World Conference on
Timber Engineering
Oslo 2023

FIRE RESISTANCE TESTING OF CLT-CONCRETE COMPOSITE FLOOR SLABS UTILIZING SELF-TAPPING SCREWS AS SHEAR CONNECTORS

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ABSTRACT: In massive production, mass timber sections made of engineered wood, such as cross-laminated timber (CLT) panels, accelerated the pace of the construction of tall wood buildings in North America in the past few years. However, more stringent fire safety measures are applicable to tall timber buildings. Most critically, floor systems in mass timber buildings can be made more robust, span longer distances and exhibit enhanced fire resistance by adding a top layer of concrete to allow a timber-concrete composite (TCC) floor system when adequate shear connections are utilized. This paper presents the experimental results of the fire resistance tests of two full-size, one-way TCC floor slabs that utilized self-tapping screws (STS) as shear connectors. The main objective of this new experimental study is to investigate the enhancement of the fire performance when designing a CLT panel as a TCC floor assembly through achieving the required composite action with a top concrete layer at the interface between the two materials. Test results show that a minimum fire resistance of two hours required by applicable building codes for mid-rise residential buildings has been achieved for CLT floor panel by designing it as a TCC floor assembly, taking advantage of the composite action activated by the utilization of 45-degree inclined STS as shear connectors.

KEYWORDS: Timber-concrete composite sections, Fire resistance, Self-tapping screws, Shear connectors

1 INTRODUCTION

A key aspect of structural engineering research and design is looking at the optimization of sections and finding more efficient solutions to fundamental behaviours. That is the primary motivation and reasoning behind the design of composite structural members. They are maximizing the strengths of materials and compensating for the weaknesses. While many composite members can be designed, timber-concrete composites (TCC) sections are of great interest, with the timber material resists the tensile stresses and concrete resists the compressive stresses.

TCC sections are an excellent solution for both designing new structures and restoring existing timber structures since a fundamental improvement is in service for vibration and drastic change possible for fire resistance rating requirements in current building codes and design standards. Thereby, increasing the possibility of not only building tall with timber but also leaving the material exposed, impacting the architectural concept of the structure, and increasing the use of engineered-wood products (EWPs) as a design solution.

As under current standards, the only possibility to design tall mass timber building is with incorporating a type of construction known as Encapsulated Mass Timber Construction (EMTC). This forms an alternative solution for tall wood buildings to meet the code objectives and functional statements pertinent to the requirements of the combustible construction [1]. EMTC is defined as a type of construction in which a degree of fire safety is attained using encapsulated mass timber elements with an encapsulation rating and minimum dimensions for the structural timber members and other building assemblies [2].

In recent years, there has been a new surge of interest and studies for the introduction of EWP in taller mass timber buildings. Such products include cross-laminated timber (CLT) panels, which has been gaining popularity since they were first introduced in the early 1990s in Europe. Not initially examined in Canada until 2007, and not until 2017 when it was fully implemented into CSA-O86 *Engineering design in wood* standard [3]. CLT panels are mass timber sections made by gluing and pressing wood lamellas with alternating fibre directions (±90°) [4]. The panels shall have an odd number of lamellae (Typ. 3, 5, 7, or 9) arranged symmetrically around the centre layer, with the thickness of each layer ranging from 20 to 45 mm.

It is typical in mass timber construction to pour a concrete layer on top of timber floor slabs to improve their vibration and acoustic characteristics as well as to provide a space for conduits to run electrical and plumbing

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https://doi.org/10.52202/069179-0241

utilities. However, this practice is a missed opportunity to improve the overall structural behaviour and fire resistance of such timber floor sections. TCC sections have the involved materials (i.e., timber, concrete, shear connectors, etc.) working together in each respective strength and thus, altering the location of the neutral axis of the composite section to achieve the maximum possible strength and stiffness.

Contrary to popular belief and hesitation when considering mass timber materials for construction, they have excellent fire resistance and perform well under elevated temperature conditions. Although without verified test results, it causes a limitation of the industry's progression and possibilities when considering building tall in timber and options to have structural elements left exposed.

2 LITERATURE REVIEW

2.1 CLT BEHAVIOUR UNDER FIRE

To design TCC sections utilizing CLT panels, it is essential first to understand the expected behaviour and performance of the mass timber panel as a standalone element. More extensive research programs have focused on CLT panels when exposed to fire. Most of the fire testing completed when studying the behaviour of CLT floor slabs followed standard fire testing conditions. It is the most straightforward approach for comparing results with different parameters or materials for equivalent fire severity. However, studying test specimens under natural fire conditions allows a more accurate representation of fire in a realistic setting. The key benefit of natural fire exposure is adjusting for different ventilation conditions. This mainly affects the fire growth rate, as when a fire reaches the point of flashover, this influences the duration of the steady state burning stage of the fire.

The studies conducted by Mindequia et al. [4] and Wiesner et al. [5] were both part of the Epernon Fire Test Programme, a multi-partner collaborative research project launched in 2017 and focussed in its studies on the comparison between natural and standard fires in their effects on buildings. For the studies conducted by Frangi et al. [6] and Wang et al. [7], the primary study parameter was changing the thickness and number of plys used in the composition of the CLT panels, as well as the corresponding changes in the temperature profile and charring rate of their test specimens. In the study conducted by Mindeguia et al. [4], the structural capacity of the CLT panels was investigated, while Wiesner et al. [5] examined the thermo-mechanical behaviour of the CLT panels.

As with studying the fire performance of any construction material, it is crucial to understand the development and progression of heat transfer within the material. It is even more critical with CLT panels and other engineered-wood products. Such products are not homogenous, and their composition involves adhesives, even in relatively small amounts. Having accurate temperature readings throughout the sections is critical, as this information is essential to determine the actual charring rates and depths.

When fire contacts wood, a charred layer on the side of contact is formed, and as the heat continues to grow, the thickness of the char layer increases. Advantageously, this char layer protects the remaining uncharred core of the cross-section that is not yet exposed to fire. However, there is still a reduction in the cross-section area sustaining the applied loads. When studying the fire performance of CLT panels, a significant difference in the cross-section overall fire resistance is whether the charred layer falls off or remains intact. If the charred layer falls off, the protective function it gives is lost; thus, a new char layer starts forming. When a layer falls off, there is an increase in the charring rate as the underlaying layer becomes exposed to elevated temperatures that are higher than its initial temperature at the beginning of the fire test. Falling off of those layers is described as a delamination effect. This can occur locally at isolated locations, or globally when most of a ply falls simultaneously from a CLT slab exposed to fire.

Charring rate is evaluated by determining the thermal progression throughout a fire test and then, comparing temperatures afterward to determine the time each point reached 300°C. In general, the nominal charring rate of solid and glued-laminated timber sections under one-dimensional standard fire exposure is 0.65 mm/min, given by Eurocode 5. While, in general, the values agree reasonably well with the standard value from Eurocode 5, there is still some differences. This suggests that the charring rate alone is insufficient for predicting the residual loading capability of CLT floor slabs.

Thermocouples are essential to monitoring temperature, but they are limited by their placement location and can only determine when that spot reaches the critical temperatures. By removing the charred thickness and measuring the remaining section, a more holistic view of the slab performance and the differences across the slab can be achieved. Therefore, the char layer depth recorded in each experimental study is an important parameter as it influences the residual sections of a CLT slab that remain after fire exposure to sustain the applied loads without collapse.

2.2 DESIGN OF TCC SECTIONS

For TCC sections, two key assembly types of sections can be used: beam-type assembly and slab-type assembly. First, the beam-type system consists of a concrete slab supported by timber beams made of either mass timber or EWPs. A thin wood layer can also be placed between the concrete and beams to act as permanent formwork. The second type is the slab-type assembly which consists of a concrete slab on top of a solid mass timber panel. An important distinction between the two assembly types, besides the timber components being in either the shape of beams or slabs, is the exposure of the concrete to fire.

https://doi.org/10.52202/069179-0241

When designing such TCC sections, there are two methods to follow, the γ-method and the Elasto-Plastic Method (EPM). The former is the more common and original design concept. At the same time, the latter is relatively new and explicitly implemented for ductile connectors as the γ-method assumes elastic behaviour before the point of yielding. When EPM is within the plastic range and afterwards, the shear connectors begin to yield. Both design methodologies need to be checked, but EPM is critical to the design of TCC sections for shear connectors with less stiffness, such as self-tapping screws (STS).

One of the three fundamental aspects of the design of TCC sections is the shear connectors used to connect the two materials, giving the location to transfer stresses between the different materials. This results in many possible connectors that can be used, with their pros and cons in quantity required, level of skilled labour for insulation, cost per unit, availability, and research studied with validated results and behaviour in ambient and fire conditions. Therefore, to advance the understanding of the behaviour of TCC sections more experimental examining of the various shear connectors in full-scale testing setup to capture in-situ conditions and the overall performance of the sections is needed.

STS are a commonly used type of metal fasteners in timber structures, whether used for connections or for strengthening structural elements and connections. They can either be fully or partially threaded; while in TCC sections, the fully threaded screws are the preference. This is mainly due to the more uniform load transfer between the fully threaded screw and the timber material, which results in better withdrawal resistance. Thus, enhancing the strength and stiffness of the shear connections developed by those STS in TCC sections. STS that are fully threaded is hardened to develop a high yield moment and tensile and torsional strengths, while their long threads provide reliable embedment in the timber elements [3]. A benefit of their inherit design is that typically no pre-drilling is required, meaning they are faster to install than their counterpart shear connectors. All that makes them cost-efficient shear connectors for TCC sections, which requiring significantly less quality control measures or skilled labour during installation.

2.3 TCC SECTIONS BEHAVIOUR AT AMBIENT TEMPERATURE

The majority of completed studies are on the behaviour of TCC sections at ambient temperature. However, only a few studies have been completed recently after streamlining to focus on sections utilizing CLT panels and STS as shear connectors. Many factors influence the design and strength of the screw-type shear connections: overall dimensions, embedment length, angle of inclination, and screw spacing. Those parameters alter the strength, stiffness, and overall behaviour of TCC sections. The study completed by Gerber [8] included an extensive experimental program studying different types of connections used in different timber materials and testing variances of each type of shear connectors. TCC sections experimentally tested in that study included: (a) screws at 30-degree angle of inclination, (b) screw pairs at 45-degree angle of inclination, and (c) screw pairs at 45-degree angle of inclination with an interlayer. The research study also included different screw lengths and diameters. In a relatively recent study completed by Mirdad and Chui [9], three different parameters were investigated in different TCC sections: screw embedment length in the timber; thickness of the insulation layer used; and the screw angle of inclination with the horizontal.

Another experimental study completed by Salem and Virdi [10] examined the influence of three parameters on the shear strength of TCC sections: longitudinal screw spacing; number of screw rows in the transverse direction; and age of concrete. Study parameters involved reducing the longitudinal screw spacing from 200 mm to 150 mm; increasing the quantity per row from two to three screws; and increasing the concrete curing age from 14 to 28 days. Interestingly, results of that study show that reducing the screw longitudinal spacing or increasing the number of screws in the row resulted in a similar increment in the maximum load sustained by the different TCC sections. However, the authors of that study recommended increasing the number of screw rows over decreasing the screw longitudinal spacing as this allows a more uniform distribution of the shear stresses in the transverse direction of the TCC section.

As part of the previously mentioned study conducted by Gerber [8] and after completing the pilot testing phase which included a series of shear tests, four-point flexure bending testing on long TCC slabs was completed. Test specimens involved CLT slabs as the timber component with screws at 30-degree angle of inclination in the shear flow direction. The screw spacing in the longitudinal direction alters, with a spacing of 150 mm in the high shear zone near the supports increased to 300 mm in the low shear zone in the middle of the slab. Higgin et al. [11] also conducted flexure bending tests as a part of their experimental program. However, their samples were tested under three-point flexure bending, and they utilized 45-degree orientated screws in the shear flow direction with two different spacing arrangements. In the first arrangement, the screws were installed at a constant spacing equal to 305 mm along the length of the specimen. While in the second arrangement, screws were widely spaced at 610 mm within the low shear zone in the middle of the slab and spaced at only 305 mm in the high shear zone near the supports.

While each of the parameter investigated in the previously mentioned studies influences the strength and stiffness of the experimentally examined TCC sections, it ultimately affecting their performance in flexure bending and the corresponding flexural rigidity based on the load-

https://doi.org/10.52202/069179-0241

displacement relationships developed for the different TCC sections. Results from Gerber [8]

Typically, TCC sections, especially when considering a timber component that utilizes a CLT panel along with STS as shear connectors, exhibit brittle failure under extreme flexure bending. As observed in tests completed by Gerber [8], all specimens subjected to flexure bending and utilized STS into CLT panels exhibited brittle failure, specifically a timber tensile facture. However, the author of the said study noted that the specimens exhibited brittle failure modes (i.e., concrete crushing or tensile fracture) failed at more significant applied loads compared to those that exhibited ductile failure modes (i.e., connector yielding or screw withdrawal).

2.4 TCC SECTIONS BEHAVIOUR UNDER FIRE

While TCC sections, when under ambient conditions, is more extensivity researched and studied both in terms of experimental and numerical analysis, there is lacking information when the fire conditions are involved. As previously mentioned, the need for further investigation to study CLT panels under fire exposure; the same goes for TCC sections. As for any TCC slab-type assembly, the behaviour of the overall floor is highly dependent on the behaviour of the timber component and the shear connections.

In fire conditions, the material ability to resist forces is affected due to the increased temperature and reduced timber area due to charring. This loss in strength leads to a shift in the location of the cross-section neutral axis and thus, result in loss of the stiffness of the TCC section. Complex thermal and mechanical responses must be considered when examining TCC sections exposed to fire, thereby increasing the challenge to develop both simple analytical methods and advanced numerical procedures to quantify their fire resistance according to the relevant codes [6]. However, to develop such models, there is a demand for more reliable experimental results to run comparative analyses to verify their reliability. Considering the limited research focused on studying of TCC sections using STS as shear connectors and having the timber component made of CLT panels, more large-scale fire experiments on such slab-type TCC floor systems are highly needed [13].

In that regard, an experimental study on long span TCC floor slabs was conducted by Osborne [14]. In that study, three key depths were important to consider, which are the depths at the interfaces between the first three ply's (i.e., 35 mm, 70 mm, and 105 mm). The first ply charred at 60 min, beginning to fall at 90 min, giving a char rate of 0.52 mm/min. The second ply charred at 105 min, falling at 120 min, giving a charring rate of 0.68 mm/min. Then the third ply was charred at 150 min, falling at 180 min, giving a charring rate of 0.68 mm/min. Since the TCC slab reached failure due to mid-span deflection at 187 min, the testing was terminated. Therefore, the charring rate began like that of the accepted European standard of 0.65 mm/min, but as the ply fell and delamination occurred, the charring rate further increased. Another important measurement was the temperatures measured at the interface between the concrete top layer and the CLT panel, where there was only a slight increase of about 20°C and only 5°C at the mid-depth of the concrete layer by the end of the fire tests. Also, the temperature of the screws was important to be monitored, as it increased by 93°C by the end of the fire tests. However, this did not occur until the tip of the screw reached a temperature of 100°C. Afterwards, the heat quickly transferred through the screw from the tip to the head and increased much more rapidly once the wood fell around the tip of the screw and was directly exposed to the fire. It is worth noting that although the temperature in the screw was raised, there was negligible heat transfer to the concrete top layer.

Relatively similar thermal behaviour was seen for the TCC slab assemblies examined by Shephard et al. [13]. In that study, the heat transferred from the exposed side to the interface between the concrete and the timber component and raised the temperature at the interface to 59°C and the temperature at the mid-thickness of the concrete layer to 72°C by the end of the fire tests. Also, the charring rates determined in that study was 0.66 mm/min based on the burning of the first ply. However, it was determined at 0.8 mm/min based on the burning of the subsequent plys. Greater charring rates also lead to a greater loss of timber section with an average depth remaining of 25 mm, which would be only the very top ply of the CLT panel. Unlike the study conducted by Osborne [14], where both the fourth and fifth ply remained uncharred, one reason for the difference could be that the adhesive used in manufacturing the CLT panels utilized in the TCC specimens experimentally examined by Shephard et al. [13] affected the delamination occurrence. Although the placement of the screws and corresponding spacing were different between the TCC slabs of those two studies [13 and 14], this would cause a difference in their mechanical behaviour in terms of strength and stiffness, but not the charring rate of the CLT panels. Another possibility is the influence that the panel-to-panel joint affected the fire performance of the TCC floor assemblies examined by Shephard et al. [13]. This is a much-needed topic for further exploration, as the panel-to-panel connection is a very critical component in a mass timber floor system, especially in fire conditions.

3 EXPERIMENTAL PROGRAM

While TCC sections have been studied for many years across various countries, limited testing and verification are completed in Canada. This shows that the possibility of TCC sections being implemented into the Canadian *Engineering Design in Wood* standard [3] requires more extensive experimental testing, computer modelling, and numerical analyses. Currently, TCC sections have only been designed using performance-based guidelines, as the prescriptive methods are still lacking in many published wood design standards.

Following typical fire resistance design procedures, TCC floor assemblies were subjected to monotonic loading before being exposed to standard fire. Each floor assembly was exposed to CAN/ULC-S101 standard fire time-temperature curve for the two fire tests of the research study presented in this paper. In Canada, a minimum fire resistance rating of 45 minutes is required for structural timber components. However, considering the new era of erecting tall wood buildings and the introduction of EMTC, the goal has been changed to achieve a minimum fire resistance rating of 2 hours for buildings more than six stories.

3.1 TEST SETUP

Fire endurance testing was carried out at Lakehead University Fire Testing and Research Laboratory (LUFTRL) located on Thunder Bay campus, Ontario. This state-of-the-art facility, accommodates a large custom-designed furnace with two natural-gas fed burners that can raise the furnace's temperature to 1300 °C. The furnace is equipped with a control panel that can be set to follow a programmable fire time-temperature curve.

The roof of the furnace is comprised of three separated strips that are joined together. As for this research, each of the 900-mm wide TCC floor slab was placed instead of the middle roof strip, thereby acting as part of the furnace roof. Thus, test slabs were exposed to standard fire only from underneath, which reflected one-dimensional heat transfer, Figure 1.

Figure 1: *Interior of the testing furnace with one of the TCC floor test assemblies installed*

The overall dimensions of any TCC floor assembly are 5300 mm x 900 mm, with a clear span of 5000 mm. As the furnace itself is not load-bearing, the TCC floor slab rests on simple supports placed on the transverse beams of the exterior loading/supporting steel framed structure. Thereby, not the entire span (5000 mm) of the floor slab was exposed to fire, but rather a middle length equivalent to the interior length of the furnace chamber (3750 mm) was exposed to fire. This allowed 75% of the floor slab length to be exposed to fire and guaranteed to keep the supports outside the furnace. Meanwhile, under the four-point flexure bending applied on the TCC floor slabs, the greatest shear, moment, and deflection locations were always within the furnace chamber.

To accomplish the objectives of this experimental study, measurements and experimental data were required to evaluate and quantify the performance of the TCC floor slabs when exposed to standard fire. It is essential to provide reference and insight to the recorded visual observations of the floor assemblies as they were designed to achieve a fire resistance rating of 2 hours. Thus, fire tests were terminated shortly after reaching this fire resistance time mark. As tests was duplicated, the first specimen (Slab 1) was exposed to fire for 125 min, while the second specimen (Slab 2) was deliberately exposed to fire for extended period (145 min). Thereby being able to show no sudden change or failure occurrence shortly after the 2-hour threshold.

Test assemblies were loaded to the design load, including 2.0 kPa dead load (in addition to self-weight) and 2.4 kPa live load, representing in situ loading for typical residential occupancy loading. Each specimen was designed to achieve a 2-hr fire resistance, thereby doubling the fire resistance of the CLT panel as a standalone element as reported by the manufacturer, Nordic Structures. The design of each TCC specimen and its shear connections was determined by adopting the clauses and equations in the Canadian Wood Design Handbook [2], Design Guide for TCC Floors in Canada [15], and European Design Code for screw capacity.

3.2 MATERIALS

3.2.1 CLT Panels

This research project utilized CLT panels supplied by Nordic Structures, Quebec, Canada. The principal mechanical properties of the sections were provided by the manufacturer and verified by the Canadian Construction Materials Centre (CCMC) in Evaluation Report CCMC 13654-L [16]. A 5-ply CLT panel was chosen when considering the experimental setup, overall specimen dimensions, and applied loading. Nordic Structures manufactures two different 5-ply CLT panels, one with all ply thickness being 35 mm, giving an overall depth of 175 mm; while the other is with the major strength direction plys of 35 mm thickness each and the minor strength direction plys of 19 mm thickness each, giving an overall depth of 143 mm. The slenderer one was chosen to align with the research objectives.

3.2.2 Concrete

The concrete used in this experimental study was normal strength concrete with 28-day compressive strength designed for 30 MPa. Coarse aggregates were dolomite based with a maximum aggregate size of 16 mm and a nominal diameter of 13 mm. Smaller-diameter aggregates are common in TCC sections as it allows for the mix to

https://doi.org/10.52202/069179-0241

flow and bond around the shear connectors adequately. Water-cement ratio used was approximately 0.56 and no additives were used in the concrete mix. Additionally, the minimum reinforcement ratio of 0.002 of the concrete cross-sections was achieved by placing a wire mesh with 150 mm grid of 6-mm diameter steel wires. This is mainly to control tension cracking due to concrete shrinkage.

3.2.3 Self-Tapping Screws (STS)

The type of STS used in this study were SWG ASSY VG plus cylindrical head, Figure 2. The properties of those screws include diameter (8 mm), total length (240 mm), embedment length in CLT (150 mm), insertion angle 45°, longitudinal spacing (150 mm), transverse spacing (350 mm), bending strength (1015 MPa), tensile strength (18.9 kN), and shear strength (641 MPa). The product evaluation report for the utilized STS provides the full technical specifications for the screws [17].

3.2.4 Insulation Layer

The seen benefit of including insulation layer at the interface with respect to increasing the moment arm between the timber and concrete components, decreasing overall weight, and increasing the thermal and vibration characteristics, a layer of insulation was added to both test specimens. However, due to the less desirable effects of placing STS directly through the installation layer with the decrease in strength and stiffness as the screw tends to twist and bend, the insulation was only placed between the rows of screws. Type of insulation was FOAMULAR CodeBord XPS Insulation cut to strips of 200 mm wide and placed intermediate between screw rows, Figure 3.

3.3 FABRICATION OF TEST SPECIMENS

Due to the detailed composition of TCC floor slabs, it is a multi-step process that must be followed to fabricate each test specimen. Special care was taken to ensure accurate measurements of the thermal data during fire testing. This step is vital as it directly reflects results and conclusions drawn.

High-temperature insulated Type-K thermocouples were installed at specific locations in the CLT panel, concrete slab, and on selected STS. In total, there were 37 thermocouples installed in each test specimen at specified depths, Figure 4. The thermal data measured by the installed thermocouples provides information on the transfer of heat through the specimen and the temperature of different components at a given time during the fire test. Thus, can be used to observe the relationship between time, temperature, and the depth into the floor assembly cross-section. As shown in Figure 4, thermocouples TC1 through TC7 were installed in the CLT panel, located at the interface between each ply and at the mid-depth of the major plys. TC8 was installed at the interface between the concrete and the CLT panel, TC9 at the mid-depth of the concrete layer, TC10 and TC11 around one of the STS, and TC12 on the concrete layer top surface.

Figure 2: *Installation of STS in CLT Panel*

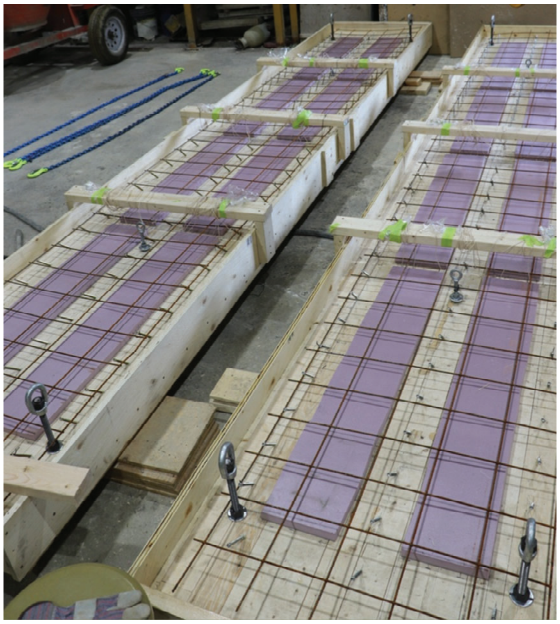

Figure 3: *Prepared CLT slabs before casting concrete*

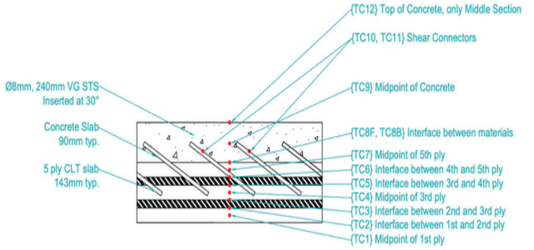

Figure 4:*Thermocouple layout (sectional elevation view)*

Figure 5 shows the final appearance of the two fabricated TCC floor slabs while taking off their formworks after 7-day concrete curing age.

Figure 5: *Removing formwork from TCC floor slabs*

4 RESULTS & DISCUSSION

4.1 MEASURED TEMPERATURES

During any fire testing on structural elements, it is essential to monitor and analyse their thermal behaviour, even more so when considering combustible materials like CLT to understand the rate of heat transferred and charring of the section. Unlike other materials where structural integrity is only diminished, with wood products, this occurs in addition to the loss of cross-section. Thereby, this significantly influences the ultimate strength and stiffness as well as the cross-section loss that is unrecoverable. Examining CLT when exposed to fire conditions is complex but extremely important to designing TCC with slab-type assemblies and providing adequate reliability in fire conditions.

Results were analysed in two distinct ways. First, compared the slabs against themselves by looking at the overall sections and studying the differences with the three separate thermocouple locations: left side, midspan, and right side. The left and right lines are just offset from the location of the point-loading application. Second, is comparing the slab against each other, tracking if duplicate specimens are consistent.

Temperature profiles were developed for each slab and based on the thermal measurements it is confirmed that both TCC floor slabs are in good agreement with each other and very comparative in terms of rate and heat transfer through the slab cross-sections. The first five thermocouples are the most critical, with TC1 being 17.5 mm inward, TC2 being 35 mm, TC3 being 54 mm, TC4 being 71.5 mm, and TC5 being 89 mm, as they are first to experience the effects of fire. Also, the rate at which their temperatures are increased dictates the overall performance of the TCC floor assembly. Additionally, temperature measured by TC5 was used as the test critical temperature where the fire tests were to be terminated if its temperature reached the 300 ˚C (wood charring temperature) to protect the utmost major strength ply of the CLT panel.

4.1.1 Temperature Profiles

Figures 6 and 7 show the entire fire test duration and temperature profiles of data averaged for the thermocouples installed at the same depths at the different three sections along the length of each slab. This is to better examine the overall performance of the slabs and compare them against each other more simply. All presented time-temperature curves show relatively smooth profiles with a more gradual increase in temperature (e.g., no sudden jumps in increased temperature). This is attributed to the minimal delamination the CLT panels experienced during fire tests. As there are no sudden spikes in the thermal behaviour of the fire tested TCC floor slabs, no significant amount of charred timber fell during testing on the furnace floor. Delamination is a critical issue for CLT panels in fire conditions, and

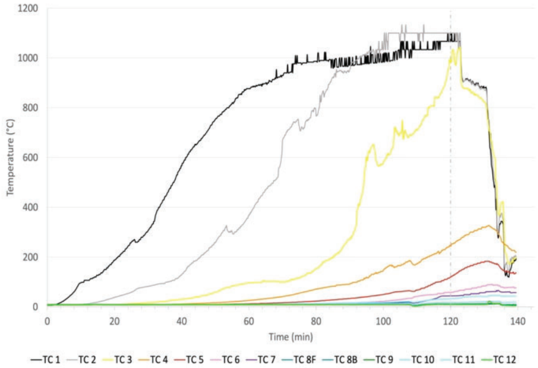

Figure 6: *Slab 1 average temperature readings*

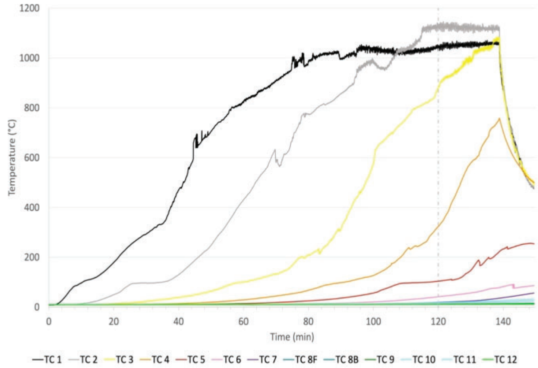

Figure 7: *Slab 2 average temperature readings*

4.1.2 Critical Thermocouple Comparison

The most critical thermocouple (TC5) was carefully monitored throughout fire tests. The measurements of that thermocouple were used to terminate the fire test. The said thermocouple (TC5) is located at the interface between the third and fourth ply of the CLT panel, thereby having this thermocouple not reaching the charring temperature allowed for this minor-strength direction ply to protect the utmost and final major-strength direction ply. Since the examined TCC floor specimens were one-way slabs, only the major-strength direction plys resisted the applied

https://doi.org/10.52202/069179-0241

loading and thus, were used to determine the strength and stiffness of the CLT panels under fire exposure.

After examining the developed time-temperature profiles at the targeted 2-hour fire resistance time mark, the measurements of TC5 reach approximately 100-150°C. Therefore, the location is undoubtedly experiencing the effects of the fire but not at the point where significant strength of the CLT panel was lost.

4.1.3 Heat Transfer Through TCC Sections

Monitoring the fire development and charring progression of the TCC sections throughout the fire testing comes down to evaluating how heat transfers through the floor slabs. Apart from the thermocouples that are exposed initially and others not until near the end of the fire test, it is essential to examine the temperatures measured by the thermocouples that are protected from previous layers of wood and those located in the concrete top layer.

Thus, examining the time-temperature profiles shows that very minimal temperature increase occurred above the temperatures measured by TC5. Meaning a lack of heat transfer to the top of the slab, although the bottom is experiencing a fire temperature of approximately 1000°C. Proving a lack of heat transfer through the slab as most of the installed thermocouples did not reach temperatures higher than 40°C after the 2-hour fire duration. It also should be noted that those thermocouples that measured increased temperatures are mostly TC6 and TC7, which are still located in the CLT panel. Comparatively, the thermocouples found in the concrete and at the interface between materials barely increased (approximately 10°C only) from the initial starting temperature before the fire test began.

4.2 CHARRING BEHAVIOUR

4.2.1 Charring Rates

A crucial aspect in studying the behaviour of timber materials when exposed to fire is the rate and development of the charred front. While compared to contemporary theories and reasons for the hesitation when increasing the construction of tall timber buildings, these combustible products perform very well in fire conditions. Heat transfer through the different plys that form a CLT panel takes a significant amount of time. Proving the insulation properties of the material, and while the temperature threshold of loss of strength is low, it takes an extended period while exposed to an elevated temperature to reach this point.

The nominal charring rate from the European Code is 0.65 mm/min. Additionally, this is the recommendation from the Canadian Wood Council in the Canadian *Engineering Design in Wood* Standards [3] for CLT. The charring rate is 0.65 mm/min when the char depth is within the first ply of a CLT panel and an increased rate of 0.80 mm/min is considered when the charred front progresses beyond the first glue line. The 0.80 mm/min charring rate is exceedingly higher than expected and previously recorded behaviour.

Results from charring rate calculation can be seen in Tables 1 and 2, showing each thermocouple location as well as the averaged results for the entire test specimen. The typical behaviour can be observed from the results where there is initially a lower charring rate as the fire is just beginning and, therefore, not at the hottest temperatures. Then increases while the fire continues as the CLT is ignited and charring starts to develop upward. However, notice that later locations continue to decrease again as although there is a developed char layer, it works as a layer of insulation to the unburned internal plys.

Table 1: *Slab 1 calculated charring rates based on thermal measurements*

Averaged temperature across the slab for TC No.	Charring rate (mm/min)
TC 1	0.59
TC 2	0.67
TC 3	0.59
TC 4	0.56

Table 2: *Slab 2 calculated charring rates based on thermal measurements*

Averaged temperature across the slab for TC No.	Charring rate (mm/min)
TC 1	0.57
TC 2	0.66
TC 3	0.61
TC 4	0.60

The overall average charring rate is approximately 0.60 mm/min with standard deviation of only 0.0396. It also shows the reliability of the European Standard charring rate of 0.65 mm/min and the good agreement with the experimental results of this study.

4.2.2 Residual CLT Thickness

Comparing Figures 8 and 9 shows the difference when the char layer is removed, thereby exposing the remaining wood to resist the applied loads. The apparent difference in appearance makes it easy to differentiate between charred and robust wood.

Only Slab 1 had the char removed as the test had a duration of 125 min where this fire test was terminated shortly after passing the 2-hour fire resistance time mark. Therefore, it was essential to know how much wood was remaining. At the same time, it is understood that more fire exposure for the other slab (Slab 2) would simultaneously lead to a more significant reduction in the residual wood section.

https://doi.org/10.52202/069179-0241

Figure 8: *Slab 1 right after fire testing and before the char layer was removed*

Figure 9: *Slab 1 after 2-hr standard fire exposure and the char layer removed*

It is relatively easy to distinguish between the major and minor plys from Figure 9, with the different ply orientations. However, it is more challenging to know the difference between the middle major ply and the top major ply from the figure alone. Thus, Table 3 presents the residual depth at the three different sections along the first fire tested floor slab. The residual section is more accurate following the centreline of the slab in the longitudinal direction rather than near the edges of the slab.

Table 3: *Residual CLT depths with 2-hr fire exposure in Slab 1*

Location	Residual depth
Left side	54.0
Centreline	68.9
Right side	64.6

It should be noted that the residual depth values greater than 54 mm would indicate that the charring progressed into the third (or middle) ply along the major strength direction. The residual section would be in the fourth ply based on the predicted values using an increased charring rate. While according to the experimental results of this study, with average charring rate calculated based on thermal measurements at 0.60 mm/min, which is very close to the European code nominal charring rate (0.65mm/min), the residual section would be in the third ply.

5 CONCLUSIONS

The new insurgence of structural design involving mass timber elements and increasing the buildings height restrictions under a prescriptive design methodology is tethered to the understanding of the structural fire performance of the main structural systems utilized in such tall timber buildings. Addressing these concerns requires extensive experimental programs to study such mass timber elements and verify their actual fire resistance ratings. Studying TCC sections offers valuable knowledge in expanding their use and design procedures and opening possibilities to further progress the mass timber construction. Both in terms of building taller in timber and having these elements exposed, thereby not limiting design options to EMTC.

Based on the results obtained from the experiments presented in this study to investigate the behaviour of TCC slab-type floor assemblies, the following conclusions can be drawn:

1. TCC floor assemblies can successfully be designed to meet the required 2-hour fire resistance rating. An essential requirement to create tall mass timber buildings and limiting factor in the Canadian *Engineering Design in Wood* standard.

2. The correct design and procedures can enhance the fire resistance of CLT panels by converting the floor systems to TCC sections with the addition of shear connectors and top concrete layer. This successfully takes a CLT panel rated for 1-hour fire resistance and achieve 2-hour fire resistance under the same loading. Thereby doubling the fire resistance time and proving the impact that TCC sections can have on the industry and design recommendations.

3. The thermal behaviour of the two TCC floor assemblies was comparable to each other, providing consistency in results and outcomes while studying time-temperature curves and charring behaviour. Furthermore, it agreed with the standardized charring rate of timber under the European Code nominal value of 0.65 mm/min, and test specimens did not globally delaminate.

4. Even though the exposed CLT was experiencing elevated temperatures of approximately 1000°C near the end of the 2-hr fire tests, there was still minimal heat transfer at the interface between the top concrete layer and the CLT panel or at any depth in the concrete. This demonstrates the benefits of the TCC slab-type floor assembly over the beam-type assembly as it is not needed to consider the thermal effects on the concrete component. Additionally, when the wood charred ply remains intact it acts as an excellent insulator to the inner and yet unexposed plys.

In conclusion, the unique results of the full-size experimental fire tests presented in this paper enhance the current understanding and assist in reducing the knowledge gap on the actual behaviour of TCC floor assemblies utilizing CLT panels when subjected to fire in Canada and globally, especially considering the rarity of large-size fire testing programs. Additionally, providing reliable experimental results for designers to validate the performance-based design and assign appropriate fire resistance times are very beneficial.

ACKNOWLEDGEMENT

This research project has been mainly funded using the Discovery Grant awarded to the second author by the Natural Sciences and Engineering Research Council of

https://doi.org/10.52202/069179-0241

Canada (NSERC). The authors would like to thank Nordic Structures for their support and generous in-kind contributions in form of providing all CLT panels used to fabricate the large-size TCC floor test assemblies examined in this project. Thanks are extended to Pioneer Construction Inc., Miller Precast Ltd., and Harris Rebar (Thunder Bay) for their in-kind contributions. Thanks are due to lab technologist, Mr. Cory Hubbard for his great assistance during the experimental investigation stage of this project.

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