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NEW ENCAPSULATION TECHNIQUE FOR STRENGTHENING AND ENHANCED FIRE RESISTANCE OF MASS TIMBER STRUCTURAL ELEMENTS

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ABSTRACT: The widespread applications of mass timber elements in tall wood construction necessitate effective fire protection strategies. Building codes require mass timber to perform like a non-combustible construction in fire scenarios by encapsulating it with fire-rated, non-combustible material. This study introduces a new encapsulation technique: a fabric-reinforced cementitious matrix (FRCM) to provide fire protection and strengthen mass timber structural elements. The thermal stability of the FRCM system is derived from its matrix composition. Firstly, two mortar mixes, PM-1 (1:1 Portland cement to sand by weight) and PM-2 (1:2 Portland cement to sand), were tested to determine an optimal mix composition for the FRCM system. The compressive strength test revealed that PM-1 had a higher 28-day strength (49 MPa) than PM-2 (39.2 MPa). However, after fire exposure, PM-1 retained only 8% of its strength (4 MPa), while PM-2 retained 14% (5.5 MPa). Moreover, PM-2 further demonstrated lower thermal conductivity (0.542 W/m·K) than PM-1 (0.551 W/m·K) and was considered the optimal composition for the FRCM system. Secondly, a 50 mm thick FRCM system using PM-2 was applied as an encapsulation layer to a glulam column and evaluated through a standard fire test. The fire test was terminated after 30 minutes due to explosive spalling at the lower end of the column; however, post-fire test inspection revealed that the glulam remained in near-original condition, confirming that the FRCM provided adequate fire protection for the test duration (i.e., 30 minutes). These findings confirm that FRCM encapsulation can attain a minimum encapsulation rating of 50-70 minutes, as specified by the National Building Code of Canada, through controlled casting to avoid excessive moisture accumulation that triggers spalling.

KEYWORDS: Mass timber, tall wood buildings, fire safety, encapsulation, fabric reinforced cementitious matrix, standard fire

1 – INTRODUCTION

Recent global interest in sustainable design has prompted the acceptance of timber as an eco-friendly alternative to concrete and steel [1, 2]. In addition to its reduced carbon footprint, timber offers advantages such as rapid construction, high strength-to-weight ratio, and low energy consumption [3]. The development of engineered mass timber products such as Glued-Laminated Timber (Glulam) and Cross-Laminated Timber (CLT) further promotes the growth of timber construction, making it a viable option for high-rise building construction while preserving its sustainability benefits [4, 5].

Despite recent advancements, the widespread use of engineered mass timber in high-rise buildings is hindered by the significant concern regarding their fire safety [6]. Since wood is a combustible material, it contributes to the fuel load, adding more challenges for fulfilling the required fire safety measures in mass timber buildings [7]. The additional heat from structural timber could significantly impact fire dynamics and complicate fire compartmentation [8]. For instance, Mitchell et al. [6] reported that compartment fires in timber structures reach 80–180°C higher than in non-combustible compartments, thus leading to more fire severity. Therefore, building codes limit the use of mass timber in tall buildings, mandating that it provide a level of fire safety equivalent to non-combustible construction.

Encapsulation is a broadly adopted practice to achieve fire safety equivalent to non-combustible construction, by providing a physical barrier to delay or prevent ignition of mass timber [9]. The latest editions of the International Building Code (IBC-2021) [10] and the National Building Code of Canada (NBCC-2020) [11]

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allow mass timber buildings up to 270 ft (82.3 m) and 137 ft (42 m) in height, respectively. Meanwhile, these buildings shall be encapsulated with fire-rated materials, providing a minimum protection rating of 50 minutes. The conventional encapsulation methods, i.e., fire-rated gypsum boards [12], cement boards [13], spray-applied fire-resistant materials (SFRM) [12], intumescent coatings [14], and rock fiber insulation [12], provide sufficient protection under standard fire conditions; however, they may not be effective in certain severe fire scenarios. Chorlton et al. [15] recently studied that gypsum boards provide sufficient encapsulation under laboratory fire exposure but fail to ensure adequate safety in field fire conditions. Similarly, Hartl et al. [16] observed different encapsulation ratings for gypsum board and intumescent coating under different heating exposures. These observations revealed that conventional encapsulation methods may not provide sufficient protection in actual fire scenarios, which significantly vary in intensity and duration.

Accordingly, the current study introduces a novel encapsulation technique for mass timber in the form of Fabric-Reinforced Cementitious Matrix (FRCM), which would serve as an improved encapsulation alternative and a synergistic strengthening method. FRCM is a composite material that leverages the synergistic properties of high-strength fabrics (i.e., carbon, basalt, and glass) and cement-based mortars [17]. The performance of encapsulated mass timber structural elements exposed to standard fire has been investigated at the Fire Testing and Research Laboratory (LUFTRL) at Lakehead University, Canada. As part of the study presented in this paper, a pilot fire test was conducted on an FRCM-encapsulated glulam column. The paper further outlines the selection of appropriate mortar mix for the FRCM system, the application of FRCM to glulam columns to develop composite action, and the evaluation of the encapsulated system under standard fire exposure in detail.

2 – MATERIALS AND METHODS

2.1 FRCM CONSTITUENT MATERIALS

The composition of a conventional FRCM system includes Portland cement and carbon fabric as constituent materials. The sand was sourced locally and tested according to ASTM specifications (ASTM C128 and ASTM C 566) to determine its specific gravity, moisture content, and absorption capacity, all listed in Table 1. Portland-limestone cement, classified as Type GUL per CSA A3000 standards, served as the primary binder. The specific gravity, fineness, ignition loss, and Blaine surface area of the cement were evaluated using ASTM specifications, with the obtained values listed in Table 1. A bidirectional carbon grid (BCG) with 20 mm grid spacing was employed as reinforcement in the FRCM system. BCG was selected based on its superior thermal stability. The detailed properties of the BCG are presented in Table 2.

Table 1: FRCM Constituent material properties

Properties	**Material Type**	
	Sand	**Cement**
Specific gravity	2.72	3.07
Fineness	2.15	5% (retained on 45 µm Sieve)
Moisture content	1.7 (%)	----
Absorption	0.70	----
Loss on ignition	----	5.8 (% weight)
Blaine	----	480 (m^2/kg)

Table 2: Properties of Carbon Grid [18]

Properties	**Bidirectional carbon grid (BCG)**
Resistant area per	44 mm/m^2
Weight	130 g/m^2
Thickness	0.044 m
Ultimate Tensile	138 kN/m
Axial stiffness per	9200 kN/m
Break elongation	1.50 %

2.2 GLULAM SECTION

The glulam section, manufactured by Nordic Structures, Canada, and named Nordic Lam+ Glued-Laminated Timber, was utilized as the primary structural element, encapsulated with the new method. The glulam was manufactured of Spruce-Pine-Fir laminations and complies with CSA O122 and CSA O177 standards, offering superior properties to solid-sawn lumber. Table 3, presented below, lists the mechanical properties of the glulam section.

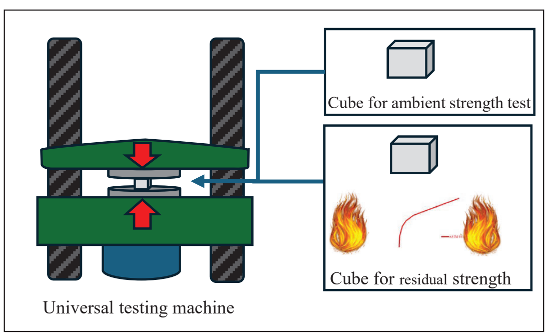
Table 3: Strength Properties of Glulam [19]

Property	**Description**
Appearance grade	Architectural
Stress grade	24F-ES/NP
Bending moment	30.7 MPa
Compression parallel to the grains	33.0 MPa
Compression perpendicular to the grains	7.5 MPa
Tension parallel to the grains	20.4 MPa
Tension perpendicular to the grains	0.5 MPa

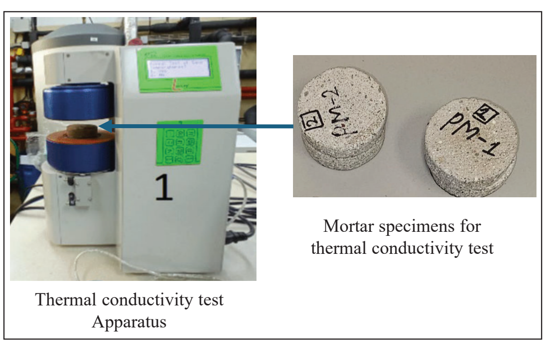
2.3 MORTAR MIX EVALUATION

Mortar is a crucial FRCM component, significantly impacting its strength, durability, and overall performance under elevated temperatures. The study investigated two mortar mixes for the FRCM system. The first mix consists of one part cement and one part sand (PM-1), whereas the second mix consists of one part cement and two parts sand (PM-2). Compressive strength and thermal conductivity tests, as shown in Fig.1a and Fig. 1 b, were performed to identify an optimal mix between PM-1 and PM-2.

The compressive strength of each mix was evaluated under ambient conditions using five 50-mm cubes, and an additional five cubes were exposed to a 2-hour standard fire to assess strength degradation after fire exposure. The results from the compressive strength test and thermal conductivity test were used to select an appropriate mix for constructing the FRCM system.



(a)



(b)

Figure 1. Mortar mixes evaluation, (a) Compressive strength test; (b) Thermal conductivity test.

2.4 FABRICATION OF THE FRCM ENCAPSULATED GLULAM COLUMN

Columns are the most critical structural elements, and since they could be exposed to fire from all four sides, they are highly vulnerable and thus susceptible to collapse in the event of fire. Therefore, the current study selected and encapsulated a glulam column using the newly introduced FRCM-based encapsulation system, as shown in Fig. 2. The glulam column, measuring 250 mm × 250 mm in cross-section and 1500 mm in length, was encapsulated with a 50 mm thick FRCM layer containing a high-strength carbon grid embedded at its mid-thickness. To ensure composite action between the FRCM and glulam, rectangular notches (15 mm deep and 50 mm wide) were cut into the glulam, illustrated in Fig. 2a.

In the fabrication process, the carbon grid was first attached to the glulam at 25 mm (Fig. 2 b), and then a 50-mm-thick layer of mortar with the carbon grid at its mid-thickness was cast around it. The glulam was not protected with any waterproofing sealant; therefore, wet curing was kept to a minimum to avoid moisture accumulation in the glulam section, and only a damp cover was used to maintain optimal curing conditions for the mortar.

(a)

(b)

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(c) (d)

Figure 2. Fabrication of encapsulated glulam column, (a) Rectangular notches on glulam section; (b) Carbon grid attached to the glulam; (c) Glulam with attached carbon grid ready for casting; (d) Encapsulated glulam section after casting.

2.5 STANDARD FIRE EXPOSURE

The encapsulated glulam columns have been tested for their encapsulation and fire resistance ratings at LUFTRL following the CAN/ULC-S101 standard time-temperature curve. LUFTRL features a state-of-the-art, large-size furnace that tests full-size beams, columns, floors, and wall assemblies under standard or realistic fire scenarios. The laboratory is further equipped with a hydraulic loading system to determine load-carrying capacity during fire exposure, providing realistic performance assessments.

The column specimen presented in this paper was exposed to a standard fire while subjected to a 200 kN axial load, representing the maximum factored load that the glulam sections could sustain while maintaining a minimum of 60-minute fire resistance without encapsulation. As illustrated in Fig. 3, Type-K thermocouples were installed to monitor temperature profiles and encapsulation ratings. Two thermocouples (TC1 and TC2) were installed at the carbon grid, while four additional thermocouples (TC3 to TC6) were provided at the glulam-FRCM interface to assess encapsulation ratings. Additionally, two thermocouples (TC7 and TC8) were embedded 20 mm into the glulam to track the charring rate. The thermocouple placement described above was repeated at one-third of the column height from the top and bottom ends of the column (Fig. 3b), with the upper thermocouples labelled with the suffix “U” and the lower ones with “L.” For example, TC3-U represents the upper TC3 thermocouple at the interface, and TC3-L represents the lower TC3 thermocouple at the interface.

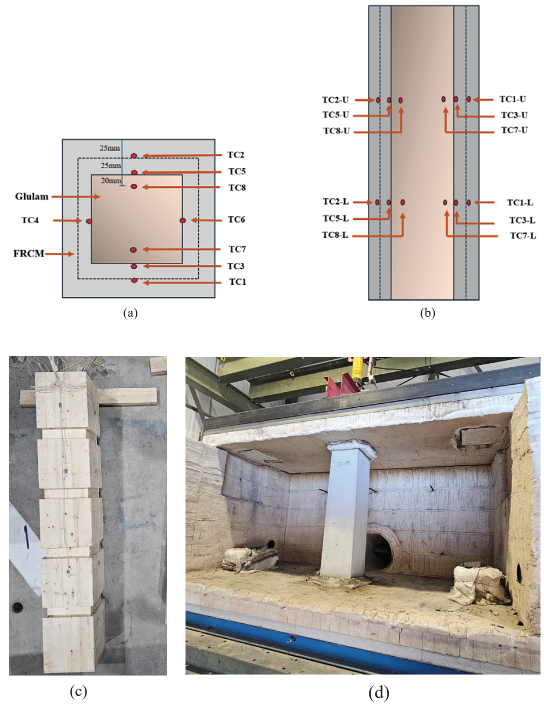

Figure 3. Thermocouples placement and Standard fire exposure of FRCM encapsulated column (a) Thermocouples placement across column section (b) Thermocouples distribution along the length of the column (c) Thermocouples installation on glulam (d) Encapsulated column ready for standard fire test at LUFTRL.

3. RESULTS AND DISCUSSION

3.1 COMPRESSIVE STRENGTH TEST AND THERMAL CONDUCTIVITY ANALYSIS

The compressive strength and thermal conductivity test results for mortar mixes (i.e., PM-1 and PM-2) are shown in Fig. 4a and Fig. 4b, respectively. The compressive strength test results revealed that PM-1 exhibited higher 28-day compressive strength (49 MPa) compared to PM-2 (39.2 MPa) due to the increased formation of calcium silicate hydrate (C-S-H) gel. However, upon exposure to standard fire for 2 hours, PM-1 experienced a significant strength degradation, retaining only 8% (i.e., 4 MPa) of its strength in ambient conditions, while PM-2 retained about 14% (5.5 MPa). The comparatively enhanced performance under fire exposure for PM-2 is attributed to lower cement and higher sand content. The lower cement content formed a lower cement paste that underwent dehydration and decomposition at high temperatures. In comparison, the higher sand content developed a more porous structure, allowing for the better release of water vapor and reducing internal pressures, which resulted in less cracking and greater residual strength. Similarly, PM-2 exhibits lower thermal conductivity than PM-1, which is potentially attributed to the porous structure of PM-2 due to the higher sand content and possibly creating more voids to reduce the overall thermal conductivity.

Based on its improved performance under fire exposure and lower thermal conductivity, PM-2 was selected as the mortar mix for the FRCM system. Thus, the full-scale FRCM encapsulated column was constructed using PM-2 as the mortar component.

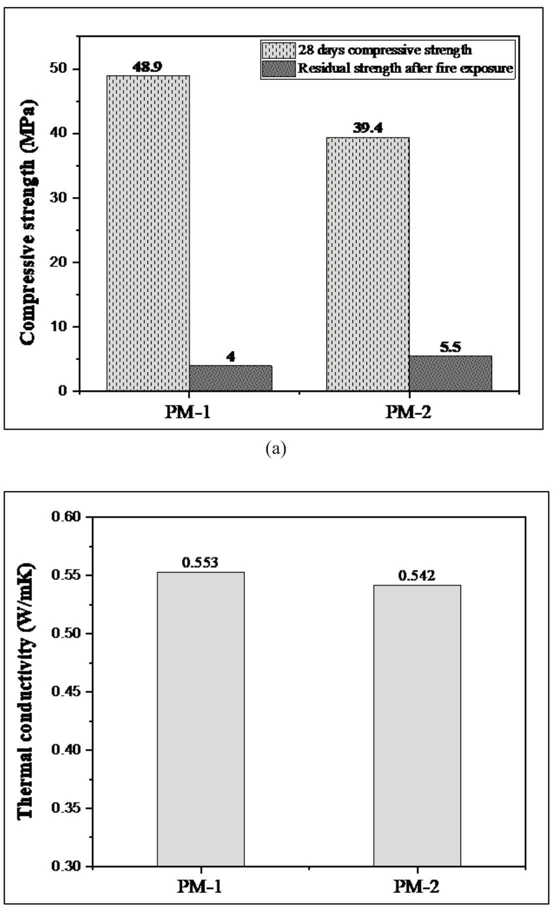

Figure 4. Mortar evaluation results, (a) Compressive strength test; (b) Thermal conductivity test.

3.2 STANDARD FIRE EXPOSURE

This section presents the time-temperature responses recorded by the thermocouples during the fire test and post-fire observations of the encapsulated glulam column.

Figs. 3a and 3b illustrate the rise in temperature across the thickness of the FRCM layer upon exposure to standard fire. The time-temperature curves indicate an approximately linear temperature rise through the FRCM, with a notable thermal lag between thermocouples positioned at the FRCM mid-thickness (TC1 and TC2) and those located at the FRCM-glulam interface (TC3–TC6). For example, at 30 minutes of fire exposure, when the furnace temperature reached approximately 850 °C, thermocouple TC1U, located at the mid-thickness of the FRCM, recorded a temperature of 261 °C. In contrast, TC3U, situated on the same face but at the FRCM-glulam interface, registered a significantly lower temperature of 127 °C. On the opposite face, TC2L (mid-thickness) recorded 222 °C, whereas TC5L (at the interface) showed only 144 °C. Similarly, additional thermocouples at the interface TC4U, TC4L, and TC6U also registered lower temperatures of 118 °C, 141 °C, and 128 °C, respectively, demonstrating the effectiveness of the FRCM system in attenuating heat transfer to the glulam surface. Furthermore, thermocouples TC7 and TC8, embedded 20 mm into the glulam, exhibited a gradual and steady increase in temperature throughout the test. This indicates that the encapsulated glulam section remained at the normal temperature conditions, further highlighting the promising fire-protective performance of the FRCM encapsulation system.

Despite the satisfactory fire protection provided by the FRCM in the first 30 minutes, the test was terminated after 30 minutes due to some deep spalling at the lower end of the column. The spalling was attributed to excessive vapor pressure caused by moisture accumulation within the glulam section, arising from a combination of contributing factors, including (1) direct application of FRCM to glulam without a moisture barrier (2) higher water-to-cement ratio for the mortar mix and (3) insufficient drying period of the system as test was conducted only after 40 days of casting. These conditions led to the buildup of internal vapor pressure during heating, which ultimately caused deep spalling at the column's base and prompted early termination of the test for safety reasons.

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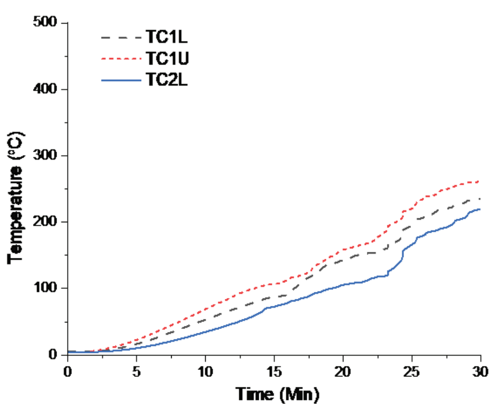
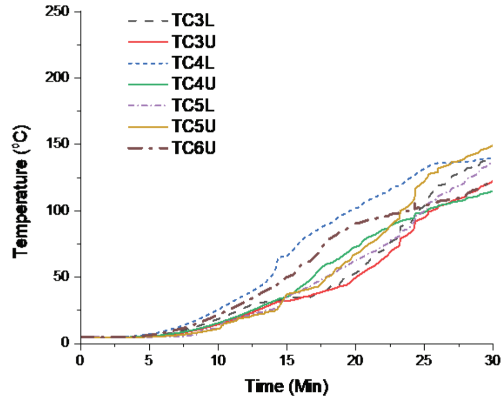
Following the test, the FRCM was removed to inspect the glulam column underneath, which showed no signs of charring. As illustrated in Fig. 4, the glulam remained in near-original condition, confirming that the FRCM provided adequate fire protection for the test duration (i.e., 30 minutes). Based on these findings, it is evident that the FRCM system has strong potential for fire protection applications in timber structures and can readily attain the minimum encapsulation rating of 50-70 minutes specified by the National Building Code of Canada for tall wood buildings, provided moisture accumulation is better controlled.

Figure 5. The glulam column recovered after the pilot fire test.



(a)



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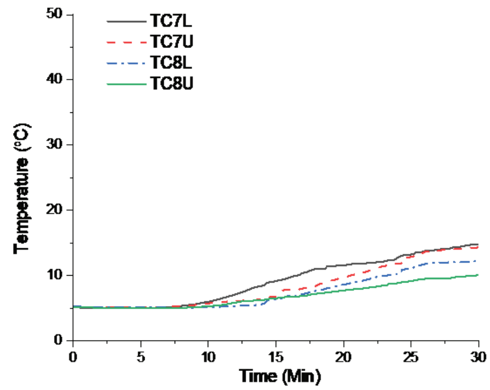

(c)

Figure 6. Time-temperature curves of all thermocouples, (a) Temperature record of the thermocouples at FRCM mid-thickness; (b) Temperature record of the thermocouples at FRCM-glulam interface; (c) Temperature record of the thermocouples inserted 20 mm into the glulam section.

4. CONCLUSIONS

The current research investigates FRCM as a fire barrier material for mass timber structural elements. The obtained experimental results lead to the following conclusions.

(1) Mortars with richer mixes (i.e., lower sand-to-cement ratios) exhibit superior performance under ambient temperature conditions. However, they demonstrate significant strength degradation when exposed to elevated temperatures. Furthermore, these mixes have higher thermal conductivity, which negatively impacts the fire-encapsulation effectiveness of the FRCM system.

(2) FRCM in a thickness range of 40-50 mm is an efficient encapsulation material that can provide a minimum encapsulation rating of 50-70 minutes,

provided excessive pore pressure is avoided by effectively controlling moisture in the system.

5. FUTURE WORK RECOMMENDATIONS

This study served as a pilot investigation into the encapsulation performance of FRCM systems for mass timber elements to identify key challenges and guide future experimental work. Based on the findings, the following recommendations are proposed for future research:

(1) Apply waterproof coatings to glulam surfaces to prevent moisture ingress.
(2) Allow the encapsulated column to dry for an extended period of at least 90 days to remove free moisture and reduce the risk of pore pressure buildup during fire exposure.
(3) Investigate using porous lightweight aggregates, such as vermiculite or perlite, as partial replacements for sand to develop mortar mixes with reduced thermal conductivity.
(4) Explore the replacement of Portland cement with thermally more stable supplementary cementitious materials (SCMs), such as fly ash or ground granulated blast-furnace slag (GGBS).

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