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SOLUTIONS FOR UPPER MID-RISE AND HIGH-RISE MASS TIMBER CONSTRUCTION

REHABILITATION OF MASS TIMBER FOLLOWING FIRE AND SPRINKLER ACTIVATION

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Client: Natural Resources Canada

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1. INTRODUCTION

Wood structures are most vulnerable to fire during the construction stage, prior to installation and activation of various fire safety systems and design elements. In completed buildings, the concept of fire resistance is used to limit the effects of fire beyond the point of origin and to prevent collapse of the structure, as are the defined by the objectives and functional statements for fire-resistance in the National Building Code of Canada (NBCC) [1]. Because of intrinsic fire safety features that are built into the NBCC (such as compartmentalization), most fires do not spread beyond the room of fire origin. In multi-family residential occupancies, the majority of fires in Canada are confined within residential suites and do not spread to adjacent units [2], suggesting that fire-resistance rated elements provide adequate compartmentalization. However, that being said, there are instances of fires involving multiple units, which have resulted in tragic losses.

With the introduction of mass timber construction in Canada, concerns have been raised regarding how these structures will be repaired after a fire. There are several existing methods to repair structures after a fire for wood-frame, steel, and concrete structures, but there is limited information available that relates specifically to the repair of mass timber structures. There are two main concerns related to fires in mass timber structures, that is direct damage from the fire itself and what impact water, from the activation of sprinklers and/or the use of firefighting hoses, might have on the structure (secondary damage). Due to lack of experience with fires in buildings of mass timber construction and uncertainty of applicability of existing rehabilitation methods, insurance companies may charge increased premiums for mass timber structures.

A survey of key mass timber influencers in Canada was conducted to determine barriers and perceived risks for mass timber [3]. The results suggested that water damage, during and post-construction, is considered to be a significant risk and is related to higher insurance costs for mass timber buildings. This is not surprising, considering water damage is the primary source of insurance claims in Canada [4], and accounts for 25% of all property insurance claims in the United States [5]. The survey respondents identified several simple design strategies to help address potential water damage including drains, leak detection systems, maintenance and repair awareness.

2. OBJECTIVE

The intent of this project is to research evaluation and rehabilitation methods that are applicable to mass timber structures following a fire. This includes addressing both fire damage and water damage from sprinkler activation and/or the use of firefighting hoses. This report provides an overview of the type of damage that might be expected following a fire and methods that might reduce potential damage (including design elements and firefighting tactics). Current and existing rehabilitation methods for wood construction will be reviewed and their applicability to mass timber structures will be discussed. This includes the ability to conduct condition assessments and repairs on building elements that can be done in place. The overall objective is to reduce uncertainty related to mass timber construction, which ultimately would allow for more accurate risk evaluation by insurance companies.

3. TECHNICAL TEAM

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4. MASS TIMBER DAMAGE AFTER A FIRE

It is difficult to generalize the extent of damage from a fire because fire size, intensity and duration depend on several factors including ignition source, growth profile, fuel load, geometry, ventilation, room linings, proximity of combustible materials, the presence of sprinklers, etc. However, when a fire is small, where fires are confined to the item first ignited it is unlikely that structural elements will be greatly impacted by a fire. If a fire is able to progress until flashover, where all combustible contents in the room are burning, more damage would be expected.

The majority of structural fires in Canada occur in residential occupancies (74% in 2014) [6]. The primary sources of ignition are cooking equipment and smoking materials in residential fires (approximately 60% combined) [6]. Most fires are contained to the object of fire origin, or the location of fire origin and do not spread [2]. This suggests that the fires are generally small in size and are controlled by occupants, or potentially by sprinklers.

How a fire might impact any wood structural elements depends on the size of the fire and the factors listed above, but is also dependent on whether the wood elements are protected with gypsum board or other protection/encapsulation material. Different categories of wood products are affected differently by fire, such as wood-frame, heavy timber, structural composite lumber (SCL), and mass timber. The main difference between wood-frame and mass timber elements is the dimensions of the section as well as the use of gypsum board to protect wood elements. Wood-frame construction typically relies heavily on the inclusion of gypsum board to achieve fire-resistance ratings.

In a fire, smoke and fire residues do not affect strength of lumber, but can affect surface appearance [7]. With continued fire exposure, such as to CAN/ULC-S101 [8] standard fire, wood is known to char at a slow predictable rate, i.e. the char front progresses deeper into the wood. The standard temperature curve, however, is not indicative of typical compartment fire scenarios. In a compartment fire, the fire profile involves a fire growth phase, fully-developed phase, and decay phase. Standard fire exposure is representative of fast fire growth and a fully-developed fuel-controlled fire. Figure 1 illustrates a comparison of the standard fire curve to a compartment fire test (PRF-03) that was conducted by National Research Council Canada (NRC) during a project to characterize fires in multi-suite residential buildings [9].

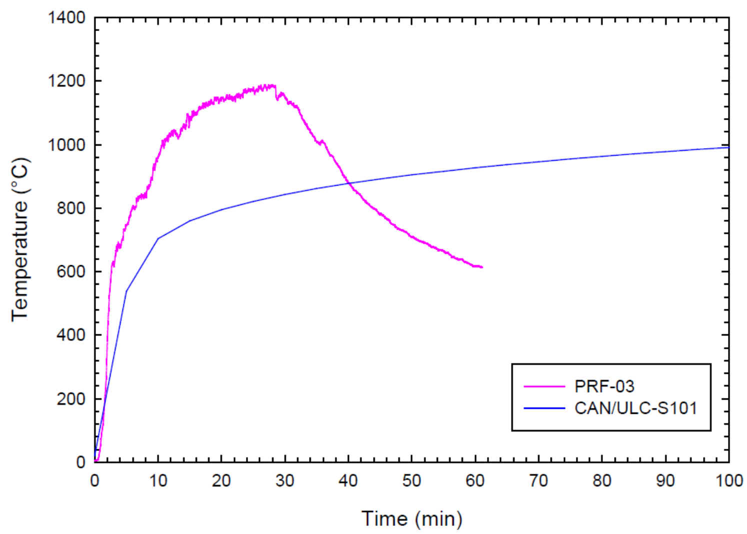


Figure 1. Comparison of standard fire curve to compartment fire [10]

Wood begins charring around a surface temperature of 300°C. The commonly used design value for charring of mass timber is 0.65 mm/min, which can be slower while gypsum board stays in place. Charred wood does not have any load-carrying capacity. Beyond the char layer a temperature gradient is developed within the uncharred wood, known as the heated zone. The depth of elevated temperatures beyond the char front is approximately 38 mm for semi-infinite slabs, like mass timber [7]. The Canadian Engineering Design in Wood Manual, CSA-O86, assumes a depth of 35 mm [11], whereas Eurocode 5, the European standard for design of timber structures, assumes a depth of 40 mm [12]. At a depth of 8 mm beyond the char layer, the temperature is roughly 200°C; at this temperature wood can have more than 80% residual strength [7]. In fire resistance calculations for mass timber elements, a conservative zero-strength layer of up to 7 mm is taken into account [13]. Exposure to temperatures below 66°C, does not greatly impact the structural integrity of wood [14].

For mass timber elements, gypsum board is not necessarily needed to meet fire resistance ratings, the wood itself can be designed to meet fire-resistance rating (FRR) requirements. However, in buildings of encapsulated mass timber construction (EMTC), which are anticipated to be included in the 2020 NBCC [15], there will be limitations on the amount of allowed exposed wood surfaces within compartments. Encapsulation, such as through the use of gypsum board or other materials, will be required to protect the mass timber elements by delaying the ignition of wood elements and limiting their contribution to fire severity. Encapsulation time can be determined as the average time that thermocouples on the timber surface reach 250°C or any one individual point reaches 270°C in unloaded CAN/ULC S146 [16] standard test. The EMTC design provisions will require 50 min of encapsulation time for protected elements, which can be achieved using two layers of 12.7 mm (½ in) Type X gypsum board.

In intermediate-scale tests conducted by National Research Council Canada (NRC) the encapsulation time of gypsum board was evaluated for standard and non-standard fire exposures attached to two layers of 15.9 mm (⅝ in) plywood [10]; the results are presented in Table 1. Non-standard fire exposures are more typical of real compartment fires, where higher temperatures can be reached more quickly, but eventually decay. This explains why encapsulation times were reached faster in the non-standard fire experiments. In a real full-involved compartment fire scenario, wood elements would begin to char sooner than the prescribed encapsulation time.

Table 1. Encapsulation times for Type X gypsum board directly applied to plywood [10]

No. of layers	Gypsum thickness (mm)	Encapsulation Time (min)	
		Standard	Non-Standard
1	12.7	25.5	20.3
1	15.9	21.9	16.3
2	2	58.8	35.2

4.1 Compartment Tests

Several cross-laminated timber (CLT) compartment fires have been conducted in Canada over the last few years to support mid-rise and tall wood construction. In the majority of the tests, sprinklers were not installed and there was no firefighter intervention to represent a rare worst-case scenario. The condition of the structure after the test is summarized herein to give an example of damage that would be expected in such a scenario. In smaller fires that are quickly extinguished damage would be expected to be far less severe.

In the mid-rise CLT test conducted by NRC [10], a fire burned in a fully furnished apartment unit where all CLT surfaces were protected with 2 layers of 12.7 mm (½ in) Type X gypsum board. The test was terminated after 185 min. Charring occurred on the interior face of CLT panels within the compartment, but the depth of charring was not measured. In these tests flames projected out the window, as shown in Figure 2, but the exterior side of the CLT panels did not char (except at the lintel) on the exterior side which was protected with an outboard insulation system. In some areas, such as a load-bearing wall (WA3), temperatures behind the gypsum board reached a maximum of 550^{o}C and stayed at that temperature until the end of the test. This indicates that flaming combustion did not occur in this location, although the wood had charred. At the floor panel, which was protected by hardwood flooring, the CLT surface ply started to char but again there was no flaming combustion. At the ceiling, in the bedroom (where the fire initiated on the bed) temperatures behind the gypsum again stayed below 500^{o}C (except at the centre of the ceiling). There was minimal or no flaming combustion of the ceiling panels in the bedroom. In the living room the gypsum board mostly stayed in place until the end of the test. Peak temperatures exceeded 600^{o}C along the centreline of the living room, indicating flaming combustion had occurred.

Figure 2. NRC mid-rise consortium CLT apartment fire test [10]

In 2014 a demonstration fire was conducted to confirm the performance of a mass timber compartment adjacent to a shaft for use in the 13-storey Origine building [17]. Images from the demonstration are shown in Figure 3. The 5-ply CLT compartment walls were protected with two layers of 15.9 mm (⅝ in) Type X gypsum board; the ceiling was protected with one layer. The shared shaft wall had an additional cold-formed steel stud wall filled with rock fibre insulation for acoustic purposes. The fire lasted for two hours before being extinguished with fire hoses. During the test the gypsum board on the ceiling fell and the first CLT ply of the ceiling was observed to fall off (the CLT conformed to the 2012 edition of ANSI/PRG 320 [18] and not to the latest 2018 edition [19]); after extinguishment sections of the 2nd layer were knocked down exposing the third layer which was lightly charred and in some places uncharred (Figure 3 b). The two layers of gypsum board stayed in place on the perimeter walls and temperatures remained below 500^{o}C at the CLT surface, indicating no flaming combustion of the CLT walls. Gypsum board fell was knocked off the walls during hose application. Only the surface ply of the walls had charred (Figure 3 c), the inner plies were unaffected. Only 5 mm of char was noted on the upper left half of the shared wall (Figure 3 d), it was otherwise uncharred. Charring occurred around the window opening, but otherwise the exterior face of the CLT was uncharred. After the fire was extinguished some water leakage was apparent under the shared wall into the shaft (Figure 3 e).

a) Compartment fire

b) Charring of ceiling. Some 2nd CLT layer in place, 3rd layer exposed

c) Charring of side wall

d) Condition of shared wall after test (NRC)

e) Charring at window opening, evidence of uncharred wood beneath gypsum

f) Water leakage into shaft during extinguishment

Figure 3. Origine mass timber demonstration fire

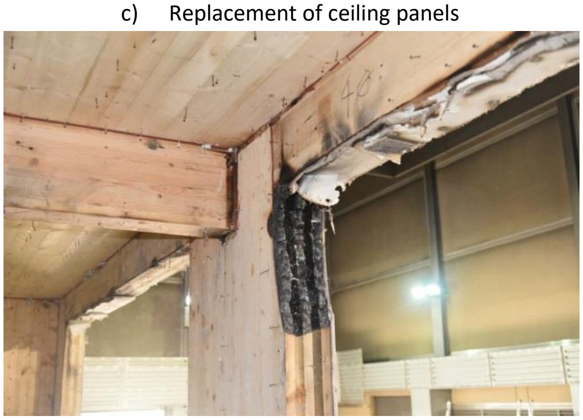
A series of five full-scale CLT compartment fire experiments were conducted by the US Forest Products Laboratory (FPL) in 2017 to support changes to the International Building Code to allow tall wood construction [20]. This included an investigation of how compartment fires are affected by exposed CLT surfaces as well as the effectiveness of sprinklers. Fires were initiated in the base of the kitchen cabinets and tests lasted up to four hours. Images from the tests are provided in Figure 4. The main structure was reused when possible. After each test all of the gypsum was removed and replaced (depending on the design of the subsequent test and extent of damage). The interior cold-formed steel stud walls and dropped ceiling were also replaced. After Test 2, which included some sections of exposed wood, the second floor ceiling was replaced. Figure 4c shows the ceiling being replaced and the charring that occurred on the exposed sections. The support columns and mid-span beams sustained fire damage during the test (Figure 4d). Damaged sections were removed and replaced with equivalent wood pieces. Some localized damage occurred near openings. This was repaired by cutting out the damaged section and replacing it with equivalent material (comparison between Figure 4 e and f). Figure 4g and Figure 4h demonstrate damage around a door frame and its repair. The repairs that were done, were sufficient for the structure to be reused for testing, but are not necessarily indicative of appropriate repair after a fire for in a building in-use. After a fire, it is important to remove all charred wood and to appropriately seal wood exposed to fire to prevent any carcinogenic off-gassing in the future. Test 4 included the use of sprinklers, and Test 5 evaluated the performance of a delayed response sprinkler; both of these tests included exposed wood surfaces in the living room and bedroom. In Test 4 the sprinklers were activated at 2 min 37 s and extinguished the fire, no charring occurred in the living room ceiling. In Test 5 the sprinklers activated at 23 min and were also still able to extinguish the fire.

a) Compartment after Test 1

b) Compartment after Test 2

c) Replacement of ceiling panels

d) Damaged column and beam



e) damage at second floor window

f) charred section removed at window

g) damage around apartment door

h) repaired apartment door frame

Figure 4. US FPL CLT compartment tests [20]

NRC conducted six large-scale CLT compartment fire tests in 2017 and 2018 at the National Institute of Standards and Technology (NIST) to assess the contribution of mass timber elements to compartment fires [21]. Images of the tests are shown in Figure 5. This work was initiated by the National Fire Protection Association NFPA Fire Protection Research Foundation (FPRF). The tests involved varying the location and degree of exposed timber elements without the installation of sprinklers or firefighter intervention. Tests lasted between 1 ½ to 4 hrs. Using gypsum board to encapsulate CLT elements was effective at delaying or preventing ignition of wood.

Test 1-1 was a baseline for comparison and used three layers of 15.9 mm (⅝ in) Type X gypsum board. After the test all of the gypsum was removed and there was no damage to the structure, but there was minor smoke deposition on the exterior corners at the wall-ceiling junction which may have been prevented had the joints been sealed (Figure 5 a). In Test 1-2, where two layers of gypsum were used, one layer remained on the ceiling and both layers were still in place on the walls at the end of the test. No char developed on the walls, only some smoke deposition. There was surface charring on the ceiling, ranging from 0 – 15 mm, with deeper char evident at joint and CLT joints. There were two localized spots of 50 mm deep charring: in a mid-ceiling joint, and in a ceiling corner. Sealing of the joints would have likely reduced charring at these two locations. To reuse the structure for the Test 1-3, the two locations of deep charred were chiselled out and plywood pieces were screwed in place. When the room was relined for the following test, longer screws were used to install the gypsum board on the ceiling because of some of the remaining surface char.

In Test 1-3 one wall was left exposed, all wall surfaces were protected with two layers of gypsum board and the ceiling with three. 85% of this wall charred up to the third ply, with a char depth of approximately 80 mm. Charring was less severe, 60 mm, close to the front window opening. For the remaining protected walls, W3 charred 35% of the surface to a maximum of 10 mm, W4 charred 50% up to 20 mm. The ceiling with three layers of gypsum generally did not char any more, except near the exposed wall up to 10 mm. There was some flame-through at joints 3 hrs into the test, which likely could have been delayed had the joints been sealed. In Test 1-4 the ceiling was left exposed and the walls protected with three layers of gypsum. Most of the ceiling lost more than two plies (70 mm), and 55% charred up to 90 mm. Two of the walls charred 25-40% up to 14 mm, and one wall only had 10% surface char. Test 1-5 had one exposed wall and three layers of gypsum on the other surfaces, it ran for nearly 3 ½ hrs. All of the surfaces charred (Figure 5 g). The exposed wall charred up to 141 mm, the ceiling 79 mm, and 52 mm in the other walls. In the final test, Test 1-6, the entire ceiling and one wall were exposed and it ran for 2 ½ hrs. The exposed ceiling and wall charred up to 154 mm, and the other walls charred up to 68 mm.

a) Test 1-1 compartment after test

b) Test 1-2 condition of CLT after test

c) Test 1-2 CLT repaired with plywood

d) Test 1-3 charring of compartment

e) Test 1-4 charring of compartment

f) Test 1-5 charring of compartment

Figure 5. NRC FPRF CLT compartment fires [21]

4.2 Sprinklers

Sprinklers are used as a means of active fire suppression; they improve life safety and protection of property and can prevent further fire and smoke damage. Sprinklers are intended primarily for life safety protection; preservation of property is more of a concern for non-residential construction [22]. They are designed to control (not necessarily extinguish) a specified fire size using small volumes of water before the fire department arrives. Sprinkler design can be a balance between fire damage and damage from excess water discharge. Any mid-rise or tall wood building will be fully sprinklered as a minimum to meet NRPA 13 [23]. When used in wood-frame construction, sprinklers are known to lower insurance premiums [24].

Typical activation temperature for residential sprinklers is around 68°C; they are intended to address a fire early enough to prevent its growth or spread. Sprinklers are very effective at controlling fires. In residential fires (in sprinklered buildings), approximately 85% of the time one sprinkler head activates [25], 90% are controlled by six or fewer heads [26]. When sprinklers are present, fires are contained to the room of fire origin 97% of the time [27].

If a sprinkler is effective, then a fire was controlled and was not able to grow, therefore limiting potential overall fire damage. Damage per fire can be 70% less when sprinklers are in use, compared to a similar unit without sprinklers which may reach flashover conditions and its fully-developed stage [28]. Figure 6 provides a comparison in the costs (in USD) of damage in instances with and without wet pipe sprinklers; in some cases as much as 75% less. If a sprinkler system extinguishes a fire, this eliminates the need for use of fire hoses.

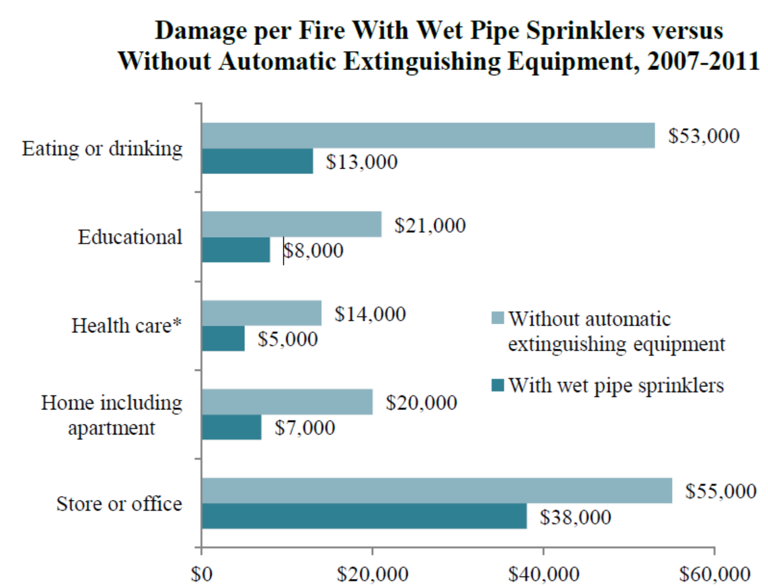


Figure 6. Damage in fires with and without sprinklers [29]

In the compartment tests discussed in the previous section, automatic sprinklers were not installed in most of the tests. These tests replicated a worst-case scenario where the sprinklers failed to activate and the fire department did not respond to a fire. In the one test that did use automatic sprinkler activation (Test 4 as part of the US FPL tests), the sprinklers activated after 2 min 37 s and extinguished the fire. In this test, temperatures were limited and there was no charring on the ceiling.

Quick response sprinklers release between 8 to 24 gpm of water, compared to 80 to 125 gpm for firefighting hoses [26]. The average volume of water used by a sprinkler to control a fire is 341 gallons, whereas the average volume used by firefighters with a hose from a hydrant is 2935 gallons [30]; hoses use up to ten times more water than sprinklers to extinguish the same fire [25]. This suggests that sprinkler exposure is much less severe than using firefighter's hoses.

A concern for sprinklers is the potential for accidental or unanticipated water leakage or discharge. This could be a result of frozen pipes, mechanical damage, installation defects, deliberate sabotage, overheating and excessive temperatures near sprinkler heads, corrosion of sprinkler elements, or manufacturing defects. It is important to ensure proper scheduled maintenance and inspection of sprinkler systems to prevent unexpected damage. Leaks in sprinkler systems are rare, and are no more common than typical plumbing leaks [25].

When water is applied to a fire, there is a possibility that it could adversely affect a wood structure. Moisture uptake and infiltration depends on assembly types and wood products, the amount of water available and the duration of wetting. Exposing wood to water can raise its moisture content, which can have an effect on strength and stiffness [31]. High moisture content levels can also lead to decay and mould over long periods of exposure. Mass timber elements, such as CLT, do not absorb water very quickly, so as long as water is promptly driven off or removed it shouldn't pose a significant problem. Wood decay and mould can become an issue for prolonged water exposure.

Most floors in mid-rise and mass timber buildings use concrete toppings for improved serviceability performance. These toppings will protect the wood from direct water contact. If water is removed quickly, it is unlikely to reach the wood. Floor-to-wall intersections and cracks in concrete may be susceptible to allow water to reach wood elements locally.

Most sprinklers in residential construction use wet sprinkler systems with fusible links, where a heat-sensitive plug is activated by increased temperatures and hot layer (fire effluents) velocity. Wet systems have pipes fully charged with water so that when the sprinkler activates water is immediately available. These types of systems use comparatively larger water droplets than some other types of systems, but the type of sprinkler heads can affect the size of water droplets and spray patterns.

Mist systems are a comparatively new type of system where pressurized water is used to produce small water droplets in the form of mist. This type of system works well to cool a fire, but not necessarily extinguish it. The mist cools flames and hot gases through evaporation, displacement of oxygen by evaporation, and limiting radiant heat [32]. A water mist system was used in Credit Valley Hospital/Peel Region Cancer Centre in Mississauga, to protect an extensive wood roof structure and columns in a building that was otherwise required to be of noncombustible construction. Testing was done at NRC which verified that the mist suppression system could extinguish 5 MW fires at the base of the exposed wood columns [33]. In the past, NRC conducted a review of water mist system research [34]. Mist systems are activated by heat detectors or other means, such as infrared technology; heat detectors can respond faster than sprinkler heads (depending on activation temperature). Less pipe work is needed for mist systems than traditional wet systems. A mist system can use a tenth the amount of water of other systems [35]. Because of the reduced amount of water demanded by this system, there is the potential for mist systems to increase the overall reliability of the system. Water mist systems are currently not recognized in the NBCC or the National Fire Code of Canada [36], therefore would require a performance-based alternative solution for approval. They are permitted in Section 904.11 of the International Fire Code [37]. British Research Establishment developed a guide on the installation of water mist systems in residential buildings, which suggests that the effectiveness of these systems is not yet well established for residential life safety applications [38]. More research into the applicability and effectiveness of mist systems for residential applications is warranted.

Tallwood House (Brock Commons) at the University of British Columbia is the tallest mass timber building in Canada. It is fully sprinklered to meet NFPA 13 [23]. The active fire protection system also includes several additional features to ensure a high degree of fire safety, such as a standard standpipe (which meets NFPA 14 [39]) and a ground-floor water curtain on the exterior glazed curtain wall (in areas that are in close proximity to the adjacent parkade) [40]. The system is connected to the municipal water supply and backed by an on-site 20,000-litre water reservoir and pump. This is sufficient to supply water for 30 minutes, for the entire sprinkler system and increases the reliability of the system to almost 100% [40]. The system is electrically supervised and monitored by the fire department. Sprinkler heads in units were recessed to mitigate the possibility of being accidentally hit and damaged or set off. The pressurized standpipe is housed within the stair core, with connections on each floor where fire departments can attach their hoses.

5. CONDITION ASSESSMENT & REHABILITATION

There are many helpful resources available related to the assessment and repair of wood structures after a fire, including, but not limited to:

- Wood and Timber Condition Assessment Manual. Ch. 5: Post-Fire Assessment of Structural Wood Members [41]
- Inspection, Testing and Monitoring of Buildings and Bridges. Ch. 6: Fire Damage of Wood Structures [7]
- Options for NDS Assessment of Heat and Fire Damaged Wood [42]
- 2nd Edition RIA Guidelines for Fire & Smoke Damage Repair [43]
- Post-Fire Analysis of Solid-Sawn Heavy Timber Beams [44]
- The Rehab Guide [31]

Some of these guides cover wood-frame construction or heavy timber construction, but none are specifically written to address assessment and repair of mass timber structures. This report is intended to address the in-situ assessment of mass timber elements following a fire. Because of the massive nature of mass timber elements it is not feasible to remove elements for laboratory testing or evaluation. Condition assessment should be done in place using non-destructive evaluation (NDE) methods, so that elements could potentially be repaired and brought back into use. The condition of the elements directly affected by the fire needs to be assessed, but it is also important to carry out an inspection of the structure as a whole because elevated temperatures leading to thermal expansion or contraction could have affected other members.

Inspection, Testing and Monitoring of Buildings and Bridges recommends conducting a visual inspection, estimation of residual timber dimensions (local removal of char), a feasibility analysis and structural evaluation to assess wood structures after a fire [7].

Because wood is a natural product, it possesses inherent variability. For this reason, it can be difficult for small, localized non-invasive tests to predict the residual strength of a member, such as to determine the Modulus of Elasticity (MOE) or the Modulus of Rupture (MOR). Detecting the difference between damaged and undamaged wood at a microscopic level can even be challenging [42].

One approach can be not to try to estimate structural properties of a member, but to take a comparative approach to similar members in a structure that were not exposed to elevated temperatures. This is useful for heavy timber, where it may be straightforward to measure dimensions of elements, but this may be more challenging for plate type construction such as a CLT construction.

The main properties that need to be evaluated for mass timber after a fire are the residual depth of members, and their residual strength. Measuring or visually assessing char depth should not be used since the thickness of wood charred is different than depth of charring, due to shrinkage and surface recession [45]. Ideally the char layer should be removed and residual depth of the section measured.

Elevated temperatures impact properties of wood and can result in visual defects, such as surface charring [42]. High temperature can also impact the effectiveness of glues in engineered wood products. Structural deterioration of wood due to high temperatures can also occur without visual evidence; this includes structural capacity loss during heat exposure and permanent strength loss after a fire. The National Design Specification (NDS) for Wood Construction [14] indicates that prolonged heating above 66^{o}C can cause permanent loss of strength, but if exposure is less than 1 h this may be reversible. Further significant degradation happens above 200^{o}C [46]. Irreversible effects to mechanical properties when exposed to higher temperatures depend on moisture content, method of heating, temperature, duration of exposure, wood species, and dimensions of wood member [42].

Beyond the charred layer, wood in the heated zone may experience some irreversible effects. In research done to evaluate the condition of fire damaged covered bridges, glulam beams were exposed to low temperatures to estimate the depth of uncharred wood and thickness of char layer [46]. This work demonstrated that past 33 mm below the char layer the wood was unaffected, but it also became evident that estimating thickness of thermal damaged layer is challenging.

For damaged heavy timber sections, it is recommended to use a certified grader to regrade the wood and determine the residual dimensions after all of the char has been removed [7]. Regarding for this purpose is visual, but can also incorporate non-destructive bending, stiffness, or density evaluation [7].

Mechanical testing can be done, but it generally includes methods that are destructive. This can include taking samples or removing whole members for laboratory evaluation. The US Forest Products Laboratory (US FPL) developed an in-situ test to evaluate the residual flexural properties of timber bridge components after fire exposure [46]. The test involves installing an aluminum block to the bottom of a beam and applying increasing loads and measuring deflections. It was shown that the method was able to predict residual flexural capacity of in-situ beams, when compared to results obtained from destructive testing.

The American Society for Testing and Materials (ASTM) is in the process of developing a standard to determine charring depth of wood utility poles exposed to simulated wildland fires [47]. The proposed method involves using a rigid wire probe to measure char depth.

5.1 Non-Destructive Evaluation Methods

FPInnovations has previously reviewed some NDE tools for wood condition assessment [48]. The US FPL published a report that investigated NDE methods specifically for fire damaged wood [42]. A few methods that may be applicable to mass timber are briefly listed below.

5.1.1 Moisture content

Moisture content can be used as an indicator of condition. The uncharred wood surface can be evaluated with a moisture meter. During a fire, moisture is driven into the wood, away from fire exposed surface, creating local elevated moisture contents, which destabilize after temperatures decrease [7]. A 1% change in moisture content can indicate a 2 to 6% change in wood strength [7].

5.1.2 Density

Wood density reduces at temperatures between 200 to 350^{o}C; at 340^{o}C density can be reduced by 40% [42]. Charred wood is considerably less dense than uncharred wood. Core samples can be taken to evaluate density and assess condition [45]. Resistance drilling can also be used to correlate changes in resistance to changes in density.

5.1.3 Resistance drilling

Resistance in a wood assembly can be assessed using micro-drilling. This is a semi-destructive procedure which drills a small hole (up to 3 mm diameter) the entire depth of a member. The electronically controlled drill evaluates resistance (based on the drill-penetration rate) and measurement profiles can be correlated to relative density gradients. The method was originally intended to correlate resistance to decay and wood quality.

Resistance drilling was used to evaluate the condition of in-situ timber elements in several high-profile heritage buildings [49]. The method was effective at quality assessment, provided multiple measurements were taken due to the localized nature of the method.

Micro-drilling on fire damaged beams demonstrated that the charred section was considerably less dense than the sound wood and the interface was easily detected [50]. Using the profile to estimate the remaining depth and thickness of the thermally damaged wood layer was more challenging.

The Resistograph® [51] is a commercially available micro-drilling tool, shown in Figure 7. A Resistograph® was used to evaluate the residual depth of nail-laminated timber (NLT), dowel-laminated timber (DLT), X-Laminated Veneer Lumber (X-LVL), and glued-laminated timber (GLT) assemblies [52] [53]. The assemblies also had sections cut after the fire, or were visually inspected, to determine the residual depth of the section. The visual measurements simply determined the residual depth of the section based on the interface between charred and uncharred wood. The visual measurements were generally in agreement with the Resistograph® measurements, within +/- 10 mm. Figure 8 is a resistance plot of a 2x6 NLT floor after 100 min exposure to a standard fire. The assembly had one layer of 12.7 mm (½ in) plywood on the unexposed side of the assembly. The plot demonstrates that there are roughly distinct sections: air (on either side of the assembly), plywood, mass timber (NLT), and charred wood. Some of the sections are well defined by a roughly horizontal line, such as the uncharred wood, but the transition to char layer appears as more of a gradient. This could be a useful preliminary evaluation tool, but because of subjective interpretation of the plot, it should not be relied on to determine exact residual dimensions of an assembly.

Figure 7. Resistograph®

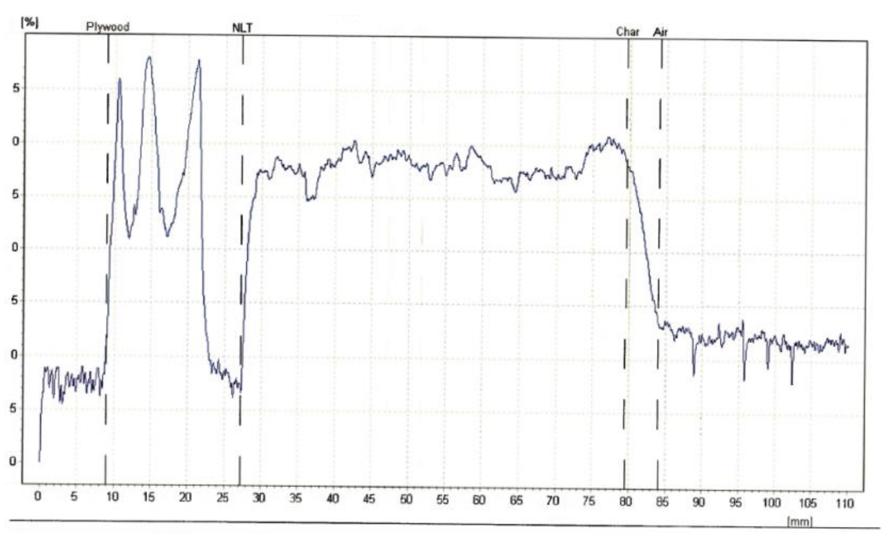


Figure 8 Resistograph® plot of NLT exposed to fire

5.1.4 Screw-Withdrawal Test

The screw withdrawal test relates maximum extraction load to residual flexural properties, it is useful for evaluating comparative condition [42].

5.1.5 Hardness

Hardness is a measure of the force required to make a specific type of indentation in a material. Hardness can be used to evaluate condition of wood members near the surface. A similar method is micro-indentation which presses a 1.5 mm long x 0.5 mm diameter pin into wood with a specific load. Alternatively, penetration testing which uses a larger diameter pin can also be used. It assesses the number of strikes needed for a rebound hammer to drive the pin a given distance into a member. Another option is the Pilodyn test which evaluates penetration depth of a spring-loaded pin.

5.1.6 Sound/Stress Wave Evaluation

Sound or stress wave evaluation involves generating an impact sound and measuring the time it takes for the sound to reach the other side. This method has demonstrated some promise to predict MOE for fire damaged wood [42]. Moisture content and dimensions of the member need to be known for accurate measurements.

5.1.7 Tomography

Tomography includes X-rays and ultrasonic imaging, measuring high-frequency wave movement as it disperses through wood to develop a picture of the interior of wood elements. Sound waves reflect off defects, such as splits or voids. FPInnovations has one of the most powerful industrial Computed Tomography (CT) scanners in the world. In a field demonstration, sonic and electrical impedance tomography was used to assess the interior condition of a tree [48]. It was shown to be useful to demonstrate wood condition (such as early signs of decay, wet wood, and heartwood). US FPL has published a review of ultrasonic NDE methods for wood [54]. Some ultrasonic testing has been done on charred specimens [55]. In these tests, time delay and wave velocity for charred specimens was minor, but Power Spectral Density (PSD) plots changed significantly with charring.

5.1.8 3D scanning

High-resolution 3D digital laser scanning of structures post-fire was investigated after a fire at the Glasgow School of Art (GSA) in 2014 [56]. There may be potential for 3D scanning technology as a condition assessment tool for timber elements following a fire. Varying the measured wavelength resulted in better clarity of images to identify affected areas, shown in Figure 9. This research also demonstrated the benefit of having 3D scans of buildings taken prior to disaster events for the purpose of comparison. 3D scanning of structures is being used with Building Information Modeling (BIM) to monitor buildings under construction and develop as-built drawings and monitoring.

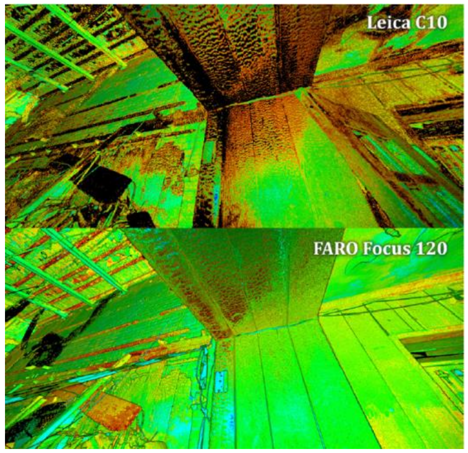


Figure 9. Comparison of laser scans of wet, fire damaged timber after a fire at GSA [56].

5.1.9 Modelling

Fire modelling can be a useful tool to recreate a fire scenario to potentially assess the condition that wood elements might have been exposed to. Maximum temperatures in a fire can be estimated following the NFPA 921 Investigation protocol [57] or from fire modeling software (e.g. CFAST zone model or FDS using computational fluid dynamics). Once details of the fire environment are determined, a heat transfer model can be developed to determine thermal gradients within wood elements, and subsequent impact on structural capacity. A flowchart of the fire modelling process developed by Buchanan [58] is presented in Figure 10. Coupling thermal and structural models in computer modelling software, such as finite element modelling, can be challenging.

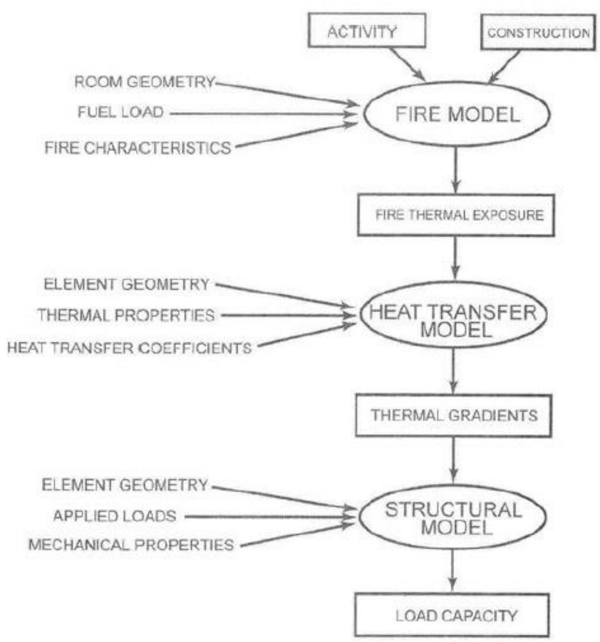


Figure 10. Flowchart for modeling fire-damaged wood members [58]

5.2 Rehabilitation Methods

Once an assessment of the condition of wood elements after a fire is completed by a qualified design professional, this information should be used to identify what can remain in place, what can be repaired, and what should be replaced. The structural importance of any members should be taken into consideration. If any element is at risk of collapse, it should be addressed immediately.

Localized charred wood can be removed with sanding, scraping, or abrasive blasting. Any deeper section can be removed with a chisel or curved blade. After all evidence of char has been removed, affected wood surfaces should be sealed to prevent residual odours.

For wood-frame wood structures affected by fire, it can be simple to replace individual members. Typically, if charring is greater than 6 mm (¼ in) on wood-frame elements they should be replaced, if the char depth is less than 6 mm then no repair is needed, the char can simply be removed [7]. If there is only light surface char, any char and fire residue should be removed. When members are structurally compromised, additional support can be added. Comparative assessment to members unaffected by fire can be useful in these situations.

For large timber members, it is common practice to neglect any impact to the heated zone when evaluating the residual capacity of fire damaged members [46] [58]. This may not be conservative, and further reduction of the cross-section may be more appropriate [46]. In some guides, once charred layer has been removed on heavy timber elements, additional removal of up to an additional 7.5 mm (0.3 in) for compression members and 13 mm (½ in) for tension members may be warranted [45]. Some repair methods assume that a 30 mm layer of wood beneath the char is exposed to elevated temperatures and undergoes thermal degradation [59]. In this method, the residual capacity of members is determined based on the residual depth of members plus the removal of an additional 30 mm of wood. Alternatively, when removing char, an additional 20% of the char depth of undamaged wood could be removed [7].

Treated or sealed wood surfaces exposed to smoke should be cleaned to remove any soot residue. Unfinished wood may be more prone to staining from soot deposition and absorption of smoke odours. Unfinished surfaces may require sanding and sealing to prevent residual odours, which can be carcinogenic. Appropriate sealers or treatments should be used. Restored structural members should not have any fire residues remaining before interior finishes are applied.

Fire damaged connections require detailed inspection, in particular where connections are in contact with wood because metal parts can conduct heat into wood. The degree of damage to connections depends on the quality of metal and the area of the surface that is exposed to fire [7]. Fire can also result in corrosive effects of connection components from residues that are driven out of wood members in a fire [7].

A list of recent studies on rehabilitation techniques for timber is provided in [60]. This included mechanical fasteners, bonding composite materials, adding or materials or near surface mounted laminates, embedded Glass Fiber Reinforced Polymer (GFRP) or Carbon Fiber Reinforced Polymer (CFRP) circular rods. A review of failure modes and repair techniques was conducted to assess the effectiveness of repairs for timber beams [61]. Some other recent promising research has included: GFRP rods to repair glulam [62], adhesively bonded composite patches [63], the use of FRP [64] [65], and perpendicular to grain reinforcement for solid timber, glulam, and LVL [66]. Research has shown that a method of attaching plywood sections with steel screws to the top and bottom of failed glulam sections (with and without delamination) can be effective at restoring strength and stiffness, in some cases increasing overall strength [60]. This method was designed to be done in-situ and may have applications for repair of glulam beams following a fire.

In the compartment tests reviewed in the previous section, small areas of damage were either cut-out or chiselled out and repaired with equivalent wood sections. This method is useful to create smooth surfaces and to restore elements with localized damaged to original dimensions. This is only applicable for localized charring of elements where structural capacity is not affected.

6. MOISTURE MITIGATION

As was previously mentioned, moisture uptake of wood depends on the amount of water available and the duration of wetting (among other things). After sprinkler activation or the use of fire hoses it is important to remove applied water from a structure as soon as is practical. Ideally all applied water would be converted to steam during extinguishment, but that is not typical [67]. Water can begin to accumulate in areas where there is not enough heat to convert the water to steam.

Firefighter responsibilities include limiting primary damage from fire and smoke, but also limiting secondary damage from indirect causes such as suppression. This includes removing water both during and after fire hose application through what is known as salvage procedures. The Essentials of Fire Fighting textbook covers Loss Control, which includes Salvage and Overhaul operations [68]. Overhaul refers to the process of extinguishing any remaining or hidden fire, after main fire extinguished.

6.1 Salvage Procedures

The following is a summary of salvage procedures as discussed in various manuals [68] [67] [69]. The principle of salvage is the prevention and reduction of damage from indirect causes, by removing water quickly and safely without damaging unaffected areas [67]. The objective is to minimize property loss before, during and after a fire; salvage begins on fire service arrival and ends when fire service leaves. It can, and ideally should, occur while suppression is ongoing, depending on resources available and situational factors. This includes minimizing damage to the structure and reducing the time to repair and bring a structure back into operation. Water should be addressed and removed as soon as is practical. Some specific tasks include expelling smoke, removing heat, controlling water runoff, removing water from the building, securing the building after a fire, and covering openings after a fire.

Salvage mainly deals with protecting property from water damage and removing water from the interior of a structure, and includes, but is not limited to, diverting water to the exterior of the building and removing water from floors and basements. Tarps and covers are used to protect contents, furnishings and the structure. They can be made of canvas, vinyl, or heavy-duty plastic. Contents can be protected in place, moved to safe location, or removed from the structure. After a fire event, salvage also includes covering any openings, such as broken windows or doors to prevent further damage, such as moisture infiltration.

Many effective salvage strategies have been developed for use in wood-frame, steel, and concrete construction. Some of these strategies should be further refined and developed for specific use in buildings of mass timber construction.

Loss control impacts suppression, because it includes the conscious application of water and considering how water will impact the structure. The start of suppression can be delayed until vital contents are protected or removed and nozzles should be tuned off when not in use. Sprinklers should be deactivated as soon as practical (after a fire declared under control); this can be done using sprinkler wedges or stops, or by turning off the water at the sprinkler system control valve. Sprinkler wedges and stops should be replaced with new sprinkler heads as soon as practical. Pre-fire planning for structures should include firefighters familiarizing themselves with the type of sprinkler and location of shut off valves, so that sprinklers can be turned off quickly. The department should also be aware of available drainage systems, and presence of any pumps.

The amount of water that will be needed for suppression should be estimated and the ability to catch that amount of water on floors below should be assessed before suppression begins. Also, it is important to be aware that water can impose additional load and can contribute to collapsing of structural members (a potential concern for wood-frame structures) [69]. A 250 gpm nozzle will release more than a ton of water per minute [69], suggesting that using multiple hoses can quickly increase applied loads in a building when releasing large volumes of water.

Hall or floor runners should be put down as firefighters enter the building to protect floors, carpets, and stairs from water and debris that could be tracked in. Personal contents on the floor below should be protected first with tarps and covers and the floor should be ‘bagged’, i.e. covered completely, and edges rolled. An example of a floor cover with rolled edges is shown in Figure 11. Cover edges can be raised on chairs, boxes, etc. to ensure water doesn’t overflow at edges. Edges can even be nailed to baseboards to prevent overflow.

Figure 11. Catchall floor cover [68]

When water needs to be removed from a structure, it can be channelled towards a drainage point or to the exterior. Removal chutes direct water to a drain or outside, or to a catchall, a temporary pond to catch water. If using existing plumbing, it should be verified that any drains are clean and open. Significant damage can occur if drains are obstructed. Toilets can be removed and existing sewer connections can be used, water can also be dumped into tub, showers, and sinks. An example of water being routed towards a toilet drawn is shown in Figure 12. Residual water can be cleaned with wet/dry vacuums, squeegees, etc.

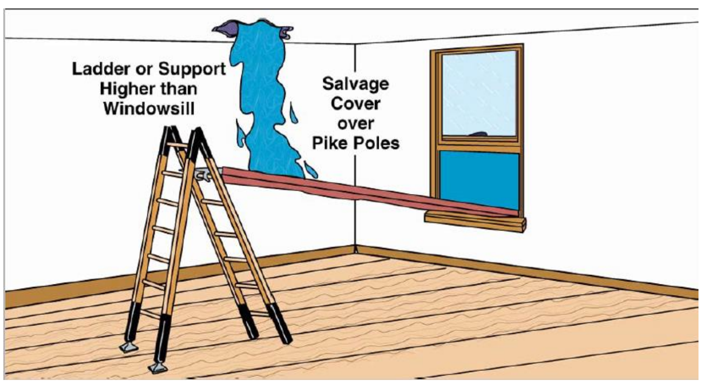
Figure 12. Routing water towards a toilet drain [69]

Larger volumes of water can be moved to the ground level, then exterior, using stairways, elevator shafts, or chutes. In multi-storey buildings, it is not ideal to use exit stairways and elevator shafts because the water has a longer distance to travel and therefore more opportunities to cause damage. Waterproofing and proper drainage are more effective at reducing water damage [67]. When stairways are used the treads and risers should be protected with a cover, as shown in Figure 13. Note rolled edges to prevent overflow. Before water is moved using an elevator shaft, it is necessary to check if floor drains are open. If water does pool in a basement or elevator shaft, dewatering devices or pumps are used to move water. Protection should be provided at elevator openings in storeys below before water is moved. In a mass timber building it may be difficult to dry wood surfaces at the base of a shaft, whether elevator shafts should be used for salvage operations in mass timber buildings should be considered further. It may be prudent to provide alternative means to remove water from upper storeys.

Figure 13. Use of salvage cover to protect and divert water down stairway [67]

Water damage is sometimes caused by water following vertical pipes or columns downward [67]. Covers should be tightly bound around vertical through-penetration pipes, with the cover bagged on the floor to catch the water. Water damage can also be caused by leaking hose lines connected to a wet standpipe, or leakage from hoses or loose couplings [67]. Floors should be protected by spreading a cover underneath hoses and bagging the cover to trap excess water or be diverted it to the exterior.

In wood-frame construction there is an option to cut holes in floors and construct chutes on floors below to move water. This is only done when there is a large volume of water and there are insufficient drains or means to otherwise move the water. Examples of removal chute are shown in Figure 14. In this case, water can accumulate between floor and ceiling. It may be prudent to provide additional drains in mass timber construction, because cutting through the floor quickly is likely not an option.



a) [69]

b) [67]

Figure 14. Routing water to exterior using chutes

Once water has been removed from a structure, it is important to remove covers to promote air circulation to surfaces. Windows and doors can be opened to promote drying. Ventilation fans can also be useful.

Salvage operations should be reviewed as they pertain to mass timber construction to evaluate if they are any additional measures or differences to procedures that should be considered. It may be appropriate to provide additional attention on protecting exposed wood elements. Educating firefighters on mass timber construction techniques would also be beneficial to ensure effective salvage operations.

6.2 CLT drying

FPInnovations has conducted research on the drying performance of CLT elements, in particular relation to building durability during and after construction. Research on the wetting and drying performance of on-site moisture protection for CLT confirmed that moisture is slow to penetrate into the wide surface of CLT, whereas CLT edges are more susceptible to moisture absorption due to end grain exposure [70]. This research also looked at drying rates of wet CLT after being covered with drywall or 38 mm thick rigid mineral wool insulation. CLT was wetted through outdoor exposure for one month and then samples were left to dry in a shed (damp exterior conditions). The mineral wool insulation had a negligible impact on drying capacity. One layer of 12.7

mm (½ in) thick drywall reduced drying rates by 20%, and three layers reduced the drying rate by 50%. This slowed drying confirms that any wetted wood should be dried before recovering. The moisture content measured 6 mm below the CLT surface, mostly remained below 20%. In an enclosed building, lower humidity (through space heating or dehumidifiers) would likely speed up drying rates.

Figure 15. CLT specimens with gypsum board or mineral wool drying in shed [70]

6.3 Moisture Remediation

After water has been used to control a fire, all excess moisture should be promptly removed from the area. Salvage operations are intended to remove the majority of water, following this, the area should be dehumidified and left to dry. Hygrometers can be used to detect residual moisture levels in exposed wood. Mould will not grow on wood when the moisture content is below 20% [71]. Appropriate monitoring during drying is important to ensure there is no residual water and/or to limit shrinkage cracks due to excessive drying.

Water moves with gravity, therefore it is important to inspect walls and ceilings in areas below water application. Infrared cameras can be used to identify locations of water infiltration that may be hidden behind walls and in ceilings. Any wood surface that got wet, or is suspected of excess moisture, should be inspected. Any surface with evidence of water should have surface membranes removed so that wood elements can adequately dry to prevent any potential moisture issues (i.e. mould growth).

FPInnovations has conducted various research projects on how different wood products are affected by moisture [72] [70] [73] [74] [75]. Much of this research is related to moisture infiltration during construction, but many of the core concepts of wood (in particular mass timber) drying are also relevant.

7. CASE STUDIES

There have been a few select fire or water exposure events in mass timber buildings. There are no known cases of large fires in completed mass timber structures in North America. This may be partially attributed to the rigorous fire safety design of these buildings.

7.1 Origine Building

The Origine building is a 13-storey mass timber building in Quebec, QC that was completed in 2017. In 2018 a sprinkler was accidentally activated. All discharged water was cleaned up and any affected surfaces were replaced.

7.2 FondAction CSN Building

The FondAction CSN building was the first 6-storey mass timber building in Canada. It was built in Quebec, QC and completed in 2010. In April 2008 there was a fire.

7.3 Arbora Building

In October 2018, a fire broke out on a third storey balcony at one of the Arbora buildings in Montreal, QC. The building is a 8-storey mass timber building above a 1-storey concrete podium. Arbora consists of three similar buildings, which currently makes it the largest residential mass timber building complex in the world. Images from the fire, during exterior suppression, and damage after the fire are shown in Figure 16. The fire was confined to the balcony, but there was damage to the interior after a window broke. Interior damage from the fire was limited, but water did enter the structure through the window. The structure and fire safety features were effective at preventing further fire spread.

a) Fire

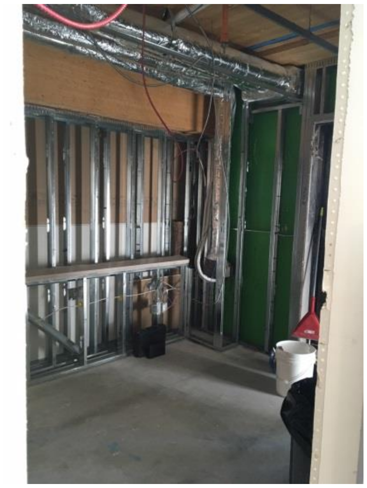
b) Hose application

c) Balcony damage

d) Damage to opening from interior

Figure 16. Arbora fire Oct 2018

After the fire, all residual water was cleaned up and any affected gypsum board within the compartment was removed, as shown in Figure 17. Flooring in the affected area was also removed. A cut was made in the concrete topping to assess whether any water had reached the mass timber substrate. It was determined that the temperature of the mass timber was at ambient (around 20^{o}C) and moisture content was between 12-13%. This suggests that water from suppression did not penetrate the concrete slab and the mass timber was not adversely affected. The prompt removal of water following the fire, and the presence of a concrete topping prevented water from reaching the mass timber beneath.



a) Interior damage removed and cleaned

b) Condition of slab after water removal

Figure 17. Arbora unit rehabilitation

7.4 Redstone Building

The Redstone Arsenal Building is a hotel constructed on a military base, in Huntsville, AL. The building is shown in Figure 18. It used over 1200 CLT panels, as well as wood beams and columns. The CLT exterior walls are 125 mm thick and the CLT floor was 175 mm thick. All walls are protected with gypsum board. During construction in 2016, an electrical fire occurred in the basement during the electrical panel installation [76]. Damage was essentially limited to the electrical equipment, with minor damage was sustained to gypsum walls in the electrical room. The fire was quickly suppressed and the CLT itself was never exposed to flames. Because of the security of this building (because it is on a military base), interior images could not be shared. This example suggests that fires can be adequately controlled in mass timber buildings and fire damage to the structure can be limited or minimal with adequate protection.

Figure 18. Redstone Arsenal hotel under construction (photo credit LendLease) [77]

8. CONCLUSIONS

Fire and subsequent water damage are a concern in mass timber buildings; this may be due in part to lack of knowledge and lack of experience. How a mass timber structure can be rehabilitated following a fire and water application was investigated.

Based on statistics, the majority of residential fires are small and only localized fire damage might be expected. Most fires are controlled by a singular sprinkler head, requiring limited amounts of water application. Whenever water is applied to control a fire, any residual water should be addressed quickly because water infiltration into wood is related to the duration of wetting. Following good salvage practices is an important component to limiting the potential impact water may have on a structure after a fire. Because of differences between mass timber buildings and other more traditional types of construction, salvage operations should be reviewed as they pertain to mass timber construction to evaluate if they are any additional measures or differences to procedures that should be considered, including considering the protection of exposed wood elements. This also includes the education of the fire service on salvage concerns specific to mass timber.

After a fire, a condition assessment of all affected timber elements should be carried out. In the majority of fires, which are small, localized charring will likely not have a significant effect on structural elements, but any charred surfaces should be removed and the condition of the residual element assessed. Any surfaces, such as gypsum board, that have been affected by the fire or water should also be removed to ensure water is not concealed behind them. If water is present, wood elements need to be dried before surfaces can be recovered.

For larger fires, where structural elements might be impacted, the condition of the structural elements should be assessed to determine whether elements can be repaired or require replacement. This report reviewed various non-destruction evaluation methods to assess the condition of wood after fire exposure. The applicability of various structural repair methods for mass timber should be further investigated. The development of an evaluation and rehabilitation guide, specifically targeting mass timber following a fire, should be developed.

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