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Thermo-mechanical performance of Carbon Fiber Reinforced Polymer (CFRP), with and without fire protection material, under combined elevated temperature and mechanical loading conditions

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ABSTRACT

In civil engineering, when a CFRP-reinforced structure is subjected to fire, both the structure and CFRP are simultaneously affected by elevated temperature and mechanical loading. In the Eurocodes, the strengths of concrete and steel are described to be reduced with increased temperature; however, the codes do not describe the performance of hand-laid CFRP. This paper presents the thermomechanical performance of hand-laid CFRP with and without thermal insulation under different mechanical loading conditions. Experimental tests were conducted to identify the maximum transient heating temperature and duration to which CFRP can be exposed at different levels of mechanical load. The results show that when the applied load increases, the rupture temperature and maximum exposure duration decrease. At 20°C, the rupture temperature of CFRP gradually decreases when the applied load increases from 10% to 50% of the material's ultimate strength; at room temperature, as the applied load reaches 75% of the ultimate strength, the rupture temperature significantly decreases.

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Likewise, the exposure duration gradually decreases when the applied load varies from 10% to 50% of CFRP's ultimate strength, and decreases considerably when the applied load is 75% of the ultimate strength. Additional tests were conducted on CFRP protected by an insulation material to characterize the effectiveness of the used insulation material used on the performance of hand-laid CFRP subjected to thermal and mechanical loading. Finite element models were used to investigate the thermal conduction, and these models were successfully validated by the experimental results. Thus, the models were confirmed to predict the fire protection capability of the used insulation material reliably and accurately.

Keywords: carbon fibre reinforced polymer (CFRP); elevated temperature; thermo-mechanical behaviour; fire protective system

1. Introduction

In recent decades, carbon fibre reinforced polymer (CFRP) has been increasingly used in civil engineering applications for both reinforcing and retrofitting structures. With its advantages of a high strength-to-weight ratio and favourable corrosion and fatigue resistance, CFRP is often employed to enhance the strength, stiffness and ductility of concrete structures such as columns, beams, and slabs. There are two major methods of applying CFRP in these contexts: by directly bonding a laminate CFRP plate, known as pultruded-CFRP (P-CFRP), on the surface of a concrete structure using adhesive, or by wrapping woven textile CFRP around the concrete structure and securing it with resin. In the latter method, the CFRP is referred to as in-situ CFRP, hand-laid CFRP, or manually-fabricated CFRP (M-CFRP). The following subsections present previous studies on the temperature-dependent behaviour of CFRP, the effects of fire or elevated temperatures on structures strengthened by Fiber

Reinforced Polymer (FRP) without and with insulation material, and the objectives of this study.

1.1. Temperature-dependent behaviour of CFRP

Since CFRP's first application in civil engineering, there has been tremendous interest in its functional capability in fire conditions. Considerable research has focused on the mechanical performance and properties of P-CFRP at elevated temperatures. However, to the best of the authors' knowledge, the performance of hand-laid CFRP under elevated temperatures (above 200°C) has not yet been studied. Over past decades, several researchers have focused on the evolution of the tensile performance of P-CFRP following two popular procedures: in the first procedure, specimens were heated to a predefined temperature and then mechanically tested until rupture following a direct tensile test program (thermo-mechanical procedure); in the second procedure, after being heated to a predefined temperature and then cooled to an ambient temperature, specimens were tested following a direct tensile test program at room temperature (residual procedure). Particularly, Y.C. Wang et al. performed a series of tensile tests on P-CFRP at temperatures ranging from 20°C to 600°C following the thermo-mechanical procedure [1]. Their results showed that the tensile strength of P-CFRP is reduced by approximately 50% as the temperature increases up to 240°C, and at 600°C, its tensile strength was reduced by almost 90%. K. Wang et al. measured the tensile strength of a P-CFRP strip following the thermo-mechanical procedure at temperatures ranging from 22°C to 706°C [2]. Their results demonstrated that the P-CFRP strip's tensile strength was reduced by approximately 50% at 350°C and by more than 80% at 600°C. Yu and Kodur studied the influence of temperature between 20°C to 600°C on the degradation of the tensile properties of P-CFRP strips and rods following the thermo-mechanical procedure [3]. Their results showed that the tensile strength was reduced by approximately 50% for strips and 40% for rods at 300°C, and by approximately 90% for both strips and rods at 600°C; furthermore, the tensile modulus decreased by approximately

30% for both strips and rods at 400°C and by 67% and 47% at 500°C for strips and rods, respectively. Cao et al. tested the thermo-mechanical tensile strength of CFRP sheets (M-CFRP) with two different methods of loading control (by load and displacement increments) between 16°C and 200°C [4]. Their results indicated that the tensile strength of CFRP sheets was significantly reduced with increasing temperature: from 16°C to 55°C, the tensile strength was reduced by approximately 30%, and remained in the vicinity of this value until 200°C. The tensile and lap-splice shear strength properties of M-CFRP composites [5] at temperatures ranging from 23°C to 200°C have been performed. Recently, Nguyen et. al. experimentally and analytically studied the behaviour of hand lay-up CFRP under simultaneous thermal and mechanical loadings with the elevated temperature upto 600 °C [6]. The results showed that the ultimate strength decreased by 50% at 350 °C while the Young's modulus only decreased by 30% at 600 °C.

When subjected to a thermal load, most thermosetting resins and amorphous polymers show one major transition, which occurs within a narrow temperature range called the glass transition temperature (T_g). The T_g of commercial products used in civil infrastructure applications varies between 50°C and 90°C [7]. When the temperature in the material reaches the T_g of the polymer matrix, the matrix becomes softer, and its mechanical properties (Young's modulus, tensile strength) are significantly reduced. Therefore, the contribution of the matrix to the composite's tensile strength gradually becomes negligible. This contribution reduces to zero after the total decomposition of the matrix, characterized by a decomposition temperature, T_d (250°C–500°C) [7, 8]. The matrix decomposition process usually releases heat, smoke, soot and toxic and/or combustible volatiles [8]. This possibly accelerates the matrix decomposition, influences the mechanical properties of the fibre and also restrains the deformation measurement.

1.2. Effects of fire or elevated temperatures on structures strengthened by FRP without and with insulation material

When a fire occurs, structures and FRP-reinforced materials are subjected to heat and mechanical loads at the same time. Several investigations have focused on the performance of CFRP-reinforced concrete structures under fire or near-fire conditions [10-14]. Bisby et al. investigated the residual performance of CFRP-reinforced concrete beams and columns subjected to fire [10]. The residual confining performance of an externally wrapped specimen secured by normal-temperature epoxy and then exposed to fire has been studied [11]. The fire performance of CFRP-reinforced concrete beams under various mechanical load levels has also been investigated [12]. Al-Abdwais et al. observed concrete structures reinforced by CFRP with a cement-based adhesive at elevated temperatures [13]. Firmo et al. experimentally studied the performance of a CFRP-reinforced concrete beam at an ambient temperature and numerically developed these results to describe the fire performance of CFRP-reinforced concrete structures [14].

Additional research has been conducted on the shear and compression strengths of concrete structures or pretensioned CFRP-reinforced slabs under various temperature and mechanical conditions. Masoud et al. numerically studied the performance of a concrete slab reinforced by FRP bars at elevated temperatures, disregarding the degradation of the bonding between the FRP bars and concrete [15]. The application of their results was recommended only where the CFRP bars were anchored to prevent bond failure in a fire. Hajiloo et al. investigated the performance of concrete slabs reinforced by FRP bars under 55% of the ultimate moment resistance in a fire condition [16]. Their results indicated anchoring recommendations that can maintain the structure's performance for up to 3 h. Tan et al. investigated the residual shear-strengthening performance of a glass FRP-wrapped beams after exposure to a temperature-time history [17], following ASTM E-119 [18]. Tan et al. also reported on the performance of a fibre-reinforced cement composite, basalt FRP laminates, and basalt FRP-strengthened beams subjected to elevated temperatures [18–20]. Terrasi et al. and Maluk et al. reported on the fire behaviour of CFRP prestressed

high-performance self-consolidating concrete (HPSCC) slabs through an experimental study on thin slabs exposed to a standard fire [21, 22]. Among the main concerns with FRP-reinforced structures at elevated temperatures is the effect of the adhesive-substrate bond strength on the structural performance [23–30]. Several reinforcement methods and adhesive types have been proposed to improve the adhesive-substrate bond performance under elevated temperature or fire conditions. Non-structural solutions to improve the performance of CFRP-reinforced structures under fire conditions include several insulation systems that have been proposed to protect the structures so that the service duration can be extended to meet fire safety requirements [8, 23–27, 31–39]. Various fire regulations recommend protecting structural elements with certain insulation materials requirements [23, 24], or protecting only the anchorage zone [8, 25–27, 34, 36, 37]. Further recommendations have been made with regard to different material types, such as vermiculite/gypsum mortar insulation material [31, 32] or vermiculite/perlite mortar insulation [36]. Numerical models have also been proposed to investigate the efficiency of insulation materials in terms of enhancing the fire performance of FRP-reinforced structures [34, 40–42]. Bond loss between CFRP composites and concrete substrate without insulation protection has also been analysed and modelled by Dai et al. as well as Biscaia et al. [43–47].

1.3. Objectives of this study

As noted in previous research, to the best of the authors' knowledge, very few studies have focused on the thermo-mechanical behaviour of hand-laid CFRP and the performance of this material under combined elevated temperatures (above 200°C) and mechanical loading conditions has not yet been experimentally studied. There are also no experimental or numerical results regarding the insulation material's capability to protect hand-laid CFRP under combined elevated temperatures and mechanical loading. In this research, the performance of a hand-laid CFRP simultaneously exposed to elevated temperature and mechanical loading was investigated to determine the temperature and duration of exposure

at which failure occurred. An insulation material was also experimentally tested for its thermal performance and was then applied to thermally protect the CFRP material in the thermo-mechanical testing regime. The efficiency of the insulation material was then analysed and numerically extended to the fire-temperature condition.

2. Experimental materials and methods

This section presents experimental devices, specimens and experimental procedures that were used for this study.

2.1 Experimental devices

In this research, a thermo-mechanical testing system (Figure 1) was used to study the thermo-mechanical behaviour of a M-CFRP material. The system included two main parts: a thermo-mechanical machine (TM20kN-1200C) and a laser extensometer. During the test, the TM20kN-1200C controlled the force and temperature applied on the sample according to a determined procedure, and the laser extensometer measured the elongation of the M-CFRP specimen, from which the tensile axial strain of the sample was calculated [49].

The TM20kN-1200C included a mechanical component (Figure 1a) and a furnace (Figure 1b). The mechanical component can apply direct tensile loading onto the test specimen with a loading capacity of up to 20 kN at a programmable loading speed. The furnace was a cylindrical oven with external dimensions of 40 cm in height and 30 cm in diameter, and the dimensions of the oven's heating chamber were 28 cm in height and 10 cm in diameter. This furnace could generate high temperatures of up to 1200°C at a maximum heating rate of 30°C/min. The temperature level and the heating rate were programmable so that the testing systems could control the target temperature levels and ramp rates automatically. The furnace was insulated to guarantee that the temperature of the closed system inside of the furnace was that established by the program. A rectangular opening on

the side of the furnace allowed two laser rays from the laser extensometer to measure the elongation of the specimen. This opening could be closed in case the laser extensometer was unused. To measure the loading level, a force sensor was placed outside the furnace to measure and control the applied force. Six thermocouples were placed inside the furnace, including three on the wall of the heating chamber and three on the sample surface, to follow the temperature in real time and control the furnace accordingly.

Figure 1. Thermo-mechanical testing system: a: mechanical machine; b: furnace; c: laser extensometer.

2.2. Specimens

In this research, the M-CFRP was prepared from unidirectional woven carbon fibres added to a polymer matrix. According to the supplier's datasheet, the carbon textile weighed 310 g/m^2 and had a thickness of 0.32 mm , and the tensile strength of a carbon monofilament was 4902 MPa , with a tensile modulus of 230 GPa . The elongation failure of the carbon fibre was 2.1% , and the minimum bond strength and shear strength of the polymer matrix were 14

and 12 MPa, respectively; the elastic modulus of the polymer was 2 GPa and its T_g was 40°C, as specified in the supplier's datasheet. The carbon textile was first divided into test specimens that each contained four fibre rows, and aligned on a flat surface. The polymer matrix was prepared by mixing two components of epoxy following the recommended ratio and then brushed onto the textile, after which the polymer matrix was allowed to harden, forming mechanical and chemical bonds with the carbon fibres.

In most tensile testing procedures, the two ends of a sample are gripped by two clamps, and the tensile axial force is transmitted to the sample by the friction of the regions of contact between the clamps and the sample. However, the tensile strength of the material tested here was much greater than the friction force. Therefore, to transmit the tensile force from the mechanical components to the composite material effectively, two aluminium plates were attached to each end with an epoxy adhesive (Eponal 380). The shear resistance and tensile resistance of the epoxy were 15 and 29.5 MPa, respectively (from the supplier's datasheet). Figure 2 details the dimensions of the specimens tested without the insulation material (M-CFRP, Figure 2b) and with the insulation material (M-CFRP-Ins, Figure 2a).

The insulation's capacity for structural protection was first studied through a heat transfer test via a cylindrical sample (Figure 3), and then throughout an insulated CFRP specimen (Figure 2a). Five thermocouples (TC1 to TC5, Figure 3) were arranged inside and outside the sample to follow the temperature evolution at different positions on the specimen. The insulation material was non-combustible vermiculite/gypsum mortar (Tyfo® VG insulation). As indicated on the supplier's datasheet, the insulation's density was 0.458 g/cm³; its compressive strength and bond strength were 0.893×10^{-3} and 8.012×10^{-5} MPa, respectively; its combustibility satisfies ASTM E136.

performance was defined as the exposure duration. The rupture temperature and exposure duration were the two main factors employed to represent the thermo-mechanical performance of the specimens in the testing regime. Figure 5 details the heat transfer test conducted with the insulated cylindrical sample. In this test, the temperature surrounding the sample was increased from ambient temperature (T_a) to 1100°C at a heating rate of 30°C/min. The performances of M-CFRP and M-CFRP-Ins are presented and discussed in the following sections.

Figure 4. Thermo-mechanical testing regime; T_a : ambient temperature;

T_r : rupture temperature; F_c : control force; F_w : applied force.

Figure 5. Thermal test with

insulation

3. Experimental results and discussion

Table 1 displays the ultimate strength and Young's modulus of the studied M-CFRP at room temperature. As can be seen in this table, the ultimate strength of this M-CFRP was between 816 and 1001 MPa, and its average measured Young's modulus was 62.2 GPa. These tensile properties were calculated based on the average dry dimensions (width and thickness) measured at every 5 cm along the specimen's length. The obtained ultimate strength was then used to identify the mechanical load to be applied on the M-CFRP material in the thermo-mechanical testing regime.

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Table 1. Properties of M-CFRP at room temperature.

ID	C.20.a	C.20.b	C.20.c	Average value
Temperature (°C)	20	20	20	20
Ultimate stress (MPa)	922.8	816.5	1001.3	913.5
Young's modulus (GPa)	58.2	60.6	67.9	62.2

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Table 2 shows the thermo-mechanical performance of M-CFRP under different loading conditions in terms of the failure temperature (T_{rup}) and exposure duration. In this table, the applied load ratio (f_w) is identified as the ratio between the stress level that corresponds to the applied load and the average ultimate stress of the material obtained at 20°C. These results show that when the applied load ratio (f_w) was less than 0.5, the rupture temperature (T_{rup}) ranged between approximately 540°C and 650°C, whereas the exposure duration varied from 20 to 52 min. When f_w was 0.75, the T_{rup} was low, between 45°C and 64°C, and the exposure duration was less than 3 min.

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Table 2. Thermo-mechanical performance of M-CFRP under different applied load ratios (f_w).

Sample ID	C.T. 010.a	C.T. 010.b	C.T. 010.c	C.T. 025.a	C.T. 025.b	C.T. 025.c	C.T. 050.a	C.T. 050.b	C.T. 075.a	C.T. 075.b	C.T. 075.c
Applied load ratio, f_w	0.1	0.1	0.1	0.25	0.25	0.25	0.5	0.5	0.75	0.75	0.75
T_{rup} (°C)	630	629	650	578	598	613	543	540	46	45	64
Exposure duration (minutes)	31.2	32.7	36.8	23.7	25.7	20.1	52.1	22.5	0.4	0.4	2.2

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The results obtained from M-CFRP-Ins under the thermo-mechanical testing regime are presented in Table 3. The table shows the exterior and interior temperatures (T_{ex} and T_{in} , respectively) of the insulation layer at the rupture point of the sample, as well as the exposure

duration. Results were obtained for two cases of imposed load ($f_w = 0.2$ and $f_w = 0.3$). The rupture temperatures for the two loading cases were 780°C and 880°C, respectively, and the exposure durations were 48 and 37 min.

Table 3. Thermo-mechanical performance of M-CFRP-Ins.

Sample ID		C.T.020.Ins	C.T.030.Ins
Applied load ratio, f_w		0.2	0.3
T_{rup}	T_{ex} (°C)	780	880
	T_{in} (°C)	867	688
Exposure duration (minutes)		47.93	36.58

Figure 6 shows the temperature evolutions at the three different positions on the insulation material shown in Figure 3. At the beginning of the test, the exterior temperature increased from the initial condition with a ramp rate of 30°C/min, reaching 900°C in approximately 30 min. Subsequently, this temperature continued to increase with a ramp rate of 4°C/min, reaching approximately 1100°C in 50 min. In the first phase, the interior temperatures at TC4 (T_{in_1}) and TC5 (T_{in_2}) started to increase approximately 7 to 14 min later than the exterior temperatures, with ramp rates of 6.3°C/min and 8.9°C/min, respectively. When the temperatures at TC4 and TC5 reached approximately 100°C, there was a plateau phase in which the temperature increased only slightly with ramp rates of 1.3°C/min and 0.4 °C/min, respectively, in approximately 13 and 30 min. In the final phase, the temperature at TC4 increased steeply with a ramp rate of 23°C/min, whereas the corresponding rate at TC5 was 38°C/min. Subsequently, these two temperatures reached 800°C in approximately 30 and 20 min, respectively. The tests were terminated because of safety considerations when these temperatures reached 1029°C and 1007°C.

Figure 6. Evolution of exterior (T_{ex}) and interior (T_{in_1} ; T_{in_2}) temperatures of the insulation material during heat transfer tests (thermocouple positions are shown in Figure 3).

Figures 7 and 8 show the temperature evolutions at the exterior and interior of the insulation material during the thermo-mechanical tests for the two loading cases. When the applied load ratio was 0.2 (the corresponding imposed load was 2317 N), the actual exterior temperature increased from room temperature (approximately 20°C) with a ramp rate of 28°C/min and reached 600°C in approximately 20 min (Figure 7). Subsequently, the ramp rate decreased until the M-CFRP-Ins ruptured. The evolution of the interior temperature also exhibited three distinct phases: in the first phase, the temperature gradually increased from the initial temperature to 95°C with a ramp rate of 11°C/min. This phase occurred over approximately 5 min. In the second phase, the interior temperature slightly increased with a ramp rate of 0.65°C/min for more than 10 min before rapidly increasing with a ramp rate of approximately 40°C/min in the third phase. With an applied load ratio of 0.3 (corresponding to an imposed load of 3476 N), the exterior temperature increased with a ramp rate of 24.5°C/min and reached 600°C in approximately 20 min (Figure 8). The increase in the interior temperature also exhibited distinct phases. In the first phase, the temperature gradually increased for approximately 5 min from the initial temperature to approximately

293 94°C. In the second phase, the temperature slightly increased with a ramp rate of 0.95°C/min
 294 over approximately 15 min before steeply increasing at a ramp rate of 58°C/min until rupture.

295
 296 Figure 7. Evolution of external and internal temperatures of M-CFRP-Ins with an applied load ratio (f_w) of 20%

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 298 Figure 8. Evolution of external and internal temperatures of M-CFRP-Ins with an applied load ratio (f_w) of 30%.

299 The temperature increase exhibited by M-CFRP-Ins (Figures 6, 7 and 8) was stable at
 300 approximately 25.4°C/min to 30°C/min until reaching approximately 600°C–800°C,
 301 whereas the actual heating rate inside the furnace significantly decreased from 4°C/min to
 302 6.5°C/min, depending on the test case, because of the homogeneous temperature
 303 requirement. This may explain why, at the same mechanical load ratio of 0.25, the specimen

C.T.025.b failed at 598°C after 25.7 min, whereas the specimen C.T.025.c failed at 613°C after 20.1 min (Table 2).

According to the obtained results, the rupture temperature of M-CFRP decreased as the applied load increased. Figures 9 and 10 show the evolution of the rupture temperature and thermal exposure duration of M-CFRP as the imposed load increased (M-CFRP.T2 and M-CFRP.T2.Avg). When the applied load ratio increased from 0.1 to 0.25 (or to 0.5), the rupture temperature gradually decreased from 636°C to 596°C (or to 541°C) (on average), and the exposure duration varied from 33 min to 23 min (or to 30 min), respectively. When the applied load ratio increased to 0.75, the rupture temperature significantly decreased to 52°C, and the exposure duration decreased to 1 min (on average). The heat transfer test on M-CFRP-Ins showed that in the radial direction, the temperature evolution was delayed in conjunction with the thickness of the insulation layer (Figure 6). The evolution of the interior temperature of the insulation material clearly exhibited three distinct phases.

The results also showed that the thermo-mechanical performance of M-CFRP-Ins varied under different mechanical loading conditions (M-CFRP.T2-Ins, Figure 9 and Figure 10). In particular, the temperature of the M-CFRP-Ins increased approximately 150°C at $f_w = 0.2$ and approximately 300°C at $f_w = 0.3$ (Figure 9). Likewise, the exposure duration increased more than 20 min for $f_w = 0.2$ and more than 15 min for $f_w = 0.3$. These results showed that the exterior temperatures at failure were higher than the failure temperatures of the uninsulated materials (Figure 9). The interior temperatures at failure of these test cases were also higher than those of the uninsulated cases. As can be interpolated from Figure 9, at $f_w = 0.2$, the interior temperature at failure of the insulated specimen was approximately 750°C, compared to approximately 610°C for the uninsulated specimen; at $f_w = 0.3$, the interior temperature at failure was approximately 687°C, compared to approximately 570°C for the uninsulated specimen.

Figure 9. Failure temperature of M-CFRP at different applied load ratios (f_w).

In the two insulated cases, the temperature ramp rates on the M-CFRP surface were approximately 40°C/min and 57.8°C/min (Figure 7 and Figure 8), higher than the heating rates on the insulation surface, which were approximately 28°C/min and 25.4°C/min respectively. These results reflect the lower mass loss rate of epoxy resin at higher heating rates from 10°C/min to 40°C/min [30, 37]. In the insulated cases, the direct contact between oxygen, the epoxy matrix and carbon fibres at high temperatures was very limited, whereas without insulation, the presence of oxygen in the heating chamber could accelerate the ignition of carbon fibres [50].

Figure 10. Exposure time of M-CFRP at different applied load ratios (f_w).

4. Finite element modelling

A finite element modelling was investigated to study the efficiency of the insulation material under different temperature conditions. A previously developed heat transfer model for predicting temperature in an insulated concrete section with a finite-volume code was applied. The partial differential equation of heat conduction was expressed as:

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) = \frac{\partial}{\partial x} \left(k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_z \frac{\partial T}{\partial z} \right)$$

Where: T is temperature, t is time, k is thermal conductivity, ρ is density and c is heat capacity.

4.1. Numerical model

The experimental insulation material, as shown in Figure 2, had a length of 280 mm, width of 60 mm, and thickness of 40 mm. Because of the symmetrical loading and boundary conditions, a one-eighth model was generated and analysed using the finite element code ANSYS APDL (Figure 11). The finite element model of the insulation material had a length of 140 mm, width of 30 mm, and thickness of 20 mm. The one-eighth model can simplify the

computation process by reducing the number of elements while maintaining the reliability of the analysis. The element type chosen for the transient thermal analysis was SOLID70 (a 3D 8-node thermal solid), as shown in Figure 12. With a maximum meshing element size of 2 mm, there were 11852 elements for the numerical calculations conducted to simulate the experimental tests.

Figure 11. One-eighth symmetry finite element model with meshed elements during heating.

Figure 12. SOLID70 : 3D 8-node thermal solid [51]; 8 nodes of the element SOLID 70: I, J, L, K, O, N, M, P; key numbers from 1 to 6 : 6 faces of the element SOLID 70: 1 (J-I-L-K), 2 (I-J-N-M), 3 (J-K-O-N), 4 (K-L-P-O), 5 (L-I-M-P), 6 (M-N-O-P).

To obtain accurate predictions of heat transfer within the insulation material, the thermal properties at 20°C were adopted from previously published studies on the same insulation

type [36]: thermal conductivity, $K_0 = 2.5 \times 10^{-4}$ W/mm·K; specific heat, $C_0 = 1654$ J/kg·K; and density, $\rho_0 = 2.69 \times 10^{-7}$ kg/mm³. The evolution of the insulation material's thermal properties in relation to temperature is summarized by Hawileh et al. [36] (see Table 4).

Table 4. Evolution of normalized thermal properties of the insulation material [36].

Temperature (°C)	20	100	150	200	300	400	500	600	700
Normalized specific heat C/C_0 (20°C)	1.00	3.60	0.80	0.55	0.55	0.50	0.45	0.45	0.45
Normalized thermal conductivity K/K_0 (20°C)	1.00	1.00	0.45	0.45	0.45	0.50	0.60	0.80	0.80

The evolution of the exterior temperature condition was modelled following the temperature evolution in the experimental tests (Figure 7 and Figure 8). In this process, three cases of transient heat transfer were observed: two cases simulated two of the experimental temperature conditions applied to M-CFRP-Ins, and the third case extended the model to the fire-temperature condition.

4.2. Numerical results

To examine the validity of the model, the finite element model and experimental results were compared. Figure 13 shows the temperature distribution in the insulation volume of the C.T.020.Ins case (see Table 3). Figures 14 and 15 show the temperature evolutions of the exterior temperature ($T_{\text{ext.}}$) and the interior temperature ($T_{\text{int.}}$) obtained numerically (-.N) and experimentally (-.E) for the two cases C.T.020.Ins and C.T.030.Ins (see Table 3). The exterior point was located on the middle of the surface of the insulation volume and the interior point was located on the middle of the interface between the CFRP material and the insulation material (measured by thermocouple in the experiment, Figure 2). In the numerical

model, the interior point was selected to be 2 mm from the axial axis of the volume (corresponding to the position of thermocouple in the experiment).

Figure 13. Temperature distribution of the C.T.020.Ins case (°C).

As can be seen from Figures 14 and 15, the exterior temperatures obtained with the numerical model were generated according to the exterior temperatures obtained in the experiments. The predicted interior temperatures for the two cases were very close to the results obtained in the experiments. In the C.T.020.Ins case, the experimental interior temperature rapidly increased; the numerical values were close but still lower than the exterior temperature. The numerical model did not include a mechanical load, and the insulation material was assumed to be continuous and isotropic, whereas in the experiments, the material was subjected to mechanical loading, which may have influenced the performance of the insulation material.

Figure 14. Temperature evolution of exterior temperature ($T_{ext.-}$) and interior temperature ($T_{int.-}$) of C.T.020.Ins case: numerical result (-.N) and experimental result (-.E).

Figure 15. Temperature evolution of exterior temperature ($T_{ext.-}$) and interior temperature ($T_{int.-}$) of C.T.030.Ins case: numerical result (-.N) and experimental result (-.E).

From the successful calibration of the input thermal properties based on the two experimental tests, a third model was generated to observe the insulation material's capacity to protect CFRP under a temperature condition that approximates that of an actual fire. The third thermal analysis model had the same material properties; however, the geometry varied in terms of the thickness of the insulation layer, from 1 to 5 cm, as shown in Table 5. The model was then applied to simulate a thermal load on the insulation surface with a temperature evolution in accordance with the standard fire curve specified in ISO-834 [52].

Figure 16 displays the evolution of the exterior and interior temperatures as a function of time in different cases. As can be seen from Figure 16, the temperature applied on the specimen's surface (N.T_ext-ISO 834 curve) in the model was exactly equal to the standard fire curve (standard ISO 834 curve). The interior temperature curves for the different thicknesses (N.T_int.Xcm, with X from 1 to 5 cm) showed that the thicker the insulation material, the longer that the heat conduction was delayed.

Table 5. Geometry of the fire-testing model (one-eighth model).

Thickness of insulation layer, cm		1	2	3	4	5
Specimen dimension, cm	Length	14	14	14	14	14
	Width	2	3	4	5	6
	Thickness	1	2	3	4	5

Figure 16. Exterior and interior temperature evolution of insulation volumes with different thicknesses under standard fire-temperature condition.

5. Discussion of the insulation material's capability to protect M-CFRP under fire conditions

Table 6 summarizes the average failure temperature of M-CFRP under different applied load ratios. According to this summary, when the applied load ratio increased from 0.1 to 0.5, the failure temperature gradually decreased from 636.4°C to 491.8°C. At the load ratio of 0.75, the failure temperature significantly decreased to 51.7°C.

Table 6. Thermal resistance of M-CFRP under different applied load ratios.

Applied load ratio	0.1	0.25	0.5	0.75
Average rupture temperature, °C	636.4	596.3	491.8	51.7

Although the results from the M-CFRP-Ins tests showed that at the time of failure, the temperature of M-CFRP-Ins was higher than that of M-CFRP, further experiments and analysis need to be undertaken to confirm this tendency. In civil engineering, when a fire occurs, there are several phenomena that must be considered: structures are subjected to service loads, temperatures are elevated, chemical reactions or degradation of the material occurs, and there is toxic smoke. This research focused on the performance of M-CFRP and M-CFRP-Ins under combined elevated temperature and mechanical loading conditions, without considering other phenomena, such as material degradation due to elevated temperature. According to current guidelines for fire safety designs, the main role of the insulation material is to protect the structure under elevated temperatures. Furthermore, the mechanical properties of several commercially available insulation materials are not significant in comparison with the corresponding properties of the structure and construction materials. The results presented here can be applied to predict the performance of M-CFRP under combined mechanical and temperature loads in case of fire. Furthermore, the

experimental and numerical results can be applied to estimate the temperature evolution behind insulation layers with certain thicknesses at different elevated temperatures. The experimental M-CFRP-Ins results showed that the real temperature at the M-CFRP surface (under the insulation layer) at failure was higher than that of without the insulation material. However, if the failure temperature in the case without the insulation material is defined as a failure criterion for M-CFRP, then it is possible to apply this criterion to predict the failure of insulated M-CFRP specimens that are simultaneously subjected to both mechanical loading and elevated temperature. Therefore, within the scope of this research, the surface temperatures of M-CFRP at failure in the two tested cases (with and without insulation material) are not significantly different, disregarding the mechanical status. Based on the numerical result for the fire-temperature loading case (Figure 16), a thickness of insulation material can be proposed to protect the M-CFRP under such temperatures, with regard for the mechanical loading status and the required exposure duration, as displayed in Figure 17.

Figure 17. Extended fire performance of M-CFRP based on different thickness of insulation layer.

From a civil engineering perspective, if M-CFRP is subjected to a mechanical load up to 50% of the material's resistance capacity, an insulation material with a thickness of

approximately 4.3 cm can protect the M-CFRP under fire-temperature conditions for up to 60 min (Figure 17).

6. Conclusions

This work aimed to investigate the performance of M-CFRP and M-CFRP-Ins using a thermo-mechanical testing regime. When the imposed load increased, the maximum temperature to which the M-CFRP could be exposed decreased. When the imposed load was less than 50% of its strength at 20°C, the rupture temperature decreased slightly, from 636°C to 541°C, on average. When subjected to a load level equal to 75% of its strength at 20°C, the rupture temperature of M-CFRP sharply decreased to 52°C on average. The use of an insulation material was shown to improve the thermo-mechanical performance of M-CFRP in the tested regime. The thermal-delay capacity depended on the thickness of the insulation layer. With 2 cm of insulation thickness, the heat penetration to the M-CFRP surface was delayed by approximately 10 min (under the tested conditions). In this testing regime, the M-CFRP-Ins could be exposed to higher temperatures for longer durations because of the reduced contact between CFRP and oxygen. The numerical results showed that, under fire-temperature conditions, the insulation could protect M-CFRP to satisfy fire design requirements in terms of exposure duration, depending on the mechanical status of the M-CFRP material.

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