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EXPERIMENTAL INVESTIGATION AND ANALYTICAL MODELING OF THE CRACK WIDTH EFFECT ON THE FIRE PERFORMANCE OF CARBON TEXTILE-REINFORCED CONCRETE COMPOSITE

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Abstract

In comparison with fiber-reinforced polymer (FRP) composite, the textile-reinforced concrete (TRC) presents stability in mechanical performance at elevated temperatures thanks to a thermal protection layer by the cementitious matrix. This paper presents the experimental characterization and analytical modeling for fire performance of carbon TRC under the thermomechanical regime at constant tensile force. The carbon TRC is manufactured from the cementitious matrix with good thermal properties (refractory matrix) and the reinforcement of carbon textiles. In the experiment, the ultimate strength of the carbon TRC specimen was firstly identified from the direct tensile tests at ambient temperature. Afterwards, in the thermomechanical regime, the fire performance of carbon TRC specimens according to 5 loading levels ranging from 10% to 75% related to its ultimate strength was determined. As a result, the effect of crack appearance on this thermomechanical performance was highlighted and analyzed. For the analytical modeling, a model was calibrated with the experimental results to predict the fire performance of carbon TRC by taking into account the effect of crack width.

Keywords: textile reinforced concrete (TRC); fire performance; analytical model; crack width.

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1. Introduction

Over the past few decades, industrial textiles have been increasingly and widely used as alternative materials in the civil engineering field [1, 2]. The composite materials of these industrial textiles with the polymer matrix (FRP) or the cementitious matrix (TRC) have been increasingly and widely applied to strengthen or repair the structural elements (RC member, column, beam) [1, 3]. Thanks to

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their advantages (high strength and stiffness, slight), they have been used as reinforcement in several exceptional cases of loading or environment such as impact, seismic, or at elevated temperatures [4–6]. In the case of fire, the thermal response of the matrix layer influences greatly the changes in the mechanical properties of these composites. These changes are considered as a principle factor for the fire application of industrial textile composite. Comparing with the polymer matrix in the FRP composite, the cementitious matrix (in TRC) has a better thermal response. So, it contributes as a thermal protection layer against the action of the elevated temperature into reinforcement textiles. That's why TRC composite becomes better choice for strengthening or reinforcement in case of fire.

In case of fire in the structures reinforced with TRC material, this is subjected simultaneously to mechanical loading and elevated temperatures (potentially up to 1200 °C). For fire safety, it is necessary to know the thermomechanical performance of TRC to calculate or predict how many times the structure could be subjected to those simultaneous load combinations. Thus, it needs more experimental tests also an analytical approach for the identification of the thermomechanical performance of TRC material in the case of fire.

Concerning the experimental research on TRC composites at elevated temperatures, three loading paths were usually used to study the effect of fire or elevated temperature on the performance of the TRC specimen. The first one was called thermomechanical condition at a constant temperature (or hot condition). It means that the TRC specimen was tested under the tensile force until its failure after being reached homogeneous temperature on the specimen [7–9]. As the experimental results, TRC composite provided the strain-hardening behaviour with different working phases and a gradual reduction of mechanical properties (cracking stress, initial rigidity, ultimate stress, post-crack rigidity) with increasing temperatures. The second loading path was called the residual condition in which the TRC specimen was tested after a thermal process heating – cooling [10, 11]. The purpose of this loading path was to identify the residual performance of TRC composite after a real fire. The experimental results released a great decrease in mechanical properties of TRC composite at preheating temperature higher than 400 °C.

The last loading path was the thermomechanical condition at a constant force in which the TRC specimen was kept at a loading level (related to the ultimate strength) and subjected to the temperature heating until the failure of the specimen. This experimental test aimed to determine the elevated temperature performance of TRC composite through the rupture temperature and exposure duration. In the literature, few studies were carried out to identify the fire or elevated temperature performance of TRC composite under this loading path. The influence of the rate of temperature heating on the elevated temperature performance of carbon TRC specimens was identified in Ehlig et al. [12]. The contribution of the calcium aluminate cementitious matrix in the thermomechanical performance of carbon TRC was highlighted and analyzed in Tran et al. [7]. These results also showed the higher performance of carbon textiles comparing to another for an application in TRC composite.

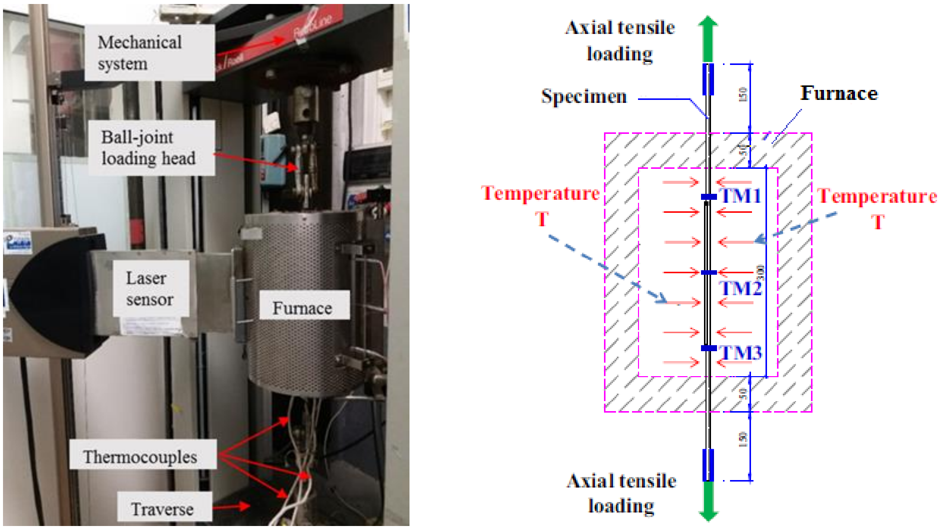
To the best of the authors' knowledge, no experimental results are available concerning the effect of crack width on the fire performance of TRC composite subjected to the thermomechanical condition at a constant force. There is also not yet an analytical model for the prediction of elevated temperature performance of TRC composite material in case of fire. This paper presents the experimental characterization and analytical model for the elevated temperature performance of carbon TRC under the thermomechanical condition at constant tensile force level. In this paper, the carbon textile, in grid form and treated with epoxy resin product to improve the mechanical performance of yarns, was combined with a calcium aluminate cementitious matrix. the ultimate strength of the carbon TRC specimen was firstly identified from the direct tensile tests at ambient temperature. Afterwards, in the thermomechanical regime, the fire performance of carbon TRC specimens according to 5 loading levels ranging from 10% to 75% related to its ultimate strength was determined. The effect of crack appearance on the thermomechanical performance of carbon TRC (failure temperature and exposure duration) was highlighted and analyzed from experimental results. An analytical model was also developed to predict the TRC's performance in case of fire.

2. Experimental works

2.1. *Experimental devices*

a. Machine of test

The thermomechanical machine used in this research, TM 20 kN-1200 °C, can generate a maximum force of up to 20 kN for direct traction tests. It is also well equipped with a cylindrical furnace that can create thermal loads around test specimens up to maximum temperature (1200 °C). The tensile load is controlled by the vertical displacement of the traverse thanks to the control program of the control system (Fig. 1(a)). The rate of load increasing depends on the type of material (ultimate strength and stiffness), in general for TRC composites, it is about from 200 µm/min to 500 µm/min. The machine's traverse related to the ball-joint loading head to transfer the tensile force to the specimens. During the test, all data (tensile force, displacement, time) were recorded at least twice per second for exploitation.



(a) Thermomechanical test (b) Test configuration inside of the furnace

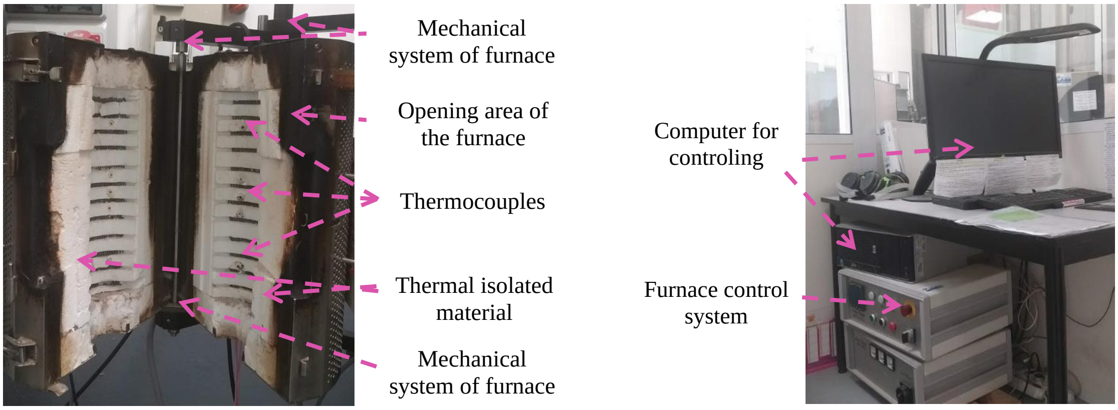
Figure 1. Thermomechanical machine, TM20kN-1200 °C (in LMC2)

b. Furnace

The furnace used in this experiment is an electric and programmable oven in a cylindrical shape. It can create the temperature heating inside up to 1200 °C with a maximum rate of 30 °C per minute. The temperature inside the furnace is controlled by the program of the control system (Fig. 2(b)). All information about temperature is recorded for the analysis of the results. This furnace is installed in the middle of the test machine by a mechanical system so that it can be placed in a correct position for thermomechanical tests.

c. Thermocouples

Six thermocouples were used to determine the increasing temperature inside the furnace during the thermomechanical test. Among them, three thermocouples were attached inside the furnace shell to measure the elevated temperature for the furnace control system. The remaining ones were attached to the surface of the specimen at the equidistant places from the middle. They aim to measure and control the temperature on the surfaces of the specimen through the control program in the computer (Fig. 2). Normally, there is an acceptable difference between their values (of about 20 °C). However, the results of the temperature on the surface of TRC specimens were chosen.



(a) Detail of the furnace for thermomechanical test (b) Test configuration inside of the furnace

Figure 2. Images of the furnace and furnace control system

2.2. *Carbon TRC specimens*

a. Material components

The carbon TRC composite material was combined with a refractory cementitious matrix and a layer of carbon textile. The continuous carbon textile (called GC1) in this experiment is in grid form (Fig. 3(a)). It was coated with an epoxy resin better working between the monofilaments. The espacement between two textile yarns is 46 mm and 41 mm, respectively for the warps and the wefts

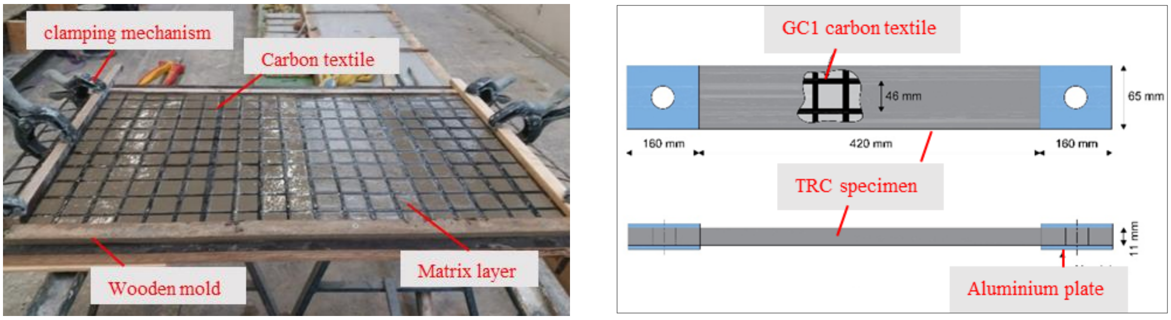
(a) Roll of GC1 carbon textile (b) Geometry of GC1 grid

Figure 3. GC1 carbon textile for an application in carbon TRC composite

(Fig. 3(b)). The cross-section of yarn is 1.85 mm^2 for both the warp and the weft. The refractory cementitious matrix consisted of calcium aluminate cement (CAC) with the 50% content of calcium aluminate and silico-aluminous-calcium synthetic aggregates containing around 40% of alumina. The high content of mono-calcic aluminate in this matrix aims to give it remarkable mechanical performance, as well as stability in strength with the elevated temperature. The maximum aggregate diameter was 1.25 mm for a small thickness of carbon TRC.

Table 1. Properties of GC1 carbon textile

GC1 Carbon textile	
Ultimate strength (MPa)	2617
Young's modulus (GPa)	256
Density (g/cm^3)	3.43
Grid geometry (long × trans) (mm × mm)	46 × 41
Type of coating	Epoxy resin
Cross-sectional area (mm^2)	1.85



(a) Hand lay-up moulding

(b) Dimension of F.GC1 specimens

Figure 4. Preparation procedure of the F.GC1 specimens

b. Specimen preparation

All TRC composite specimens (called F.GC1) were fabricated in conditions of laboratory LMC2 (University Lyon 1, France) with three following steps. Firstly, the TRC rectangular plates with a dimension of 740 mm in length, 500 mm in width, and 11 mm in thickness were molded by using a hand lay-up moulding technique (Fig. 4(a)). The cementitious matrix was reinforced by one layer of GC1 carbon textile with a volume fraction of 0.88%. After that, the TRC plates were also cut to result in 5 TRC specimens with a dimension of 740 mm of length, 65 mm of width, and 11 mm of thickness (Fig. 4(b)). With the specimen cutting method, the thermal protection effect of the cementitious matrix would be influenced for the wefts of TRC because they are exposed to elevated temperature on two sides of the specimens. However, this negative influence is small and negligible. Finally, two ends of F.GC1 specimens were reinforced with the aluminum plates (dimension of 65 mm × 160 mm) for the complete transfer of tensile force from the ball-joint loading head to specimens (Fig. 4(b)). The cross-sectional area was calculated from three measurements (width and thickness) at three different points of each specimen.

2.3. Thermomechanical loading path

Fig. 5 below presents the thermomechanical loading path used in this experimental study with two phases corresponding respectively with the application of tensile force and temperature heating. In the first one, the TRC specimen is applied the tensile force monotonically up to the studied level (from 10% to 75% related to TRC's ultimate strength at room temperature). In the second, this tensile force level is kept in the TRC specimen while the temperature increases in the furnace from room temperature until the rupture of TRC specimens. The elevated temperature performance of the carbon TRC specimen is identified through the rupture temperature (T_r) and exposure duration at high temperature (Fig. 5).

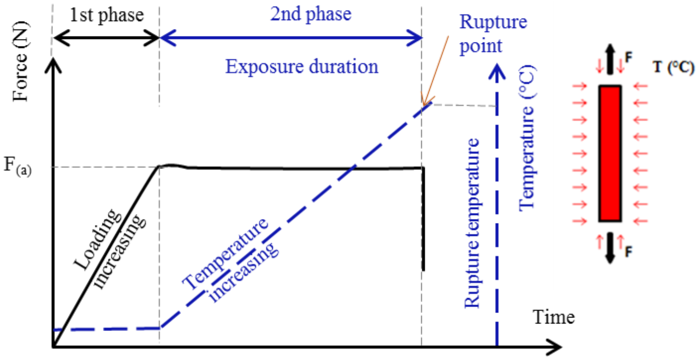


Figure 5. Thermomechanical loading path for the carbon TRC specimens

Table 2. Summary of tests for F.GC1 specimens

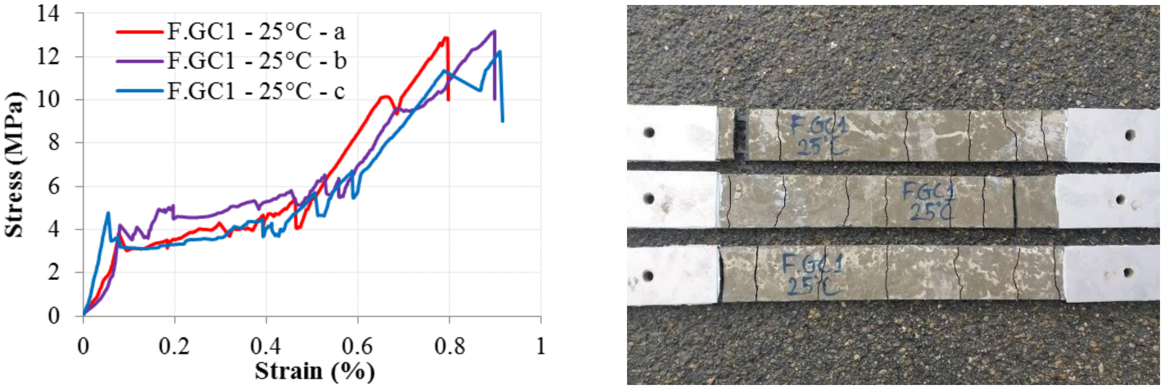
Specimens	Dimensions	Tensile force (kN)	Loading levels (%)	Number of tests
F.GC1 – 25 °C – a,b,c		-	-	3
F.GC1 – 11% – a,b,c	$S = 11 \times 65$ (mm^2); $l = 740$ (mm)	1.0	11	3
F.GC1 – 25% – a,b,c		2.4	25	3
F.GC1 – 51% – a,b,c		4.8	51	3
F.GC1 – 64% – a,b,c		6.0	64	3
F.GC1 – 75% – a,b,c		7.1	75	3
Total of tests				18

3. Experimental results and discussions

3.1. Experimental results

a. Ultimate strength of carbon TRC

The stress-strain relationships of F.GC1 specimens at ambient temperature are presented in Fig. 6(a). As in this figure, the F.GC1 composite exhibited a strain hardening behaviour with a cracking phase of the cementitious matrix. Concerning the mechanical properties of the F.GC1 specimen, it reached the ultimate strength of 12.67 MPa on average while the maximum axial strain was 0.866% on average. Regarding the failure mode of TRC specimens, it could be observed transversal cracks of the cementitious matrix on their surface after tensile tests (Fig. 6(b)). This observation was related directly to the drops in the stress of the stress-strain curves.



(a) Stress-strain relationship

(b) Failure mode

Figure 6. Experimental results on the tensile behaviour of F.GC1 specimens

From the result on the ultimate strength of the F.GC1 specimen, five applied forces used for thermomechanical tests were 1.0 kN, 2.4 kN, 4.8 kN, 6.0 kN, and 7.1 kN, corresponding respectively with 11%, 25%, 51%, 64% and 75% related to the ultimate force of F.GC1 specimens. For analysis of the opening of cracks corresponding with each applied force level, a notion was used for the post-crack point (POS point) that the cracking completely occurred in the cementitious matrix of TRC specimens. This point was identified in the same way as the previous studies in the literature [7]. The stress level is corresponding to this point was called σ_{POS}.

b. Thermomechanical performance of carbon TRC at elevated temperature

Fig. 7 shows all average temperature-time curves of the tests in the thermomechanical loading path with the applied force levels ranging from 11% to 75%. As an obtained result, the F.GC1 specimen was supported to the temperature heating up to 760 °C during an exposure duration of 27.9 minutes

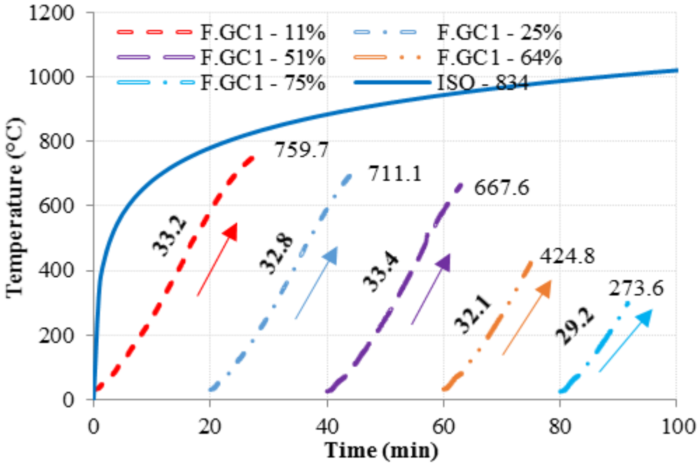


Figure 7. Temperature increasing as a function of time with different loading levels

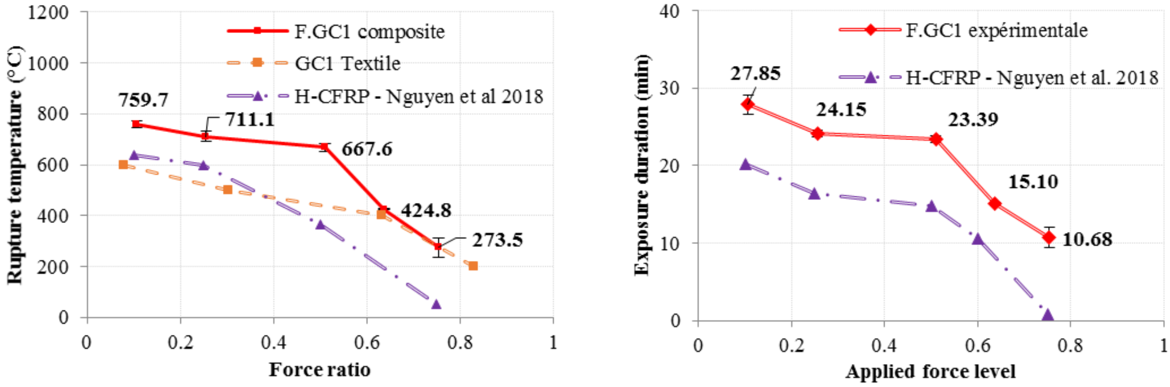
corresponding with the applied loading level of 11%. When this ratio increases from 11% to 51%, the elevated temperature performance (rupture temperature and exposure duration) of F.GC1 specimen slightly decreases, from 760 °C down to 668 °C for rupture temperature and from 27.9 minutes down to 23.4 minutes. However, with an applied force level higher than 51%, the rupture temperature of F.GC1 specimens significantly decreases to 425 °C and 274 °C, corresponding respectively with the applied loading level of 64% and 75%. As similar, the exposure duration at the elevated temperature decreases greatly decreases to 15.1 minutes and 10.7 minutes corresponding respectively with the applied loading level of 64% and 75%. This result came from the effect of the cracking and crack width in the cementitious matrix surface on the thermomechanical performance of the TRC specimen. This observation would be discussed once again in Section 3.2. Table 3 presents all the obtained values from the thermomechanical tests.

Table 3. Thermomechanical results of F.GC1 specimens

Specimens	Force level (%)	Rupture temperature (°C)	Exposure duration (minutes)
F.GC1 – 11%	11	759.7	27.9
F.GC1 – 25%	25	711.1	24.2
F.GC1 – 51%	51	667.6	23.4
F.GC1 – 64%	64	424.8	15.1
F.GC1 – 75%	75	273.6	10.7

3.2. Discussions

Fig. 8 presents the evolutions of the thermomechanical performance of F.GC1 (rupture temperature and exposure duration) depending on the applied loading level. In Fig. 8(a), it could be observed the evolution of rupture temperature, which was divided into two intervals of the applied loading level. The first interval was a slight reduction of rupture temperature from 11% to 51% of applied force level, while the last one was from 51% to 75% applied force level, characterized by a significant decrease of rupture temperature. In comparison with the previous experimental result on the



(a) Rupture temperature versus applied force level

(b) Exposure duration versus applied force level

Figure 8. Evolution of elevated temperature performance of F.GC1 specimens depending on the applied loading level

Handmade-CFRP in Nguyen et al. [13], it could be found the better thermomechanical performance of carbon TRC than H-CFRP to subject constant tensile loading and increasing temperature. In this case, the refractory matrix has a role as a thermal protection layer against temperature heating and contributed to the elevated temperature performance of TRC composite. The rupture temperature of the F.GC1 specimens was higher about 150 °C than the H-CFRP composite in the same applied force level (Fig. 8(a)).

Regarding the results of exposure duration, its evolution could be divided into two intervals as that of rupture temperature. It is because of the similar heating rate of all thermomechanical tests conducted on TRC specimens at different applied force levels. This exposure duration slowly decreases about 3 minutes at the first interval while it quickly reduces about 13 minutes at the last one. This result related to the contribution of the refractory matrix layer to the thermomechanical performance of F.GC1 through different working phases. It was from non-cracking, cracking appearance, and crack width. In comparison with the experimental results on H-CFRP in [13], it could be found an improvement of about 10 minutes of the exposure duration of carbon TRC. This result shows the perspective in the use of carbon textile reinforced refractory concrete composite for fire application.

3.3. *Analytical approach*

a. Effect of crack appearance on the thermomechanical performance

As experimental results, it could be found the refractory matrix has contributed to the elevated temperature performance of the F.GC1 composite. However, this contribution depends on the appearance and opening of cracks on the cementitious matrix surfaces caused by mechanical tensile force. Fig. 9 presents the relationship between the applied force level and failure modes of F.GC1 specimens. This observation explains the decrease of the TRC thermomechanical performance with two intervals depending on the applied force level. When the applied stress was smaller than the post-crack value (11% and 25%), there were several transversal cracks on the surface of TRC specimens. However, the width of these cracks was small and influenced negligibly the heat transfer in the cementitious matrix. So, F.GC1 specimens still ensured improvement of the elevated temperature performance of about 200 °C compared with the GC1 carbon textile (Fig. 8(a)). When the applied stress increased more than the post-crack value, the cementitious matrix had cracked completely, and these cracks were opening on the surface of the cementitious matrix under tensile force. Thus, the cementitious matrix has gradually lost its role as a thermal protection layer for the GC1 textile against temperature heating.

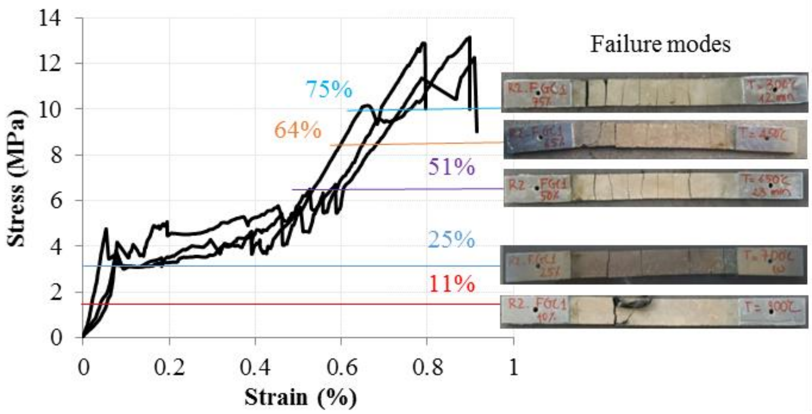


Figure 9. Relationship between applied force level and failure modes of F.GC1 specimens

From Fig. 8(a), it could be observed that the thermomechanical performance significantly decreased in this second interval. In comparison with the results on carbon GC1 specimens, no improvement was found for the elevated temperature performance of the F.GC1 composite.

For considering the effect of the cracking on the thermomechanical performance of F.GC1 specimens, it's necessary to determine the opening of cracks according to each applied force level. It could be supposed that there was no slip between the carbon textile and cementitious matrix, as well as do not consider a small deformation in the matrix layer. So, the width of cracks was calculated from the total elongation of the TRC specimen, by dividing it by each crack on the surface. Therefore, the widening of cracks determined by the following equation, and its calculated values are presented in Table 4.

$$W_i = \frac{\Delta_{TRC}}{n_{cr}} \tag{1}$$

where W is the width of crack on the surface of the cementitious matrix (mm); Δ_{TRC} is the elongation of F.GC1 specimen under mechanical tensile loading (mm), determined from stress-strain curves at room temperature corresponding with each stress level (Fig. 9); n_{cr} is the number of cracks, identified as the number of drops in force in the time-dependent force diagram of thermomechanical tests (the first phase).

Table 4. Width of cracks corresponding with different applied force levels

Applied force level (%)	Stress (Mpa)	Strain (%)	Elongation Δ_{TRC} (mm)	Number of cracks n_{cr}	Width of crack, W (mm)
11%	1.40	0.0381	0.16	0	0
25%	3.36	0.0826	0.35	4	0.087
51%	6.71	0.5462	2.29	9	0.256
64%	8.39	0.6521	2.74	9	0.304
75%	9.93	0.7258	3.05	10	0.305

b. Analytical model

The analytical model for elevated temperature performance of TRC composite was based on Mouritz and Gibson's model [14, 15]. However, to consider the effect of crack opening on the elevated temperature performance, parameter W was added in this model. So, the elevated temperature performance (rupture temperature) depending on the applied force level (f) is drawn as the equation below:

$$T_r(f) = \left[\frac{T_l + T_h}{2} - \frac{T_l - T_h}{2}\tanh\left(\frac{K_m}{W}\left(f - f_g\right)\right)\right] \tag{2}$$

where $T_r(f)$ is a rupture temperature at applied force level f; T_l is the temperature for the lowest applied force level (0.11 in this study); T_h is the temperature for the highest applied force level (0.75 in this study); f_g is the applied force level around which the reduction relationship is quasi-symmetric, normally corresponding to a 50% reduction in the property value. The K_m parameter in the analytical model of the F.GC1 composite is calibrated with the experimental results on F.GC1 specimens. W is the width of crack on the surface of the cementitious matrix (mm), determining from Table 4.

Table 5 presents all the parameters in the analytical model for the prediction of the elevated temperature performance of the F.GC1 composite. As obtained results, the analytical model provided the evolution of the fire performance of carbon TRC composite as a function of applied force level. It could be found there was a great reduction of rupture temperature in the applied force level raging from 0.4 to 0.7, according to the width of cracks. Fig. 10 presents the comparison between the experimental data and the prediction of thermomechanical performance from the analytical model. From Fig. 10, a good agreement between experimental data and the analytical prediction was found. This result demonstrates the ability of this analytical model to consider the effect of the cracking and width of cracks in the cementitious matrix on the thermomechanical performance of the TRC composite.

Table 5. Values of parameters in the analytical model for F.GC1 composite

Material	Fire performance	Parameters			
		T_l	T_h	f_g	K_m
F.GC1	Rupture temperature (°C)	759.7	273.6	0.58	2.25

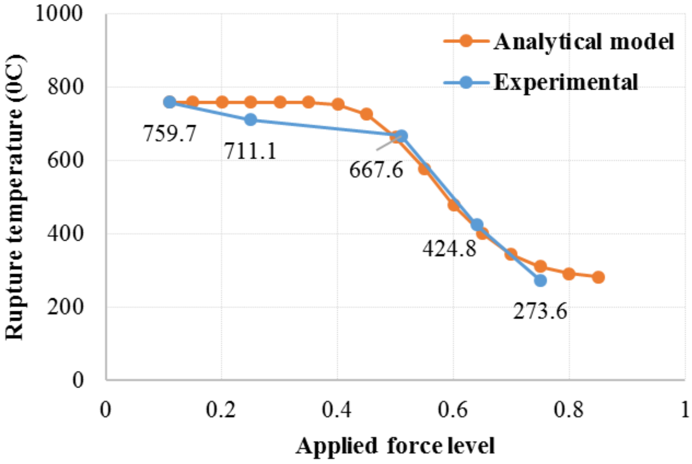


Figure 10. Comparison between experimental data and prediction from analytical model

4. Conclusions

In this experimental characterization and analytical modeling, the thermomechanical performance of carbon TRC composite was identified. The following conclusions can be drawn from the results:

- The F.GC1 specimen has notable performance in the thermomechanical condition at a constant force. It could be subjected to the highest temperature of 759.7 °C in the longest exposure duration of 27.9 minutes corresponding with the applied loading level of 11%. This carbon TRC specimen also presented better performance than GC1 carbon textile and the Handmade-CFRP composite thanks to the thermal protection role of the refractory matrix.

- The cracking and width of cracks in the surface of the cementitious matrix affected the heat transfer, leading to the reduction of thermal protection contribution of this layer. The elevated temperature performance of carbon TRC evolved with the applied force level: slight decrease with the value lower than 51% and notable decrease with the value higher.

- The analytical model could allow predicting the rupture temperature of the TRC composite when it was subjected to the thermomechanical condition at a constant force. This model also could consider the effect of the width of crack in the surface of the cementitious matrix on TRC's thermomechanical performance.

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