STUDY OF THE BENDING BEHAVIOUR OF TEXTILE REINFORCED CEMENTITIOUS COMPOSITES WHEN EXPOSED TO HIGH TEMPERATURES

J. Blom (1), J. Van Ackeren (1) and J. Wastiels (1)

(1) Department of Mechanics of Materials and Constructions, Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussel, Belgium

Abstract

The textile reinforced cement composite (TRC) used in this study has inorganic phosphate cement (IPC) as matrix, and randomly distributed chopped glass fibre textile as reinforcement. One of the major benefits of IPC compared to other cementitious materials is the non-alkaline environment of IPC after hardening, so ordinary E-glass fibres are not attacked by the matrix and can be used as reinforcement. By using a fibre volume fraction which exceeds the critical fibre volume fraction, the fibres can ensure strength and stiffness at applied loads far exceeding the range in which matrix multiple cracking is developed, which results in a real strain hardening behaviour in tension. TRC with glass fibres as reinforcement exhibit relatively high strength and ductility and thus provide an interesting new material for construction even at high temperature. The material itself is characterised by a linear behaviour in compression and a marked non-linear tensile behaviour. A calculation method for bending is presented to derive the load displacement curves of a textile reinforced cementitious composite beam which is exposed to high temperature (300°C). The method uses data from experimental tensile tests of similar specimens exposed to the same temperature, to calibrate the material stress – strain model.

1. INTRODUCTION

A FRC is called a high performance material when the use of fibres leads to tensile strain hardening. This can only be obtained by using a fibre volume fraction which is exceeding the critical volume fraction. If so, the fibres can ensure strength and stiffness at applied loads far exceeding the range in which matrix multiple cracking occurs [1]. Textile reinforced cementitious composites with glass fibres as reinforcement exhibit relatively high strength and ductility and thus provide an interesting new material. Another advantage is that they can resist high temperatures without producing toxic gasses, and that they are absolutely incombustible according to the European standard EN13501-1. Due to the ability to cope with high temperatures, IPC may be used under high temperature. The behaviour in tension and compression of the above mentioned material is well documented in literature. The Aveston Cooper and Kelly (ACK) theory is one of the earliest developed models [2]. In compression, this material exhibits a linear elastic behaviour up to failure. Since the use of fibre
reinforcement in the form of textiles allows the introduction of a high fibre volume fraction, a distinct strain hardening behaviour can be obtained in tension [3]. In an initial step based on the ACK theory, the bending behaviour of slender TRC beams can be analytically described [4],[5]. The proposed method takes in account the material deterioration due to the thermal load. By using the experimental data obtained by a tensile test on specimens which are exposed to an elevated temperature the ACK model parameters can be derived [6],[7].

2. DEVELOPMENT OF AN ANALYSIS MODEL

2.1. TRC in tension and compression

According to the ACK theory, three distinct stages can be detected in the stress-strain curve of a unidirectional reinforced brittle matrix composite. In the first stage the material behaves linear elastic. The composite stiffness in stage I \( (E_{c1}) \) can be derived from the law of mixtures see equation (1). In this first stage a perfect “elastic” bond between matrix and fibres is assumed. The failure strain of the matrix is lower than the failure strain of the fibres. At the ultimate matrix strain the composite will crack. If the fibre volume fraction is higher than the critical fibre volume fraction, the fibres will be able to sustain the additional loading. According to the ACK theory this stage is called the “multiple cracking” stage. In the third stage “post cracking” the matrix is completely cracked. The fibres will carry the load in this final stage, until failure. In the linear elastic stage (stage I), according to the ACK theory, the stiffness of the composite \( E_{c1} \) is a function of the fibre volume fraction \( V_f \), the volume fraction of the matrix \( V_m \), the stiffness of the fibres \( E_f \) and the stiffness of the matrix \( E_m \). The matrix-fibre interface bond is assumed to be elastic and the composite stiffness \( E_{c1} \) can be determined by the law of mixtures:

\[
E_{c1} = E_f V_f + E_m V_m
\]  

(1)

The ACK theory is modified, due to imperfect matrix-fibre adhesion, warping or misalignment of the unidirectional fibres, inclusion of air voids, etc. the fibre volume fraction has to be lowered with a fibre efficiency factor \( \eta_f \). Also the stiffness of the matrix has to be reduced with a matrix efficiency factor \( \eta_m \). The modified law of mixtures can be written as follows:

\[
E_{c1} = E_f V_f' + E_m V_m'
\]  

(2)

The effective fibre volume fraction can be calculated by using the following equation:

\[
V_f' = V_f \cdot \eta_f
\]  

(3)

Taking the efficiency of the matrix in account results in the following equation:

\[
V_m' = V_m \cdot \eta_m
\]  

(4)

When the first crack is introduced, the ultimate strain of matrix \( (\varepsilon_{mu}) \) and composite multiple cracking strain \( (\varepsilon_{mu}) \) are equal. The composite multiple cracking stress \( (\sigma_{mu}) \) can be determined by the following equation (5) with \( (\sigma_{mu}) \) defined as the ultimate matrix stress:

\[
\sigma_{mc} = \frac{\sigma_{mu} E_{c1}}{E_m}
\]  

(5)

When the first crack appears and reaches a fibre, debonding of the matrix-fibre interface occurs and further matrix-fibre interaction results from friction. The frictional interface stress \( (\tau_o) \) is assumed to be constant along the debonding interface.
The debonding length $\delta_0$ can be calculated from the equilibrium of the forces along the crack. In case of circular fibres with a radius ($r$) the following expression (6) can be used to derive the debonding length:

$$\delta_0 = \frac{\sigma_{mc} r V_0^*}{2 \tau_0 V_f^*}$$

(6)

Increasing the load will lead to multiple cracking, if the fibre volume fraction is above the critical volume fraction. According to the ACK theory, at a certain unique composite stress $\sigma_{mc}$ multiple parallel cracks are introduced in the matrix. Cracks are introduced until saturation is reached. The distance between neighbouring cracks is situated between $\delta_0$ and $2\delta_0$, with an average of $1.337 \delta_0$. After multiple cracking, the strain of the composite $\varepsilon^{\text{stageII}}$ can be calculated as follows (7) from integration of the strain field between two cracks with distance 1.337:

$$\varepsilon^{\text{stageII}} = (1 + 0.66\alpha)\varepsilon_{mc}$$

(7)

with $\alpha = \frac{E_a V_a^*}{E_f V_f^*}$

(8)

Once full multiple cracking has occurred, only the fibres further contribute to the stiffness in stage III (post-cracking stage). The stiffness of the composite $E_{c3}$ in this stage is thus:

$$E_{c3} = E_f V_f^*$$

(9)

Figure 1 illustrates a theoretical (ACK) stress-strain curve with these three distinct stages: linear elastic stage (I), multiple cracking stage (II) and post cracking stage (III).

![Figure 1: experimental and theoretical stress-strain curve, according to the ACK theory](image)

2.2. TRC beam element in bending

Since the behaviour of TRC in tension shows three stages, three expressions are needed to define the equilibrium of forces and moments if a specimen is loaded in bending. By expressing the equilibrium of forces and moments, the position of the neutral axis (which will be further written as $a$) and the maximum occurring tensile strain ($\varepsilon_t$) in the section can be calculated for each cross section along the beam. Subsequent integration of the bending stiffness for each differential beam element with height $h$ and a unit width, over the total length, will lead to a force displacement diagram. For each cross section one of the following
sets of equilibrium equations can be used depending on the value of the maximum tensile stress.

As long as the composite behaves linear elastic (stage I) along the whole beam section the following expressions can be used, with $M_e$ defined as external moment:

\[ a = \frac{h}{2} \quad \text{(10)} \]

\[ M_e = \frac{2}{3} a^2 E_i \varepsilon_i \quad \text{(11)} \]

Once the composite maximum tensile strain is situated in the multiple cracking stage (stage II) the equilibrium equations can be based on the internal strains and stresses in Figure 2.

By expressing the equilibrium of forces (12) and moments (13), the position of the neutral axis and the maximum occurring tensile strain ($\varepsilon_c$) in the section can be calculated for each cross section along the beam:

\[ E_i \varepsilon_i \frac{a^2}{2(h-a)} = \delta \sigma_{mc} + \delta^* \sigma_{mc} \quad \text{(12)} \]

with $\delta = \frac{\varepsilon_{mc}}{\varepsilon_i} (h-a)$ and $\delta^* = h - a - \delta$

\[ E_i \varepsilon_i \frac{a^3}{3(h-a)} + \delta^* \sigma_{mc} + \sigma_{mc} \delta^* (\delta + \delta^*) = M_e \quad \text{(13)} \]

Finally, the composite maximum tensile strain will be situated in the post-cracking stage (stage III). By expressing the equilibrium of forces (14) and moments (15), the position of the neutral axis and the maximum occurring tensile strain ($\varepsilon_c$) in the section can be calculated for each cross section along the beam.

\[ E_i \varepsilon_i \frac{a^2}{2(h-a)} = \delta \sigma_{mc} + \delta^* \sigma_{mc} + (\varepsilon_i - \varepsilon_{c,crack}) E_i \varepsilon_i \quad \frac{\delta^{**}}{2} \quad \text{(14)} \]

with $\delta^{**} = h - a - \frac{\varepsilon_{c,crack}}{\varepsilon_i} \delta$

\[ E_i \varepsilon_i \frac{a^3}{3(h-a)} + \delta^* \sigma_{mc} + \sigma_{mc} \delta^* (\delta + \delta^*) + \frac{(h-a-\delta^{**})^2}{2} (\varepsilon_i - \varepsilon_{c,crack}) E_i \varepsilon_i^{**} = M_e \quad \text{(15)} \]

Once the equilibria of all sections are established, the deflection in any section can be determined by double integration of $M_e / EI_{\text{section}}$ along the length of the beam. $EI_{\text{section}}$ is the bending stiffness as calculated for each section of the beam.
3. EXPERIMENTS

The experimental part was performed to examine the effect of post-curing and/or temperature load on the tensile and bending behaviour. The ACK model parameters can be derived from the stress-strain curves and the resonalyser.

3.1. Specimen preparation

The matrix is a mixture of a calcium silicate powder and a phosphate acid based solution of metal oxides. The weight ratio liquid to powder is 1/0.8. Mixing is performed using a Heidolph RZR 2102 overhead mixer. First the liquid and the powder are mixed at 250 rpm until the powder is mixed into the fluid, after which the speed is increased to 2000 rpm. E-glass chopped glass fibre mats “2D-random” with a fibre density of 300 g/m² (Owens Corning M705-300) are used as reinforcement. All IPC laminates are made by hand lay-up with an average matrix consumption of 800 g/m² for each layer, which results in an average fibre volume fraction ($V_f$) of 20%. Laminates are cured under ambient conditions for 24 hours. Post-curing is performed at 60°C or 80°C for 24 hours and both sides are covered with plastic to prevent early evaporation of water. The plates of 50 x 50 cm were cut with a water cooled diamond saw. The specimens with a width of 25 mm were used for tensile testing and the specimens with a width of 50 mm were tested in bending.

3.2. Resonalyser

The resonalyser-method is a non-destructive test based on the vibration behaviour of the specimens [8]. By measuring the resonance frequency the stiffness $E_{c1}$ can be calculated by using equation (16).

$$E = 0.0946 \frac{Df^2L}{D^4}$$  (16)

3.3. Tensile testing

The stress-strain curve data was generated using a tensile testing machine (INSTRON 5885H) with a capacity of 100 kN. The rate of cross head displacement was set to 1 mm/min. The strain was measured with an extensometer. The stiffness in the first ($E_{c1}$) and the third stage ($E_{c3}$) can be obtained from the experimental data by determination of the slope of the curves.

3.4. Bending test

For each laminate, several specimens were loaded in a four-point bending test, Figure 3. Two supports were placed with a span of 200 mm, the crosshead was equipped with horizontal bars were two cylinder were mounted with a distance of 100 mm. The force on the cross head and the displacement in the centre of the laminate were measured. The testing machine was displacement controlled; the loading rate was set to 1 mm/min.
4. RESULTS

The obtained stiffness $E_{c1}$ by means of the resonalyser are presented below, Figure (4).

![Figure 4: effect of thermal load on composite stiffness $E_{c1}$.](image)

The values for $E_{c1}$ are plotted for specimens cured for 24 h at room temperature and post-cured at 60°C in case of the left Figure and at 80°C in case of the right one. The composite stiffness $E_{c1}$ and the stiffness of the cracked composite $E_{c3}$ can be derived from the stress strain curve. Table 1 shows the values obtained for the stiffness of the cracked and uncracked composites, cured at ERT for 24h and post-cured at 60°C or 80°C.

### Table 1: effect of thermal load on composite stiffness $E_{c1}$ derived from stress-strain curves.

<table>
<thead>
<tr>
<th>$E_{c1}$ Tensile test ERT - 60 (GPa)</th>
<th>$E_{c1}$ Tensile test ERT - 80 (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T (°C) 4L 6L 8L 12L avg s</td>
<td>T (°C) 4L 6L 8L 12L avg s</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td>ERT 14.8 14.4 15.7 14.6 14.9 0.6</td>
<td>ERT 11.7 12.8 12.4 16.3 13.3 2.1</td>
</tr>
<tr>
<td>105 10.8 12 11 11.1 11.2 0.5</td>
<td>105 8.7 9.8 9.5 10.3 9.6 0.7</td>
</tr>
<tr>
<td>200 7.5 8.2 7.8 8.1 7.9 0.3</td>
<td>200 7 7.5 6.9 7.4 7.2 0.3</td>
</tr>
<tr>
<td>300 8 7.1 6.2 6.3 6.9 0.8</td>
<td>300 6.2 6.9 5.8 6.5 6.3 0.4</td>
</tr>
</tbody>
</table>
Table 2: effect of thermal load on cracked composite stiffness $E_{c3}$

<table>
<thead>
<tr>
<th>$T$ ($°C$)</th>
<th>4L</th>
<th>6L</th>
<th>8L</th>
<th>12L</th>
<th>avg</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERT</td>
<td>3.9</td>
<td>4.2</td>
<td>3.8</td>
<td>3.6</td>
<td>3.9</td>
<td>0.2</td>
</tr>
<tr>
<td>105</td>
<td>4</td>
<td>4.2</td>
<td>4</td>
<td>4.1</td>
<td>4.1</td>
<td>0.1</td>
</tr>
<tr>
<td>200</td>
<td>3.6</td>
<td>4.1</td>
<td>3.9</td>
<td>3.8</td>
<td>3.8</td>
<td>0.2</td>
</tr>
<tr>
<td>300</td>
<td>4.2</td>
<td>3.1</td>
<td>2.9</td>
<td>3.2</td>
<td>3.3</td>
<td>0.6</td>
</tr>
</tbody>
</table>

The stress-strain curves and force deflection curves are plotted for six layer specimens which were cured in closed conditions for 24h and post cured at 80°C for 24h. In Figure 5, the results of the tensile and bending test are shown for specimens that were not subjected to any temperate loading. The specimens the results of which are shown in Figure 6 were heated to 300°C for 24h.

![Figure 5](image)

**Figure 5:** experimental and analytical (red) $\sigma$-$\varepsilon$ and $F$-$\delta$ curves, no temperature loading.

![Figure 6](image)

**Figure 6:** experimental and analytical (red) stress – strain and force - deflection curves, heated to 300°C.

5. **DISCUSSION**

The temperature load causes a significant decrease (30% for 105°C and 50% for 200°C or 300°C) of the stiffness $E_{cl}$. The stiffness $E_{c3}$ is less affected, with a decrease of 1.8%, 10.9%.
and 18.7% for a load of 105°C, 200°C and 300°C, respectively. A decrease up to 50% for the tensile strength and the associated strain will occur after a thermal load of 300°C. If the temperature is limited to 105°C almost no loss is shown. The impact of the post-curing temperature on the mechanical properties is limited. The tensile strength and stiffness $E_{t3}$ are almost unchanged while the stiffness $E_{t1}$ decreases by 10% when post curing at 80°C. In figure 5&6 the experimental and analytical curves are plotted for six layer specimens cured at ERT for 24h and post cured at 80°C for 24h. By fitting the ACK model curve on the experimental stress strains curves it was possible derive the material parameters for the bending model. By observing the force deflection curves for each post-curing and temperature load, the analytical (red) and experimental force-deflection curves show a great similarity. The force deflection curves show a kink point and therefore a non-linear behaviour when no temperature load is applied. When the applied temperature is higher, this kink point may be observed less clearly. For a temperature load of 200°C or 300°C, a nearly linear behaviour can be detected. The experimental data is relatively well approximated by the analytical solution, with an average accuracy of 90%. Generally, it can be noted that the deflection curves for a post-curing at 80°C are more accurately modelled than those for a post-curing at 60°C.

6. CONCLUSIONS

The presented calculation method to derive the load displacement curves of a textile reinforced cementitious composite beam which is exposed to a high temperature (300°C) could be used successfully. Analytical and experimental force-deflection curves show a great similarity. The method uses data from experimental tensile tests of similar specimen exposed to the same temperature to calibrate the material stress-strain model based on the ACK theory. Temperature load causes a significant decrease of the composite stiffness $E_{cr1}$. The stiffness of the cracked composite $E_{cr3}$ is less affected by the thermal load. Heating up the specimens to 300°C will reduce tensile strength and strain by 50%. If the temperature stays below 105°C, the effect on the mechanical properties limited. Post-curing the specimens at a higher temperature (80°C) will decrease the mechanical properties. Generally it can be noted that the deflection curves for a post-curing at 80°C are more accurately modelled than those for a post-curing at 60°C.

REFERENCES