Experimental Approach to Identify the Thermomechanical Behaviour of a Textile Reinforced Concrete (TRC) SubJECTED to High Temperature and Mechanical Loading

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Abstract. Textile reinforced concrete (TRC), a new generation of cementitious material, is used for different applications in civil engineering. The aim of this paper is to propose a methodology to identify the thermo-mechanical behaviour of the TRC material. The studied TRC composite is made with a cementitious matrix and grid alkali-resistant glass textile. In this study, TRC specimens are subjected to two types of thermomechanical test designated by the loading path 1 and the loading path 2. The results of the thermo-mechanical tests are discussed. This study presents also an experimental methodology, using the digital image correlation (DIC) technique, which permits to identify the specific cracking mode, the crack width and the distance between the cracks of the preheated-cooled TRC specimens as a function of the uniaxial monotonic axial stress. The experimental study is then followed by an analytical model that aims to calibrate existing analytical models (Gibson and Bisby models) for the prediction of the evolution of properties (ultimate stress and post-cracked stiffness) of the TRC material as a function of the temperature.

Keywords: Textile reinforced concrete (TRC) · Thermomechanical test · High temperature · Digital image correlation (DIC) technique

1 Introduction

Textile reinforced concrete (TRC) consists of fibre reinforcements, e.g., glass or carbon fibres, which ensure the mechanical strength, and a protective cementitious matrix, which ensures the retransmission of loads towards the reinforcement. TRC combines the favourable material properties of these two components. This composite material has been shown to have potential to be used to design slender, lightweight, modular and freeform structures. This material eliminates the risk of corrosion and provides
high strength in compression and in tension [Brameshuber 2006, Rambo et al. 2015]. It has also been shown to be a suitable solution for strengthening and repairing structural elements [Contamine et al 2011, Colombo et al 2015]. Another important desirable function of TRC is the ability to make textiles fireproof. When structures are subjected to fire, they are simultaneously submitted to very high temperatures (potentially up to 1200 °C) and mechanical loadings. Several studies have focused on the tensile or bending behaviour of textile-reinforced concretes at ambient temperature [Hegger and Voss 2005, Raupach et al 2006]. Some authors [Blom et al 2014, Ji et al 2013] have studied the high-temperature behaviour, at up to 500 °C, of steel-reinforced concrete beams externally reinforced with textile-reinforced mortar (TRM) or fibre-reinforced cementitious matrix (FRCM). The performance of textile-reinforced mortar (TRM) jacketing in the shear strengthening of reinforced concrete members subjected to ambient and elevated temperatures (up to 250 °C) has also been investigated [Chowdhury et al 2012]. Until now, studies on the behaviour of textile-reinforced concrete under fire loadings [Palmieri et al., Naser et al 2012] are still rare. There have been a few studies conducted on the residual behaviour of TRC after exposure to a thermal heating process (up to a desired temperature) and to a non-controlled cooling process [Lopez et al 2013, Bisby 2016]. Few studies have been conducted investigating the thermomechanical behaviour of TRC. This study presents an experimental methodology which permits to identify the non-linear behaviour law in tension, the ultimate resistance and specific cracking mode. Finally, analytical models to predict the evolution of TRC properties (ultimate stress, post-cracked stiffness) as a function of the temperature are presented.

2 Experimental Work

2.1 Experimental Device

A 20 kN-1200 °C thermomechanical machine was used for the tensile tests (Fig. 1a). The temperature in the furnace (Fig. 1b) can reach 1200 °C. It was applied by a high-temperature resistance in the furnace and controlled by integrated thermocouple. The furnace was heated with heating rate corresponding for each target temperature. This machine is presented in detail in [Tlaiji et al 2016].

2.2 Testing Procedure

2.2.1 Thermomechanical Test (Path 1)

In thermomechanical tests, the specimens were heated to a specified temperature then loaded until failure while the same temperature was maintained. All samples are subjected with a heating increase rate in the furnace (ranging from 2, 5 °C/min to 20 °C/min) corresponding to each temperature level (ranging from 75 °C to 600 °C). When the temperature reached the target value, it is then kept constant for one hour. The tensile force applied on the specimen is monotonically increased until the maximum force that the specimen can resist. The increase in the axial force was controlled and
piloted by transverse displacement with a displacement rate of 3000 µm/min. This mechanical load was combined with the measurement of the axial strain of the specimen using a laser sensor. Figure 2 presents this test in terms of the evolution of the temperature and of the force as a function of time.

2.2.2 Transient-State Test (Path 2)

In the transient-state tests, showed in Fig. 3, the specimens were initially gripped at both ends and then subjected to a tensile force with a maximum load equal to a selected percentage of the maximum strength of TRC obtained at 25 °C (30% and 50%). After that, the temperature rises to the maximum level that the TRC can resist.
2.3 Specimens

2.3.1 Materials Used
The main composition of the TRC material tested in this study consists of a cementitious matrix and three layers of grid alkali-resistant (AR) glass textile. The compressive strength and the tensile strength of this matrix are respectively 23 MPa and 4.5 MPa. The textile type (grid AR-glass) used in this study has the same thread in two directions of the grid. This grid is large and the opening between the meshes axis is 8 mm x 8 mm which allows the passage of small aggregates.

2.3.2 Specimen Preparation
The cementitious matrix and the reinforcement textiles are cast in a mold to obtain a plate of TRC having the dimension 800 mm x 500 mm x 5 mm (length x width x thickness). After 7 days, the rectangular plates were cut, resulting in specimens of 700 mm x 45 mm x 5 mm (length x width x thickness). To prepare the specimen for the test, four aluminium plates are glued to the ends of each specimen using an epoxy adhesive (Eponal 380) to ensure transfer efficiency of the mechanical load. At least 3 days after the bonding, the TRC sample was drilled at each end to be compatible with the used loading heads. The specimen preparation is presented in detail in [Tlaiji et al. 2016].

2.4 Digital Image Correlation (DIC) Technique
Before the measurement with the digital image correlation (DIC) technique, a speckled pattern of black and white paint was sprayed onto the surface of the sample to improve resolution of displacement. A reference image is taken before applying load and then a set of images are taken at sampling rate of 0.5 s till the end of the test. The displacement of the points in the measured zone during the increase of the load can be observed from the images. As a result, the speckles at the surface of the sample displace from their initial location. By correlating the information from the two images, using the ICASOF software, the movement of different points from the initial image to the final image was identified. The results are treated on the basis of image representing the

![Fig. 3. Transient-state path](image-url)
displacement values obtained after analysis of the images by the ICASOFT software; these represent the displacement field of the specimen (c). The measurement of the displacement along the axis at the different loads makes it possible to plot the graph representing the displacement (in mm) as a function of the position on the longitudinal axis (in mm) at each loading level. Finally, using the results obtained by the software, the distance between the cracks was identified and their opening as a function of the loading was also determined. In this study, the 3G.AR composite samples were heated to several desired temperature levels (25 °C, 75 °C, 150 °C, 300 °C, 400 °C and 600 °C) and then cooled before the measurement of the displacement, using the Digital Image Correlation (DIC) technique.

3 Test Results

3.1 Results of the 3G.AR Composite in the Thermomechanical Path (TM)

Figure 4 shows the results of tests on the 3G.AR composite in the thermomechanical path. This figure represents the axial stress as a function of the thermomechanical axial strain and of the temperatures varying from 25 °C to 600 °C. In Fig. 4, there is one average stress-strain curve for each temperature. This figure shows the result of the 3G.AR specimens that were exposed to different temperatures (25 °C, 75 °C, 150 °C, 300 °C, 400 °C and 600 °C) during 1 h and were then submitted to uniaxial monotonic tensile loading. The curves at temperatures varying from 25 °C to 150 °C show three distinguishable phases in the behaviour of the 3G.AR composite. However, at 300 °C and 400 °C, two phases are observed. Additionally, at 600 °C, the curve is quasi-linear, and only one phase is shown.

![Fig. 4. Thermomechanical behaviour of the 3G.AR composite in different target temperature levels](image-url)
3.2 Thermomechanical Properties of the 3G.AR Composite

The interaction between the matrix and the reinforcement leads to multilinear behaviour. In general, at ambient temperature, the curve characterizing the behaviour of a TRC is formed from three phases: the first phase corresponds to the semi-elastic response of the material, the second phase corresponds to the progressive damage of the matrix from the occurrence and development of cracking, which is responsible for the reduction in the stiffness of the composite, and the third phase, which is quasi-linear, corresponds to the mechanical behaviour of the fibres alone. To refine the analysis of the influence of the temperature on the thermomechanical behaviour, in this study, a notation is used for the three curves representing three examples for each multilinear curve (Fig. 5). In Fig. 5, idealized stress/strain curves of the behaviour of the 3G.AR composite are shown. The used notation is detailed below: $\sigma_{UTS}$: ultimate stress level of the composite corresponding to point UTS; $E_{c3}$: stiffness of the third phase (or stiffness of the post-cracked composite). After using these notations, the evolution of some parameters, such as $\sigma_{UTS}, E_{c3}$ of the 3G.AR composite in thermomechanical loading path according as a function of the temperature was identified and is presented in the following sections.

![Fig. 5. Idealized stress/strain curves of the behaviour of the 3G.AR composite](image)

### 3.2.1 Evolution of the Ultimate Tensile Stress as a Function of the Temperature

Figure 6 represents the results of the thermomechanical (TM) tests and for each temperature (25 °C, 75 °C, 150 °C, 300 °C, 400 °C and 600 °C) in terms of the average ultimate tensile strength as a function of the temperature. The average ultimate tensile
strength of this composite is slightly reduced when this one is subjected to temperatures below 150 °C during the thermomechanical tests. However, after 150 °C, the material takes up part of its initial strength (at 25 °C) before decreasing again from 300 °C to 600 °C.

3.2.2 Evolution of the Stiffness $E_{c3}$ as a Function of the Temperature

The evolution of the post-cracked composite stiffness ($E_{c3}$) in the third phase of the behaviour of 3G.AR composite $E_{c3}$ as a function of the temperature ranging from 25 °C to 600 °C is shown in Fig. 7. From 25 °C to 75 °C, a post-cracked composite stiffness drop is observed. Then this stiffness increases from 75 °C to 300 °C before decreasing again after 300 °C.

Fig. 6. Average ultimate tensile strength as a function of the temperature

Fig. 7. Evolution of the stiffness $E_{c3}$ as a function of temperature
3.3 Results of the 3G.AR Composite in the Transient-State Path

The failure temperature for each percentage of maximal strength obtained on 25 °C (30% $\sigma_{\text{UTS, 25 °C}}$ and 50% $\sigma_{\text{UTS, 25 °C}}$) was reached when the tensile load could no longer be sustained. Figure 8 shows the temperature to cause failure of the specimens for 30% $\sigma_{\text{UTS, 25 °C}}$ and 50% $\sigma_{\text{UTS, 25 °C}}$ tensile load. In this figure, the horizontal axis represents the failure temperature of the specimen, and the vertical axis represents the ultimate load. The failure temperatures of the test specimens are given in the Table 1. It should be noted, according to the results shown in the Table 1, that there was a brutal drop (of 72%) of failure temperatures when the stress was increased from 30% $\sigma_{\text{UTS, 25 °C}}$ to 50% $\sigma_{\text{UTS, 25 °C}}$.

![Failure temperature for 30% $\sigma_{\text{UTS, 25 °C}}$ and 50% $\sigma_{\text{UTS, 25 °C}}$ tensile load](image)

**Table 1.** Failure temperatures of the test specimens

<table>
<thead>
<tr>
<th>Load (MPa)</th>
<th>Failure temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30% $\sigma_{\text{UTS, 25 °C}}$ (Test number 1)</td>
<td>2.7</td>
</tr>
<tr>
<td>30% $\sigma_{\text{UTS, 25 °C}}$ (Test number 2)</td>
<td>2.7</td>
</tr>
<tr>
<td>50% $\sigma_{\text{UTS, 25 °C}}$ (Test number 1)</td>
<td>4.5</td>
</tr>
<tr>
<td>50% $\sigma_{\text{UTS, 25 °C}}$ (Test number 2)</td>
<td>4.5</td>
</tr>
</tbody>
</table>

3.4 Results Obtained by the Digital Image Correlation (DIC) Technique

Figure 9 below shows the maximum crack width of the preheated-cooled 3G.AR composite specimens as a function of the axial stress for the different temperature levels (25 °C, 75 °C, 150 °C, 300 °C, 400 °C and 600 °C). The crack width of the preheated-cooled 3G.AR composite specimens is small (inferior to 0.42 mm) for all
temperature levels. The first crack appears on a different loading level for each temperature. The maximum crack width before specimen failure reaches 0.42 mm for the preheated temperature level of 150 °C. Table 2 below shows the maximum crack width of the preheated-cooled 3G.AR composite specimen with its corresponding stress and the average distance between cracks at the ultimate load for each preheated temperature level varying from 25 °C to 600 °C.

### Table 2. Maximum crack width and spacing between cracks

<table>
<thead>
<tr>
<th>Preheated-cooled specimen</th>
<th>3G.AR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preheated temperature (°C)</td>
<td>25</td>
</tr>
<tr>
<td>Maximum crack width (mm)</td>
<td>0.35</td>
</tr>
<tr>
<td>Corresponding stress (MPa)</td>
<td>8</td>
</tr>
<tr>
<td>Spacing between cracks (mm)</td>
<td>14</td>
</tr>
</tbody>
</table>

**Fig. 9.** Maximum crack width of the preheated-cooled 3G.AR specimens as a function of the axial stress at each temperature level

In parallel with experimental studies carried out, several semi-empirical analytical models (Bisby and Gibson model 2015) have been developed to simulate the behavior of fiber-reinforced polymer (FRP) composite materials at high temperature. However, we do not find in the literature models that concern TRC composite materials. The objective of this section is to identify and calibrate these models (Bisby and Gibson) with the obtained experimental results of the 3G.AR composite in order to describe the evolution of the thermomechanical properties of the TRC composite materials.
4.1 Gibson Model

Gibson [Firmo et al. 2015] proposed a general model which takes the form of a hyperbolic tangent function and which describes the reduction of the mechanical properties of the FRP composite as a function of temperature:

\[
P(T) = R^n \left[ \frac{P_u + P_r}{2} - \frac{P_u - P_r}{2} \tanh \left\{ K_m \left( T - T_g \right) \right\} \right]
\]

\(P(T)\): Mechanical property at temperature \(T\); \(P_u\): Mechanical property at room temperature; \(P_r\): Mechanical property after the glass transition; \(K_m, T_g\): Parameters obtained by fitting the experimental data; \(R\): Residual resin content \((0 < R < 1)\); \(n\): depends on the stress state \((n = 1 \rightarrow \text{resin}, n = 0 \rightarrow \text{fiber})\). By calibrating this model with the experimental data of 3G.AR (ultimate stress as function of temperature), we propose for this model the following parameters represented in Table 3.

<table>
<thead>
<tr>
<th>Mechanical property</th>
<th>Strength (\sigma_{UTS}) (MPa)</th>
<th>Stiffness (E_{c3}) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P_u)</td>
<td>8.45</td>
<td>1400</td>
</tr>
<tr>
<td>(P_r)</td>
<td>2.5</td>
<td>400</td>
</tr>
<tr>
<td>(T_g)</td>
<td>500</td>
<td>400</td>
</tr>
<tr>
<td>(R)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(n)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(K_m)</td>
<td>Depends on temperature (T)</td>
<td>Depends on temperature (T)</td>
</tr>
</tbody>
</table>

4.2 Bisby Model

Bisby [Firmo et al. 2015] proposed the following semi-empirical model:

\[
\frac{P(T)}{P_u} = \frac{1-a_1}{2} \tanh \left[ -b(T - c) \right] + \frac{1+a_1}{2}, \text{where } P(T)\text{: Mechanical property at temperature } T; \ P_u\text{: Mechanical property at room temperature; } a, b \text{ and } c \text{ are empirical parameters based on experimental results. For 3G.AR } a, b \text{ and } c \text{ were taken as follow in Table 4. Finally, the two models described above were successfully used to describe the degradation in the tensile properties of the 3G.AR composite and presented in the figures below (Figs. 10 and 11).}

<table>
<thead>
<tr>
<th>Mechanical property</th>
<th>Strength (\sigma_{UTS}) (MPa)</th>
<th>Stiffness (E_{c3}) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>b</td>
<td>0.0081</td>
<td>0.005</td>
</tr>
<tr>
<td>c</td>
<td>Depends on temperature (T)</td>
<td>Depends on temperature (T)</td>
</tr>
</tbody>
</table>
Conclusion

This study concerns the experimental study of the thermomechanical behaviour and the transient-state behavior of the textile reinforced concrete (TRC) subjected to high temperature levels varying from 25 °C to 600 °C. The TRC is made with a cementitious matrix and three layers of alkali-resistant grid glass textile. The results of this work show that during a rise in target temperature level, the behaviour of the studied TRC (called 3G.AR) changes. The stress-strain behaviour of glass textile reinforced cementitious composites in tension is highly non-linear. This study was also focusing on the propagation of the cracks. An investigation of the crack width and the distance between the cracks is done by using the Digital Image Correlation technique. Finally,

Fig. 10. Bisby and Gibson model for the prediction of the $\sigma_{UTS}$ of the 3G.AR composite

Fig. 11. Bisby and Gibson model for the prediction of the $E_{c3}$ of the 3G.AR composite
this experimental study is followed by an analytical model that aims to calibrate existing analytical models for the prediction of the evolution of properties of the TRC as a function of the temperature.

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References

Tlaiji, T., Vu, X.H., Si Larbi, A., Ferrier, E.: Experimental and comparative study of the thermomechanical behavior and the residual one of the textile reinforced concrete (TRC) subjected to high temperature loading. AUGC2016 conference Proceeding, Liège, Belgium (2016)