Contribution of the refractory matrix to the fire resistance of carbon TRC composite

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RÉSUMÉ. *En cas d'incendie ou dans la condition de température élevée, la matrice cimentaire du composite TRC travaille comme une couche de protection thermique. Avec de bonnes propriétés thermiques, le béton réfractaire est utilisé comme matrice dans le composite TRC pour améliorer sa résistance au feu. Ce papier présente les résultats expérimentaux sur le comportement mécanique et thermique de TRC à base de la matrice réfractaire et renforcé par des textiles de carbone. Dans ce papier, TRC de carbone est soumis au régime thermomécanique à force constante pour déterminer la température de rupture et la durée d'exposition à température élevée. Les essais de transfert thermique ont été effectués sur les échantillons cylindriques pour déterminer le coefficient de diffusion thermique à différentes température ou l'augmentation de la température au sein de la matrice. Un modèle numérique est également construit en utilisant des propriétés thermiques de la matrice pour prédire le comportement thermique de la matrice de TRC. En comparaison des résultats obtenus, on peut trouver la contribution de la matrice dans le TRC de carbone comme une couche d'isolant thermique.*

ABSTRACT. *In case of fire or at elevated temperature conditions, the cementitious matrix of textile reinforced concrete composite (TRC) plays the role as a thermal protection layer. With good thermal properties, refractory concrete is used as a matrix in the TRC composite for fire application. This paper presents the experimental results on the mechanical and thermal behaviour of TRC based on the refractory matrix and reinforced by carbon textiles. In this paper, carbon TRC was subjected to the thermomechanical regime at constant force in order to determine the rupture temperature and the exposure duration at elevated temperature. Thermal transfer tests were performed on the cylindrical specimens to determine the thermal diffusion coefficient at different temperatures or the temperature increase within the matrix. A numerical model was also constructed using thermal properties of the matrix to validate their values. In comparison with the results obtained, one can find the contribution of the matrix in the carbon TRC as a layer of thermal insulation.*

MOTS-CLÉS : *Composite TRC, comportement thermomécanique, matrice réfractaire, textile de carbone, haute température, transfert thermique.*

KEY WORDS: *TRC composite, thermomechanical behaviour, refractory matrix, carbon textile, elevated temperature, thermal transfer.*

1. Introduction

Over the last two decades, the TRC composite has been increasingly used for strengthening or reinforcement of civil engineering works. In case of fire or elevated temperature, the cementitious matrix of the TRC composite works as a thermal protection layer. Therefore, the thermal properties of the cementitious matrix are important parameters that strongly influence the heat transfer in the composite, and as well as its resistance at elevated temperature. The refractory matrix is a perfect choice for the TRC composite which is often subjected to fire or elevated temperature loading. In the literature, refractory concrete has been used successfully as a matrix in making the basalt TRC for an application at elevated temperature [RAM 17]. Refractory concrete is normally based on calcium aluminate cement (CAC) [BAR 18] or other high alumina cement [ABY 17]. The high alumina content in the matrix could make the stability of the thermal and mechanical properties of the matrix [BAR 18]. There were also experimental studies on the thermal properties of lightweight or refractory high-temperature concrete [NGU 17, KAM 15].

To the best of the authors' knowledge, rare results are available for experimental tests with the simultaneous action of mechanical loading and elevated temperature on the carbon textile reinforced refractory concrete specimens. There are also no results concerning the contribution of refractory matrix to the fire resistance of TRC composite. This paper presents an experimental and numerical study on the thermal and mechanical responses of carbon TRC subjected to elevated temperatures. In this paper, the carbon TRC is subjected to the thermomechanical regime at constant tensile force in order to determine the rupture temperature and the exposure duration at elevated temperature. Thermal diffusion in the composite is also studied by tests on cylindrical

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samples to determine the thermal diffusion coefficient of the refractory matrix. Finally, a numerical model was constructed with the thermal properties of the refractory matrix as input data in order to validate and compare the experimental result. The purpose of this paper is to highlight the contribution of the thermal properties of the matrix to the fire resistance of the carbon TRC at elevated temperature.

2. Experimental works

2.1. Materials

2.1.1. Carbon textile

The GC2 carbon textile is made of a bi-directional high-strength carbon fiber mesh for structural reinforcement with low thickness. This textile also has advantages such as very high tensile and corrosion resistance, a low weight per unit area, a simple and flexible application, a treatment with amorphous silica for a perfect adhesion to concrete aggregates, a high heat resistance. The textile yarn is formed by about 3200 monofilaments with the section area of 1.795 mm^2. The geometry of the grid in the longitudinal and transverse directions is 17 mm × 17 mm.

2.1.2. Refractory matrix

This matrix consists of a silico-aluminous-calcic synthetic aggregate (containing about 40% of alumina) with maximum diameter lower than 1.25 mm, as well as a cement consisting essentially of calcium aluminates. The high mono-calcium aluminate content of this cement (about 50%) gives the concrete good mechanical performance. The water/cement ratio in mix composition of this cement matrix is 0.35. The density of this matrix is 2584 kg/m^3.

2.2. Specimen preparation

All samples in this study were manufactured in the LMC2 laboratory. There were carbon TRC specimens for the thermomechanical test at constant force (TMCF) and a cylindrical sample of the refractory matrix for the thermal transfer test.

2.2.1. Specimens of carbon TRC

The carbon TRC (called F.GC2 in this study) is based on the refractory matrix and reinforced by GC2 carbon textile. The TRC plates were manufactured with the molding technique, after that they were kept in the laboratory condition for 28 days. Then, these plates were cut to obtain TRC specimens with the dimension of 740 mm x 51 mm x 11.5 mm (length x width x thickness). The reinforcement ratio of the F.GC2 composite calculated by the volume fraction between the GC2 carbon textile and the composite (V_f/V_{total}) is 1.79%.

2.2.2. Cylindrical specimen of refractory matrix

This specimen is cylindrically shaped with the dimension 7.8 cm x 20 cm (diameter x height). At the cross section in the middle, a thermocouple was set up to measure the temperature in the middle of this section in the test course. A steel bar is integrated into the matrix block with sufficient anchorage length to be able to keep the test specimen in the furnace during the test.

2.3. Test procedure

2.3.1. Thermomechanical test at constant force (TMCF)

The procedure of TMCF consists of two phases. The first is to apply the quasi-static mechanical load monotonically to the specimen up to the applied force level (Fa) with the loading speed of 200 μm/min. The second is to maintain this force and increase the temperature inside the furnace with the temperature rate about 30 °C/min from room temperature until the specimen rupture. The temperature corresponding to the rupture point of the test specimen is identified as the rupture temperature (Tr). The exposure duration at elevated temperature is identified as the time of the second phase (see Figure 1).

2.3.2. Thermal diffusion test

For each measurement temperature of thermal diffusion test, the following procedure is realized: the sample is stabilized at a temperature (T_{target}), the acquisition of the thermo-signal is started, after 1000 measuring points, a laser flash is deposited on the upper face of the sample, the temperature rise of the lower face of the sample over time is recorded, the methods of moments and partial times make it possible to calculate the apparent thermal diffusivity of the sample, this operation is repeated at least 3 times for each temperature point.

2.3.3. Thermal transfer test

The temperature around the specimen is increased with a maximum rate of the furnace capacity. Thermal transfer in the cylindrical specimen of the refractory matrix occurs from the outside to the inside. The test stops when there is the homogeneity of the temperature in the cylindrical specimen.

2.4. Test configuration

The equipment used in this study is the direct tensile machine which is well equipped with a small furnace to generate the temperature action. Figure 2 shows the test configurations with the equipment used on the specimens of the carbon TRC and the refractory matrix. The temperature inside the oven is controlled by thermocouples that have been attached to the specimen before the thermomechanical test.

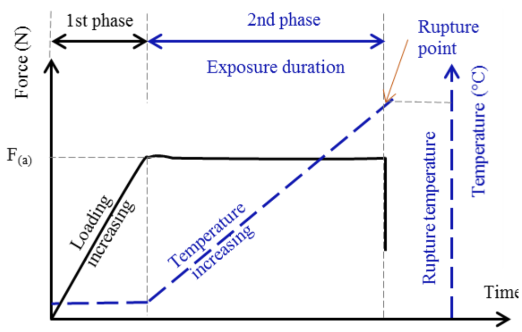

Figure 1. *Loading path for thermomechanical tests in TMCF regime*

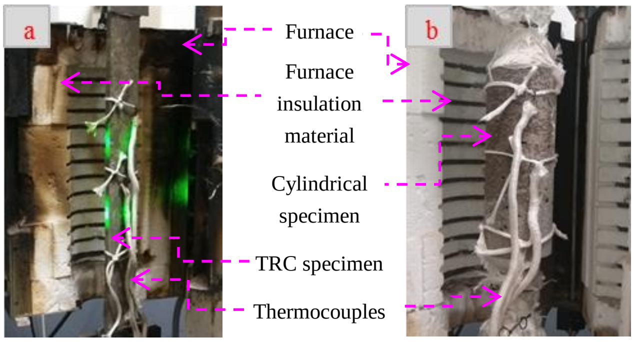

Figure 2. *Test configuration for TMCF test (a) and thermal transfer test (b)*

3. Results

3.1. Thermomechanical test in TMCF regime

Figure 3 shows the results on specimens of F.GC2 in the TMCF regime. According to Figure 3, it can be seen that the temperature increase inside the furnace was similar with that of ISO-834 [ISO 04] when the temperature increased above 800 °C. Figure 4 shows the evolution of the rupture temperature of F.GC2 as a function of the stress ratio (ratio between the applied force and the material rupture force at 20°C) by comparing with the experimental results on composite materials (in the same condition) in the literature. As results obtained, F.GC2 gave an almost linear reduction in the rupture temperature with the applied force level from 944 °C to 472 °C.

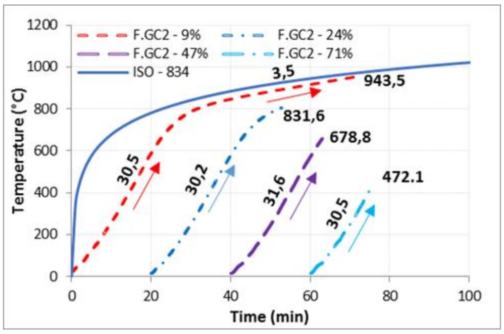

Figure 3. *Increase of temperature as a function of time at different levels of applied force*

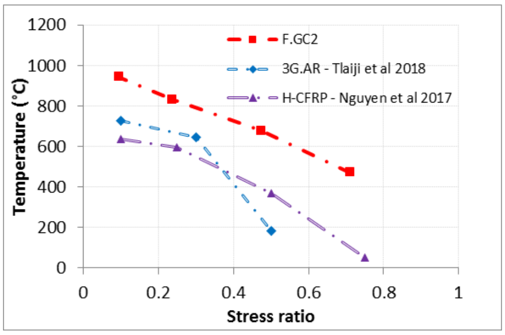

Figure 4. *Evolution of the rupture temperature (Tr) according to the stress ratio*

3.2. Thermal diffusion test

The values of thermal diffusivity of refractory matrix is the average of that obtained from the methods of moments and partial times for three measurements. As results, the average value of the thermal diffusivity decreased slightly with the temperatures from 20 °C to 150 °C. The value of the thermal diffusivity was 0.46 mm^2/s on average at room temperature and 0.39 mm^2/s at 150 °C.

3.3. Thermal transfer test

The increase of temperatures outside and inside the cylindrical specimen obtained by thermocouples is shown in Figure 5. The average temperature outside the cylindrical test specimen, measured by three thermocouples attached to its corps, increased with two intervals: the first with the temperature rate of 29.5 °C/min and the second with 3.3 °C/min. At the temperature measurement point inside the cylindrical specimen, the temperature was increased more slowly than outside the cylindrical specimen thanks to a layer of 3.9 cm thick of the matrix.

The temperature increase curve is curved at the beginning and almost linear after with the measured average rate of 22.8 °C/min. The homogeneity of the temperature in the cylindrical specimen occurred after 47.5 minutes of test and at a temperature of 751.4 °C. The maximum spread between two temperatures (outside and inside) is 250.6 °C at the time when the thermal transfer test started 19 minutes.

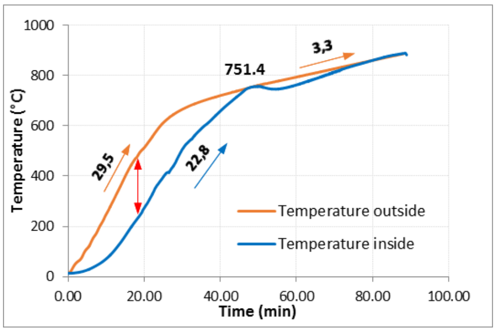

Figure 5. *Increase of temperature outside and inside the cylindrical specimen of the refractory matrix*

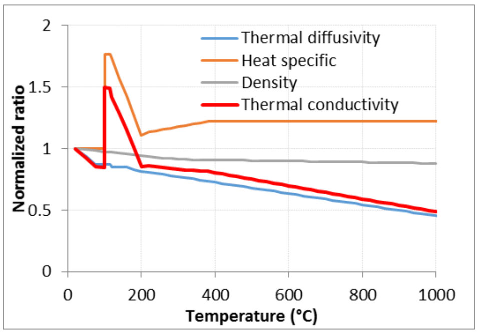

Figure 6. *Evolution of normalized thermal properties as a function of temperature.*

3.4. Discussion

F.GC2 provided the better resistance in TMCF regime than other composite materials. In comparison with the results obtained on handmade-carbon reinforced fiber polymer (H-CFRP) of Nguyen et al [NGU 18], an improvement in the rupture temperature about 300 °C could be observed from Figure 4. This result is coming from the thermal protection of the refractory matrix. The thermal diffusion results demonstrate the thermal insulation capacity of this cement matrix. With a small value of thermal diffusivity of refractory matrix, temperature heat was conducted more slowly from specimen surface into the carbon textile yarns inside the matrix. So, it needs more time to damage the specimens in comparison with that obtained from tests on H-CFRP.

4. Numerical modeling

This section presents the numerical study concerning the thermal transfer in the refractory matrix. This model could allow us to validate and verify the thermal properties of the matrix by comparing the result obtained from experimental test performed on cylindrical specimen.

4.1. Numerical model

The finite element model was built by using the ANSYS APDL software. Thanks to the geometry and temperature loading symmetry of cylindrical specimen, a half specimen has been generated with the corresponding dimensions. In this model, the element type chosen is element SOLID87 (3-D 10-Node Tetrahedral Thermal Solid) for the transient thermal analysis. The mesh size is 5 mm for all elements of this model. All outside surface of cylindrical specimen was applied elevated temperature as boundary condition for finite element model.

4.2. Material properties

The thermal properties of refractory concrete were chosen from experimental results (thermal diffusivity), from Eurocode (heat specific with water content of 2.26%) and from literature (density of refractory matrix with aluminate content about 50%). Table 1 presents the initial values (at room temperature) of thermal properties of refractory matrix and their evolution as a function of temperature is showed in Figure 6.

Table 1 : *Thermal properties of refractory matrix at room temperature*

Thermal properties	Thermal diffusivity	Heat specific	Density	Thermal conductivity
20°C	0.46 x 10^{-6} m^2/s	900 J/Kg.K	2490 Kg/m^3	1.03 W/m.K

4.3. Numerical results

The temperature of specimen at last step of thermal analysis is presented in figure 7, and the temperature increasing at inside and outside specimen is showed in figure 8. In comparison with experimental results, it could be observed the same temperature increasing inside specimen when the temperature is less than 150 °C. At elevated temperature (above 150 °C), there was difference between both temperature curves of experimental and numerical results. It could be explained this difference by two main causes. Firstly, it is missing experimental results on thermal diffusivity at temperatures above 150 °C. Its value was calculated by linear extrapolation method for numerical model at elevated temperature. Secondly, the appearance of long fissure along the specimen corps accelerated the heat transfer in refractory matrix. That's why the inside temperature obtained from experiment was higher than that of numerical model.

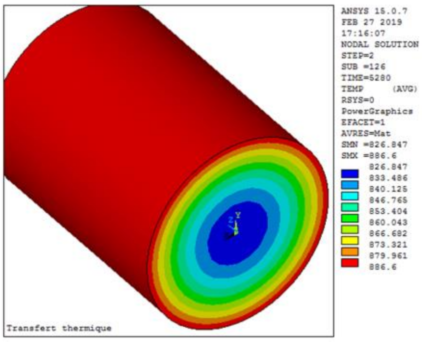

Figure 7. *Temperature of specimen at last step of thermal analysis*

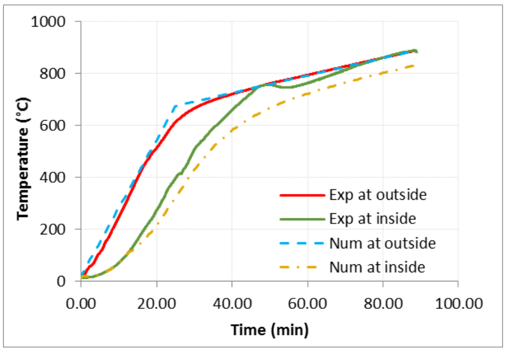

Figure 8. *Comparison between the experimental and numerical results*

5. Conclusion

As results obtained, some conclusions could be drawn for this work: the refractory matrix has an important contribution to the fire resistance of carbon TRC composite thanks to its good thermal properties. The FE model with thermal properties of refractory matrix can predict the temperature inside specimen when it is subjected to the increasing of temperature. It will be interesting to generate a FE model for TRC composite in TMCF regime.

6. Acknowledgments

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