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Fire Endurance Tests on Optimized CLT-Concrete Composite Floor Slabs with Interlayer Layup and Individual Notched Shear Connections

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ABSTRACT: Achieving optimal flexural efficiency in CLT-concrete composite (TCC) floors in fire conditions remains challenging. Adding an interlayer between the CLT slab and concrete layer enhances thermal and acoustic performance while increasing strength and stiffness by extending the moment lever arm, especially in fire conditions. This experimental study evaluates the fire endurance of four full-size TCC slabs with three different notched shear connection configurations. The first configuration was used for two identical composite floors featuring whole-wide strip notches with a 1-inch insulation layer, which improved fire resistance from 60 minutes for the sole CLT slab to 90 minutes. The second and third configurations featured two different systems of individual notched shear connections with a 2-inch insulation layer, further enhancing composite efficiency and extending fire resistance to 120 minutes. Each TCC slab (5,000 mm clear span x 900 mm width) consisted of a 143-mm-thick, 5-ply CLT panel and a 65-mm-thick concrete layer with a compressive strength of 30 MPa. Fire tests were conducted in accordance with CAN/ULC-S101 standards, applying loads of 4.80 kPa for slabs with whole-wide notches and 9.80 kPa for those with individual notches. Results show that TCC floor slabs with individual notch shear connections offer enhanced fire resistance, surpassing 120 minutes, and improved flexural efficiency. However, an analytical method needs to be developed to capture the influence of the interlayer layup on composite flexural stiffness more effectively.

KEYWORDS: CLT-concrete composite sections, individual notch shear connections, fire resistance enhancement, optimal flexural efficiency, interlayer layup, composite action.

1 – INTRODUCTION

A Timber-Concrete Composite (TTC) floor system consists of a timber component, either solid, glued laminated (glulam) [1], laminated veneer lumber (LVL) [2] or cross-laminated timber (CLT) [3-5] connected to a top concrete layer with shear connections. The primary technique for providing a sufficient composite action between the timber section and the concrete layer in TCC systems is to use shear connections, which come in various metal connectors. This could include mechanical fasteners such as self-tapping screws (STS) [6, 7], coach screws [8], HBV steel plates [9], toothed metal plates, and notches cut into the timber section with/without coach screws [10].

In pursuit of achieving optimal composite action, a few researchers have attempted to improve composite efficiency by increasing the concrete-to-timber ratio [11], which has resulted in an excessive depth of the concrete layer and a more significant carbon footprint, thus leading to a more negative environmental impact. As an alternative, the interlayer layup approach has been introduced to maintain the sustainability benefits of wood construction while improving structural performance [2]. By increasing the moment lever arm between composite subcomponents, the flexural efficiency of TCC floors can be enhanced in both ambient and fire conditions [5]. Additionally, the interlayer creates space for embedding building services conduits, further improving functionality and integration in modern construction. Moreover, since the publication of the 2017 edition of ANSI/APA-PRG-320 [12], CLT manufacturers have

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been required to ensure their CLT products can withstand charring temperatures at the glue line without excessive delamination in North America. This mandate has led to an improved charring rate requirement of approximately 0.65 mm/min, compared to the previous generation of CLT products, which had a charring rate that could reach 0.80 mm/min. As a result, CLT panels have become a more promising choice for TCC floor systems. Most critically, CLT can meet the fire safety requirements without additional fire protection, unlike LVL and GLT sections, which require an additional encapsulation layer to achieve the required fire resistance rating.

Most previous studies on the behaviour of TCC floors in ambient conditions have primarily focused on designing rigid shear connections to enhance composite efficiency, meeting serviceability limits [1, 13]. However, this emphasis on rigidity often overlooks the potential reduction in the ductility of the composite section under overload conditions [4, 14]. Current shear connections that could allow almost full-composite action include HBV steel plates [9] and adhesive bond connections [15], and whole-wide strip notch connections [5]. The first two types of connections require high site supervision costs, whereas the whole-wide strip notch connections, despite being more cost-effective, have lower fire resistance for thinner CLT panels [5]. However, the implementation of interlayer layup configurations in TCC floors reduces the necessity for fully rigid connections. Instead, individual notch shear connections present a viable and cost-effective alternative. These connections not only minimize the cutting of the top lamina of CLT compared to the whole-wide strip notch shear connections but also contribute to improved structural efficiency. They have the potential to enhance the composite section efficiency while providing sufficient ductility, provided that their structural behaviour is further studied, incorporating interlayer layup.

In the quest to minimize environmental impact and reduce construction costs, slab-type TCC floors with interlayer layup configurations present a promising solution for more sustainable and affordable building practices with sufficient ductility at overloading conditions [2, 11]. Whereas beam-type TCC floors generally fail to achieve more than a 1-hour fire resistance without encapsulation [16-18]. However, incorporating interlayer layup in composite sections introduces significant challenges regarding shear connection design. Firstly, for commonly used metal fastener shear connections, the interlayer can cause substantial reductions in the overall stiffness of the connection. According to Ceccotti [19], stiffness reduction factors for commonly used metal fasteners are approximately 25%, 44%, and 50% for gap-to-diameter ratios of 2, 3, and 4, respectively. Secondly, there is a gap in the comprehensive design methodology for TCC floors within CSA-O86 [20] and in most available studies on CLT-concrete composite floors with notched shear connections, particularly those concerning the implementation of interlayer layup. Therefore, bridging this gap would ensure that the proposed individual notch shear connections can achieve acceptable fire performance and regulatory compliance. In this study, various innovative notched shear connection configurations have been introduced and evaluated under fire endurance testing following the CAN/ULC-S101 [21]. The primary objective is to evaluate how these shear connections can enhance the fire resistance of CLT panels, extending it from 1 hour to 2 hours for a composite section featuring an interlayer layup configuration, and comparing their performance with the conventional practice of whole-wide strip notch shear connections.

This paper presents the design procedure and experimental results from fire endurance tests on two innovative individual notch shear connection configurations, comparing them with the same composite component utilizing whole-wide strip notch shear connections. The overall flexural stiffness of the CLT-concrete composite floors is also compared with the existing TCC floor design methods to evaluate the impact of interlayer layup on their flexural performance and thermal penetration effects.

2 –EXPERIMENTAL PROGRAM

The primary objective of this study is to experimentally evaluate the fire performance enhancement achieved through composite action using notched shear connections within an interlayer layup in full-size flexural testing of one-way TCC floor slabs. The aim is to achieve optimal flexural stiffness while ensuring sufficient ductility, thereby balancing structural performance requirements in ambient and standard fire conditions. As shown in Fig. 1, four full-size CLT-concrete composite floor slabs were built with three different configurations of notched shear connections, which almost provide the same amount of flexural composite stiffness in ambient conditions. All test assemblies have been tested under elevated temperatures that followed the CAN/ULC-S101 [21] standard fire curve while subjected to four-point bending at the Lakehead University Fire Testing and Research Laboratory (LUFTRL).

To simulate the same moment demand of a uniformly distributed load, four-point loading conditions were applied, as illustrated in Fig. 1-a. The slabs were simply supported at both ends using robust steel supporting beams. Experimental specimens were subjected to two-line loads via a centrally positioned spreader steel beam, precisely located at one-third of the span length from each support. Vertical deflections of the test specimens were recorded using draw-wire displacement transducers installed at three critical locations along the floor slab length: mid-span and beneath each point load. The point load transducers were positioned 1,667 mm apart and symmetrically centred along the specimen span. To prevent fire from spreading through the insulation layer, a continuous concrete layer with a width of 2 inches was placed adjacent to each notch shear connection along their centerline (Fig. 1-c and Fig. 1-d).

The first configuration involved whole-wide strip notched shear connections as shown in Fig. 1-b and Fig. 1-e). The TCC slabs utilizing this shear connection configuration demonstrated an increase in the fire resistance of the CLT panel, extending it from 60 to 90 minutes under applied load equivalent to 4.8 kPa [5]. In this current study, two innovative individual notch shear connection configurations with an interlayer layup (Fig. 1-c and Fig. 1-f; and Fig. 1-d and Fig. 1-g) are introduced, demonstrating the potential to extend the fire resistance to two hours while nearly doubling the applied load (9.8 kPa vs. 4.8 kPa). As depicted in Fig. 1, each TCC slab includes six notches along the span, except Slab 4 (Fig. 1-d) which had only four individual notches with no middle notch shear connections. Both individual notch shear connection configurations exhibit almost the same flexural strength and stiffness level in fire conditions.

The loads were applied to the test specimens at least 30 minutes before the fire test started to conform to CAN/ULC-S101 [21]. Afterwards, the applied load was maintained constant throughout the entire duration of the fire test. The common service load for residential and office building applications is 2.4 kPa for live load and 2.0 kPa for additional dead load. Due to the dimensional limitations of the experimental apparatus and the surrounding support steel sub-frame, a higher load was applied for the fire tests of this study. This suggests that innovative notch shear connections would meet design requirements in both ambient and standard fire conditions for spans shorter than 7.80 m in residential and office buildings, provided that the exact spacing of shear connections is maintained along the slab span (i.e., 10 shear connections compared to 6 in these fire endurance tests). For longer-span TCC floor slabs, vibration and deflection criteria become more critical. However, the demand-to-capacity ratio for moment and shear was expected to decrease with increasing span length.

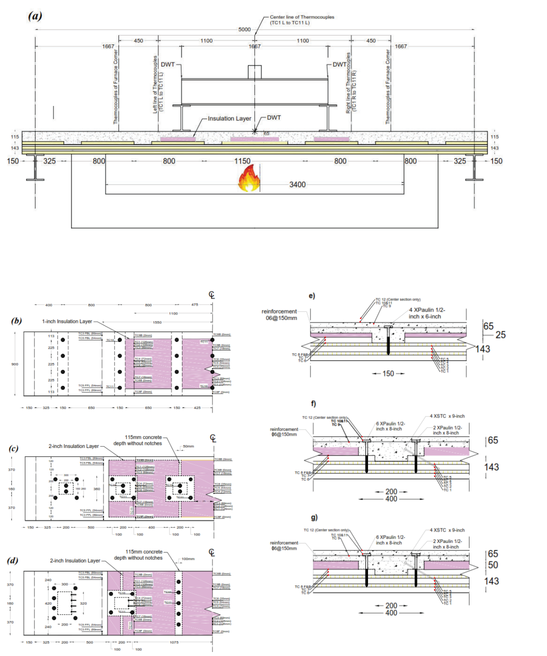

Figure 1. a) General test setup; b) Slab 1 and Slab 2 with whole-wide strip notch shear connections; c) Slab 3 with an innovative individual notch shear connection configuration; d) Slab 4 with an innovative individual notch shear connection configuration; e) Sectional elevation of the notch configuration for Slab 1 and Slab 2 with Thermocouples layout; f) Sectional elevation of the notch configuration for Slab 3 with Thermocouples layout; d) Sectional elevation of the notch configuration for Slab 4 with Thermocouples layout.

3 –TEST SPECIMEN DETAILS

Each test specimen had a total length of 5,300 mm, with a 5,000 mm clear span and a 900 mm width, utilizing Nordic X-Lam 5-ply CLT panels (143-5S) and a 65 mm thick concrete slab with a minimum compressive strength of 30 MPa, with an interlayer layup configuration. The interlayer thickness was increased to a 2-inch insulation layer for Slabs 3 and 4, compared to the 1-inch layer in Slabs 1 and 2, to achieve similar composite flexural stiffness in ambient conditions.

Slabs 1 and 2 (Fig. 1-b) were identical CLT-concrete composite floor slabs with six whole-wide strip notch shear connections along the span, each measuring 150 mm in length, 900 mm in width, and 35 mm in depth. Slab 3 (Fig. 1-c) had the same number of individual notch shear connections, each measuring 200 mm in length, 160 mm in width, and 35 mm in depth. Slab 4 (Fig. 1-d) featured a different configuration with double-wide

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notches at both ends (200 mm long × 320 mm wide × 35 mm deep) and two smaller notches in the middle (200 mm long × 160 mm wide × 35 mm deep), totalling four notches. All CLT-concrete composite floors were cast with a central shore to account for the deflection capacity of the CLT-concrete composite floor, ensuring its suitability for long-term deflection requirements, which are particularly significant for long-span TCC floors.

As illustrated in Figs. 1-e, 1-f and 1-g, each floor assembly was instrumented with 45 Type-K thermocouples inserted from the top into pre-drilled, tightly fitting holes at various depths within the CLT panels. The thermocouples were strategically placed at key locations, including the interfaces between the CLT lamellas, the mid-thickness of each major ply, and the interface between the concrete top layer and the CLT panel. Three primary thermocouple lines were arranged, as shown in Fig. 1-a, with 11 thermocouples on each of the left and right lines and 12 in the middle. Additionally, four critical thermocouples were positioned at both edges of the TCC slab specimen, where they meet the furnace side walls, to capture temperature effects at locations directly exposed to the fire vortex.

4 – DESIGN CRITERIA

According to the National Building Code of Canada [22], structural components must meet short- and long-term serviceability requirements to ensure their functionality without disruption. These requirements include limiting deflection, vibration, permanent deformation, and local structural damage, such as cracking, throughout the structure's service life. Serviceability is closely linked to flexural stiffness, which is enhanced in this study through the use of an interlayer layup, resulting in 100% composite efficiency, even with ductile notch shear connections featuring a double interlayer thickness. Furthermore, the innovative notch pattern would help delay premature non-ductile failure modes, such as gap opening and shear-flexural failure in the concrete slab. As a result, the proposed design meets ultimate limit state requirements by providing maximum composite flexural capacity while ensuring sufficient ductility.

4.1 ELASTIC DESIGN METHOD (γ-Method)

The design guidelines in North American standards do not include TCC design provisions [21]. Also, their fire resistance enhancement is not included in the prescriptive fire rating of structural components in NBCC [22] or the International Building Code [23]. Timber-Concrete Composite Floors in Canada [24] is the only available design guideline that provides the design procedure for TCC floor systems, including ambient and elevated temperatures. To determine the composite strength of a TCC system with well-recognized shear connections (in terms of stiffness and strength), Annex B of Eurocode 5 [24] provides the mechanically jointed beam theory, also known as the gamma method. In this method, shear connectors are uniformly distributed along the floor span. Since notch shear connections typically exhibit elastic behaviour, the γ method provides sufficient accuracy in determining the flexural stiffness and strength of CLT-concrete composite floors in this study.

4.2 STRUCTURAL CHARACTERISTICS OF NOTCH SHEAR CONNECTIONS

The determination of stiffness and strength for notch shear connections is not adequately addressed in the design provisions of North American standards, and the influence of the interlayer on notched connections appears to be overlooked. Initially, this study provides a concise review of the design criteria pertaining to the structural determination of notch shear connections [1, 10] and the shear-rolling effect of CLT material [25], drawing from relevant literature.

Yeoh et al. [10] determined the shear strength of notch shear connections according to Eurocode [26], in which the shear strength of a concrete notch with a lag screw can be estimated with Equations (1) and (2).

$$F_{\mathrm{n}} = 0.5 b_n l_n v^* f_c \beta^* + n_{ef}\left(\pi \phi_{cs} d_{ef}\right)^{0.8} f_{w,m} \qquad (1)$$

$$\beta^* = \frac{(l_n - 2\phi_{cs})}{2 l_n} \qquad (2)$$

Where, β= reduction factor of the shear force; b_n and l_n= breadth and the length of the notch; v^* = strength reduction factor for concrete cracked in shear; f_c= compressive strength of concrete; n_{ef} = effective number of lag screws; ϕ_{cs} = diameter of the lag screw; $f_{w,m}$= withdrawal strength of the lag screw perpendicular to the grain.

To specify the stiffness of notch shear connections, Zhang et al. [1] proposed an equation (Equation 3), which considers only the wood properties. The contribution of the significant number of lag screws to the stiffness calculation is determined based on Eurocode 5 Part 1-1(Equation (4)) [26]. This standard incorporates the empirical equations developed by Ehlbeck and Larsen [27], which provide formulas for calculating the serviceability connection stiffness of metal fasteners, specifically dowel-type, wood-to-wood fasteners.

$$k_s^n = 2.5E_\mathrm{t}t_\mathrm{n}(b_\mathrm{n}/w) \tag{3}$$

Where, k_s^n= Notch face-bearing stiffness E_t= Timber Young Modulus (GPa), t_n= Notch depth (mm), b_n= Notch width, w= CLT width.

$$k_s^m = 2n \times \rho_m^{1.5}\frac{d}{23} \tag{4}$$

Equation (4) depends on the timber density ρ_m (kg/m³) and dowel diameter (d) (mm). Additionally, the slip modulus of the timber-concrete shear connection can be estimated by multiplying the values derived for timber material by a factor of 2 when the connection involves steel or concrete. Consequently, the overall flexural stiffness of the composite system is determined using Equation (5).

$$k_s^T = k_s^n + k_s^m \tag{5}$$

All the aforementioned connection stiffness calculations were used to determine the preliminary dimensions of the test specimens of this study. Given the existing gap in the design of interlayer layup, there is an unknown stiffness reduction factor associated with interlayer layup. Therefore, the calculated stiffness values of the composite sections in the test specimens of the current study were verified against the experimental fire endurance test outcomes. However, the potential reduction in the connection stiffness and strength due to the interlayer layup still requires further investigation in both ambient and elevated temperature conditions. This reduction is likely to be mitigated by implementing innovative rotational restraints at the interface between the notches and the CLT panel (Figs. 1-f and 1-g). Such rotational restraints are expected to delay premature gap opening between the CLT and concrete, thereby reducing the likelihood of horizontal cracking within the depth of the concrete layer and guaranteeing sufficient ductility at ultimate states.

5 –RESULTS AND DISCUSSION

The experimental results include the flexural response of CLT-concrete composite floors with three different configurations of notch shear connections, measured in terms of vertical deflections at the mid-span of the slab and the points of load application. Additionally, thermal measurements were recorded based on the thermocouples implemented in each test specimen as per the layout illustrated in Fig. 1.

5.1 FLEXURAL DEFLECTIONS

The time-deflection curves for all four TCC slabs are shown in Fig. 2. The vertical lines indicate key temperature thresholds for reaching a 300°C isotherm in the CLT layups. All composite slabs exhibited similar flexural stiffness until half of the first ply in the major strength direction (longitudinal direction) was charred, after which a slight plateau was observed in the deflection curves. This plateau persisted until the first longitudinal ply was entirely charred, emphasizing the substantial thermal influence on the structural behaviour of the remaining uncharred portion of the first longitudinal ply. In other words, once approximately half of the first longitudinal ply was charred, the subsequent ply in the same direction (middle layer) began to contribute to the composite stiffness more actively, whereas the remaining uncharred portion of the first ply provided only a minimal contribution.

Once charring out of the first longitudinal ply was completed, there was a noticeable increase in the slab mid-span deflection rate compared to previous stages. This increased deflection rate is particularly evident in Slabs 1 and 2, where the heat transfer began to influence the middle ply in the major strength direction, as illustrated in Fig. 2.

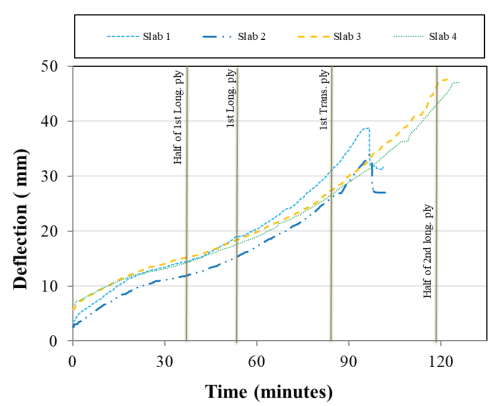

Figure 2. Mid-span deflection vs. time curves of all TCC floor slabs.

This is likely due to the insufficient flexural rigidity in Slabs 1 and 2 compared to Slabs 3 and 4. In contrast, the composite slabs with individual notches were able to sustain more than double the applied loads. This finding demonstrates the fire-resistant efficiency of TCC sections

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utilizing individual notch shear connections, where only a 160 mm-wide section of the CLT panel's top lamina was cut, compared to the whole strip (900 mm long) removed in Slabs 1 and 2.

As it is evident in Table 1, due to the influence of the interlayer, the notch shear connection design supported by the γ method provided better accuracy in determining the stiffness of the composite slabs with whole-wide strip notch connections and a 1-inch interlayer (Slabs 1 and 2) compared to the slabs with individual notches and a 2-inch interlayer (Slabs 3 and 4). The latter exhibited significant discrepancies of 66% and 74%, respectively, whereas the former showed lower discrepancies of 26% and 7%, respectively, in the stiffness calculations. However, using the same concrete depth and the same 5-ply CLT panels with those individual notch shear connections has the potential to achieve the same flexural stiffness as a composite slab section with whole-wide strip notch shear connections, while also meeting an additional fire resistance target and applying more than double the load. Therefore, an analytical approach is necessary to accurately capture the impact of the interlayer on CLT-concrete composite floors, especially those with individual notch shear connections, as these configurations are more appealing for construction due to their cost-effectiveness and reasonable fire resistance. It is worth noting that there was a slight increase in the stiffness of the composite slab section immediately after the first transverse ply was charred, indicating that under ultimate state conditions in a fire, Slab 4 exhibited better performance.

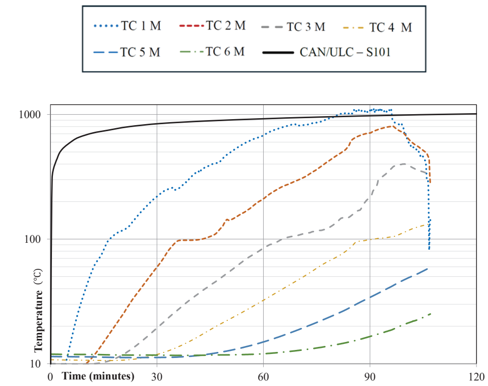
Table 1: Comparison between design and experimental composite flexural stiffness

Specimen No.	Targeted fire resistance rating	$EI_{ef}^{t,e}$ (MN. m²)	$\frac{EI_{ef}^{t,d}}{EI_{ef}^{t,e}}$
Slab 1	90 min	1.49	126%
Slab 2	90 min	1.89	107%
Slab 3	120 min	1.80	166 %
Slab 4	120 min	1.84	174 %

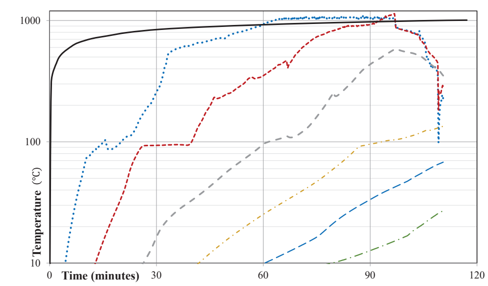
$EI_{ef}^{t,e}$ = Experimental composite flexural stiffness at targeted fire resistance rating.
EI_{ef}^{t} = the γ-method determination of flexural stiffness at targeted fire resistance rating.

5.2 THERMAL MEASUREMENTS AND CHARRING RATES

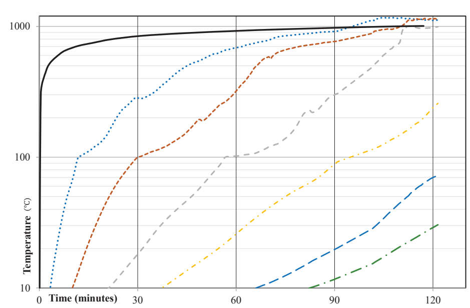
The time-temperature curves developed based on the thermal measurements of the thermocouples implemented at the mid-span of all four test specimens are shown in Fig. 3.



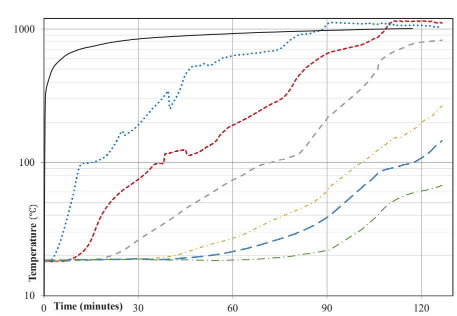
(a) Slab 1



(b) Slab 2



(c) Slab 3



(d) Slab 4

Figure 3. Time-temperature curves based on TC1 through TC6 measurements for all four TCC floor slabs.

For all fire endurance tests, the test termination criterion was set when the critical thermocouples (TC2 for Slabs 1 and 2, and TC5 for Slabs 3 and 4) reached the charing isotherm at 300°C. At this point, the furnace was stopped, and the applied loads were removed. The temperature profiles for all four TCC slabs are consistent.

Once the temperature of the thermocouples reached the range 250-300°C isotherm, the corresponding charring rates were then calculated, as shown in Table 2.

Table 2: One-dimensional average and absolute charring rates of all four TCC floor slabs.

TC No.	Location	CLT Ply	Charring rate (mm/min)	
			Slabs 1&2	**Slabs 3&4**
TC 1	Left	Half of the 1^{st} long. ply	0.61-0.40	0.66-0.46
TC 2		1^{st} long. ply	0.59-0.64	0.46-0.46
TC 3		1^{st} trans. ply	0.83-0.41	0.60-0.84
TC4		Half of the 2^{nd} long. ply	not charred	0.91[a]-0.55
		Absolute	**0.66-0.54**	**0.62-0.55**
TC 1	Middle	Half of the 1^{st} long. ply	0.45-0.56	0.52-Error
TC 2		1^{st} long. ply	0.50-0.64	0.69-Error
TC 3		1^{st} trans. ply	0.85-0.63	0.61-0.54
TC 4		Half of the 2^{nd} long. ply	not charred	0.50[b]-0.60[c]
		Absolute	**0.58-0.64**	**0.57-0.56**
TC 1	Right	Half of the 1^{st} long. ply	0.59-0.50	0.57-0.38
TC 2		1^{st} long. ply	0.64-0.57	0.57-0.55
TC 3		1^{st} trans. ply	0.67-0.67	1.24-0.56
TC 4		Half of the 2^{nd} long. ply	not charred	0.42-0.72
		Absolute	**0.65-0.60**	**0.60-0.53**
TC 1	Average	Half of the 1^{st} long. ply	0.55-0.49	0.58-042
TC 2		1^{st} long. ply	0.58-0.62	0.57-0.51
TC 3		1^{st} trans. ply	0.78-0.57	0.82-0.65
TC 4		Half of the 2^{nd} long. ply	not charred	0.61-0.62
		Overall absolute charring rate	**0.63-0.59**	**0.6-0.55**

The temperature at which a conservative charring rate was calculated: a) 260℃, b) 266℃; c) 255℃.

The charring rates were determined across the depth of the CLT panel, assuming a linear temperature variation between two adjacent thermocouples throughout the CLT thickness. This assumption facilitates the calculation of the charring rate for each ply, subsequently allowing for the determination of the absolute charring rate across the total depth of the CLT panel. According to the experimental observations, there was no delamination in the CLT panels, and the average absolute charring rate was calculated at 0.59 mm/minute for all slabs (Table 2). This rate meets the high-temperature adhesive requirements specified by ANSI [12]. Furthermore, the absence of any peaks in temperature during the tests confirmed a lack of delamination signs (Fig. 3).

Moreover, the insulation layer between the CLT slab and the concrete layer did not impact the charring rate values. However, occasional spikes in the charring rate of the transverse ply were observed, which may be attributed to its thinner thickness compared to those in the major strength direction. This phenomenon has also been noted in previous-generation CLT fire endurance tests [28].

6-CONCLUSIONS

This research aimed to better understand the impact of interlayer layup on the fire performance of CLT-concrete composite floors under the CAN/ULC-S101 [21] standard fire curve. The study compared commonly used whole-wide strip notches with a 1-inch insulation layer (Slabs 1 and 2) to two innovative individual notch connection configurations reinforced with lag and self-tapping screws to provide more rotational restraints with the application of a 2-inch insulation layer. The interlayer layup was more advantageous for the test specimens with individual notch shear connections (Slabs 3 and 4), resulting in higher composite flexural stiffness and strength (9.8 kPa vs. 4.8 kPa applied load) and also more fire enhancement (120 min vs. 90 min) than the TCC slabs with whole-wide strip notch connections.

Acknowledging the existing lack of design provisions for TCC floor systems in North American codes, a simplified design procedure is presented herein based on a thorough literature review. The γ method with consideration of literature reviews, design criteria of notch shear connections can determine the flexural stiffness of composite floors with whole-wide strip notch shear connections with a better degree of accuracy. However, there is a discrepancy of up to 74% for composite sections utilizing individual notches with an interlayer layup configuration. Therefore, there is a vital need to introduce a design guideline for TCC slabs utilizing individual noches with an interlayer for enhanced fire resistance, thereby achieving the 2-hour fire resistance rating required by most applicable codes for tall mass timber buildings.

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7-REFERENCES

[1] L. Zhang, J. Zhou, S. Zhang, and Y.H. Chui. "Bending stiffness prediction to mass timber panel-concrete composite floors with notched connections." In: Engineering Structures 262 (2022), pp. 114354.

[2] B. Kreis, W. Kübler, and A. Frangi. "Development and investigation of an innovative, light-weight, two-way spanning timber-concrete composite slab." In: Engineering Structures 286 (2023), pp. 116087.

[3] S. Lecours, T.T. Nguyen, L. Sorelli, P. Blanchet, and K. Durand. "Optimizing composite floors for sustainability and efficiency: Cross-laminated timber, concrete types, and ductile notch connectors with enhanced shape." In: Cleaner Engineering and Technology 14 (2023), pp. 100635.

[4] S. Lamothe, et al. "Lightweight and slender timber-concrete composite floors made of CLT-HPC and CLT-UHPC with ductile notch connectors." In: Engineering Structures 243 (2021), pp. 112409.

[5] J. Tashakori, and O. (S) Salem. "Fire resistance testing of CLT-concrete composite floors slabs with strip notch shear connections." In: World Conference on Timber Engineering (2023), Oslo, Norway.

[6] L. Marchi, R. Scotta, and L. Pozza. "Experimental and theoretical evaluation of TCC connections with inclined self-tapping screws." In: Material Structures 50.180 (2017).

[7] K.M. Quang, A. Park, K.T. Nguyen, and K. Lee . "Full-scale static and dynamic experiments of hybrid CLT–concrete composite floor." In: Construction and Building Materials 170 (2018), pp. 55-65.

[8] H. Tao, H. Yang, W. Liu, C. Wang, B. Shi, and X. Ling. "Experimental and nonlinear analytical studies on prefabricated timber–concrete composite structures with crossed inclined coach screw connections." In: Journal of Structural Engineering 147.5 (2021), pp. 04021043.

[9] P. Clouston, and A. Schreyer. "Design and use of wood–concrete composites." In: Practice Periodical on Structural Design and Construction 13.4 (2008), pp. 167-174.

[10] D. Yeoh, M. Fragiacomo, M. De Franceschi, and A.H. Buchanan. "Experimental tests of notched and plate connectors for LVL-concrete composite beams." In: Journal of Structural Engineering 137.2 (2011), pp. 261-269.

[11] L. Boccadoro, S. Zweidler, R. Steiger, and A. Frangi. "Bending tests on timber-concrete composite members made of beech laminated veneer lumber with notched connection." In: Engineering Structures 132 (2017), pp. 14-28.

[12] ANSI, Standard for performance-rated cross-laminated timber, ANSI/APA PRG 320-2019. 2019, APA- The Engineered Wood Association: ANSI/APA.

[13] L. Boccadoro, and A. Frangi. "Experimental analysis of the structural behavior of timber-concrete composite slabs made of beech-laminated veneer lumber." In: Journal of Performance Constructed Facilities 25.6 (2014), pp. A4014006

[14] L. Boccadoro, S. Zweidler, R. Steiger, and A. Frangi. "Calculation model to assess the structural behavior of LVL-concrete composite members with ductile notched connection." In: Engineering Structures 153 (2017), pp. 106-117.

[15] J. Kanócz, and V. Bajzecerová. "Timber-concrete composite elements with various composite connections Part 3: Adhesive connection." In: Wood Research 60.6 (2015), pp. 939-952.

[16] J. O'Neill, A. Abu, D. Carradine, P. Moss, and A. Buchanan. "Modelling the fire performance of structural timber-concrete composite floors." In: Journal of Structural Fire Engineering 5.2 (2014), pp. 113-124.

[17] A. Frangi, M. Knobloch, and M. Fontana. "Fire design of timber-concrete composite slabs with screwed connections." In: Journal of Structural Engineering 136.2 (2010), pp. 219-228.

[18] D. Shi, X. Hu, H. Du, Z, Xie, and Y. Meng. "Study on shear performance of notched connections for glulam-concrete composite beams under fire." In: Fire Safety Journal 126 (2021), pp. 103482.

[19] A. Ceccotti. "Composite concrete–timber structures." In: Progress in Structural Engineering and Materials 4.3 (2002), pp. 264–275.

[20] Canadian Standards Association. CSA O86: Engineering design in wood (2019), CSA, Mississauga, Ontario, Canada.

[21] Underwriters Laboratories of Canada (ULC). CAN/ULC S101-REV1, Standard methods of fire endurance tests of building construction and materials (2019), ULC, Scarborough, Canada.

[22] NBCC. The National Building Code of Canada. Commission on Building and Fire Codes (2020), National Research Council of Canada, Ottawa, Canada.

[23] IBC, International Building Code (2024), USA.

[24] S. Cuerrier-Auclair. "Design guide for timber-concrete composite floors in Canada (2020), FPInnovations: Pointe-Claire, QC., Canada.

[25] Y. Jiang, and R. Crocetti. "CLT-concrete composite floors with notched shear connectors." In: Construction and Building Materials 195 (2019), pp. 127-139.

[26] CEN, European Committee for Standardization Eurocode 5: Design of timber structures. Part 1-1: General–Common rules and rules for buildings. EN 1995-1-1. Brussels, Belgium: CEN., 2004.

[27] J. Ehlbeck, and H.J. Larsen. "Eurocode 5 - Design of timber structures: Joints." In: Proceedings of the International Workshop on Wood Connectors (1993), Madison, USA.

[28] L. Osborne. "Fire resistance of long-span composite wood-concrete floor systems." 2015, Research report, FPInnovations, QC., Canada.