemblies, where varying thickness (with and without fire-rated gypsum) were studied. These tests supported the added calculation methodology in O86-14, Annex B, to design CLT for structural fire resistance which uses the effective cross-section method, the uncharred region (accounting the zero-strength layer under char – 7mm) with full strength properties, to calculate member resistance. Those tests also allowed for the study of adhesives, with respect to the fall-off of plies. This initially increases the char rate on the remaining cross-section as each layer falls off since the uncharred wood becomes exposed (see Section 2.1). CLT walls and a stairwell were also considered in this test series by the NRCC.

Beyond member tests, in Canada there has been explicit attention given to connection systems. Studies at Carleton University have looked at hybrid timber connections – unprotected hybrid steel-column and Glulam-beam shear tab connections exposed to elevated temperatures. In Boadi et al. (2017), two pinned Glulam beams were tested for each shear tab connection type (exposed, concealed and seated). The connections had three-sided exposure which mimics a floor above. Thermocouples were placed at various depths on all faces of the beams. This was to generate temperature profiles to compute the charring rate and depth of the beams. The fire exposure was a real fire curve based on a room fire test conducted by McGregor (2013) on fully furnished CLT rooms, and not based on a standard fire curve. This fire exposure can work toward Objective 7 in Table 1. Two-point constant load was applied before and during fire test. The failures observed in the connection assemblies was a result of loss of strength in the wood members. This can be due to thermal degradation of the wood at elevated temperatures, with most failures being sudden and brittle. The study predicted from worst to best connections as: concealed, exposed, and seated. Significantly, but what may be expected for non-standard exposure, the charring rates of Glulam exceeded the value of 0.65 mm/min obtained for standard fire tests (the value used in design).

Likewise, in junction with Lakehead University in Canada, Gonzales et al. (2017) considered beam to column concealed connections in standard fires. These tests address the fact that there is no established method to design timber connections for fire resistance in Canada (and perhaps abroad) but they are more susceptible to failure in a fire event. Steel plates and fasteners have high thermal conductivity and are said to heat up the core of the wood, specifically in sustained heating events, and these can cause loss of embedment strength. The tests performed considered two Glulam beams connected to the opposite sides of a Glulam column. The beams were connected to the column with a concealed steel connector fastened by four bolts; the connector was composed of steel plates in T-shape section (see Gonzales et al., 2017 for detail). The researchers considered an ambient temperature test that showed failure by splitting parallel to grain along bottom/tension row of bolts. Two assemblies were then tested following standard fire exposure while subjected to constant vertical load. Charring rates were calculated based on temperatures recorded by thermocouples. A splitting failure (parallel-to-grain shear) along the bottom row of bolts was observed with 40% loss of cross section, however the system continued to support load due to fixed conditions at the beam's far ends. The governing failure mode then became row shear perpendicular to grain.

Finally, preliminary connection work has been performed and introduced by Otto et al. (2017) in an attempt to generate data regarding the effect of external plated connections. The work focused on flame spread performance, in particular the propagation of a flame across an LVL unit but obstructed by a steel plate system of various degrees of length as observed in Figure 12. Nine samples were tested with varying lengths of steel plates. The results of the spread and its effect on charring depths can be observed in Figure 13. These experiments attempt to address Objective 4. The study also looked at the role plating had on heat transfer to the timber below. Additional cone calorimeter tests were performed to compliment. The results showed that for short heat exposures, less charring occurs compared to when the steel plate had been absent, with variance depending on the length of the plate (see Otto et al., 2017).

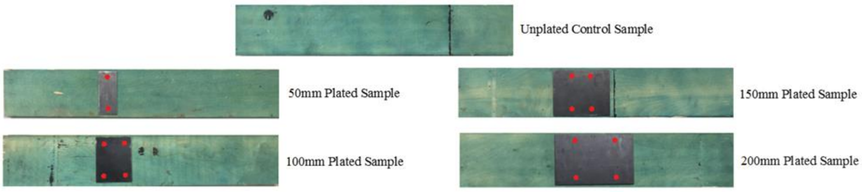

Figure 12. Flame spread connection tests

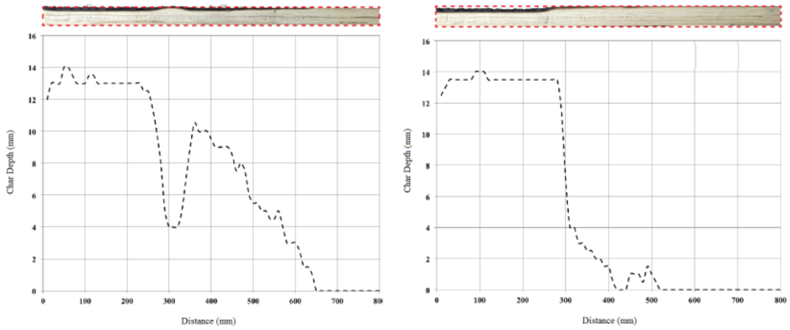

Figure 13. Char depth results of flame spread connection tests (50mm plate, right 200mm plate).

3 PRELIMINARY CONCLUSIONS AND RECOMMENDATIONS

It is beyond the scope of this paper to feature all research underway on Canadian timber construction. Tests performed on CLT compartments, facilitated by NIST and organized by the NRCC, have recently been completed at the time of writing (additional ones are being performed in the US initiated by the American Wood Council, as advised by the NRCC, ending early July 2017). Those tests, along with other international counterparts, begin to address Objectives 5 and 6 in Table 1. These tests have focused on engineered timbers contribution to fire when left exposed (with no encapsulation), the interested reader is encouraged to consult these reports when available. In conjunction with activities by others, there is significant momentum underway towards ‘promoting’ tall timber, though there are clear gaps in knowledge. The prognosis in Canada at this time is that it is fairly challenging to predict the future of tall timber, as research is currently being transitioned through aspirations to construct more dedicated fire testing facilities. This has shifted focus towards some modelling development and towards small to medium scale testing, as shown herein, by many. While this paper could have easily focused on tools for modelling, this is currently in preliminary stages in Canada, if not internationally. Requisite data for model validation for a range of different fires is essential and needs to be gathered and, in the opinion of the authors, properly peer reviewed and vetted by independent researchers of those projects for objectivity. While international workshops have been useful in mobilizing preliminary research for timber structures in fire, particularly engineered timber, there is still much to do. It is important that we align efforts with those internationally so that we can achieve all objectives laid out. In Canada, the appetite for modelling timber structures in fire is challenged because our code necessitates an objective and prescriptive based analysis. Though similar in practice to other countries, the regulatory framework will determine the types of tests and experiments, and the associated funding that will be provided for short term gains for the industry. In trying to legislate mid-rise and hi-rise construction, subsequent tests will be performed to enable those buildings using our existing codes which favor simplified analytical solutions. Hi-rise timber buildings in Canada are growing in quantity and complexity and it may not be entirely feasible to specify only applied protection in their design based on equivalency-based relations. This is especially important because we are beginning to see significant complications into engineered timber performance and necessitating more robust modelling analysis. Additional research is badly needed to the damage states expected for tall timber buildings when elements are left exposed, should a fire occur. It is necessary for insurers to know the expected duration of down time of a structure after a fire - its occupational resiliency must be understood. For these reasons, it is recommended (by the authors) that caution be applied when proposing tall timber construction, especially when it involves aspects that have not been tested and therefore cannot be certain of their behavior. The research shown herein only emphasizes the need for more knowledge to be obtained. Finally, it must be acknowledged that society wants natural and sustainable construction systems from a psychological perspective. We must engineer solutions for these complicated buildings moving forward, informed by available test data, while using the lessons learned from a few rare case studies that demonstrate the risk of not addressing fire safety in all types of construction.

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