MODELING TEXTILE REINFORCED CEMENTITIOUS COMPOSITES - EFFECT OF ELEVATED TEMPERATURES

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1 Introduction
The textile reinforced cementitious composites (TRC) used in this study are a combination of inorganic phosphate cement (IPC) with a glass fibre chopped strand mat reinforcement. IPC has been developed at the “Vrije Universiteit Brussel”. One of the major benefits of IPC compared to other cementitious materials is the non-alkaline environment of IPC after hardening. For this reason, ordinary E-glass fibres are not attacked by the matrix and can be used as reinforcement. By using a fibre volume fraction which exceeds a critical value, the fibres can ensure strength and stiffness at applied loads much higher than the range in which matrix multiple cracking occurs. This results in a strain hardening behaviour in tension. Since the combination of IPC and E-glass fibres leads to a relatively low cost composite, which is entirely made of inorganic materials, it is well suited for utilization in constructions that are exposed to high temperatures. The material itself is characterized by a linear behaviour in compression and a highly nonlinear tensile behaviour. Over the years many efforts have been concentrating on the modelling of this tensile and bending behaviour without taking the effect of temperature loading into account [1][2][3]. This paper presents an analytical and FEM based method in order to model the behaviour of a beam under tension, compression and bending . The analytical model is based on theory of Aveston, Cooper and Kelly (ACK)[4][5][6] and a method proposed by Soranakom and Mobasher [2] These models will be calibrated by using experimental data from tensile tests. In FEM software (Abaqus) two material models will be evaluated, an elastic-plastic and a hyperelastic “Marlow” model. The effect on the modelling of exposing textile reinforced cementitious composite beams to high temperature (300°C) is included in this paper.

2 TRC in tension and compression

2.1. Analytical model

According to the ACK theory, three distinct stages can be detected in the stress-strain curve of a unidirectionally reinforced brittle matrix composite. Figure (1) illustrates a experimental and theoretical (ACK) stress-strain curve with these three distinct stages.

In the first stage the material behaves in a linear elastic way. The composite stiffness in stage I \((E_c1)\) 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 \(E_m\) , as derived from the law of mixtures:

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

The ACK theory can be modified to account for different fibre alignment, imperfect matrix-fibre adhesion, warping or misalignment of the unidirectional fibres, inclusion of air voids, etc. This can be achieved by introducing a fibre efficiency factor \(\eta_f\) and a matrix efficiency factor \(\eta_m\). The modified law of mixtures can be written as follows:

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

At the ultimate matrix strain the composite will crack. If the fibre volume fraction is sufficiently
high (typically more than 1 to 2 %), the fibres will be able to sustain the additional loading and multiple parallel cracks are introduced in the matrix. According to the ACK theory this stage is called the “multiple cracking” stage. The composite multiple cracking stress ($\sigma_{mc}$) can be determined by the following equation (3) with ($\sigma_{mu}$) defined as the matrix cracking stress:

$$\sigma_{mc} = \frac{\sigma_{mu}E_{c1}}{E_m}$$  \hspace{1cm} (3)

In the third “post cracking” stage, the matrix is assumed to be completely cracked. The fibres will carry the additional load until their failure. The stiffness of the composite $E_{c3}$ in this stage is thus:

$$E_{c13} = \eta_f E_f V_f$$  \hspace{1cm} (4)

The data of 10 tensile tests for each temperature load will be averaged and used to calibrate the modified ACK model. Calibration is done by changing the fibre and matrix efficiency and adjusting the matrix cracking stress ($E_{c1}$, $\sigma_{mc}$, $E_{c3}$). The process will be repeated in order to minimize the cost function “least square” between the computed and the measured stress strain curve. In this process the stiffness of matrix and fibre are kept constant. In compression a linear behaviour is assumed.

A second model was used based on a homogenized strain hardening model for fibre reinforced concrete developed by Soranakom and Mobasher [2]. This model also uses experimental data for calibration but in this case 8 parameters ($E$, $e_{cr}$, $\eta$, $\alpha$, $\mu$, $\beta_{tu}$, $\omega$, $\lambda_{cu}$) need to be determined. The tensile part of the model is calibrated by 6 parameters which will define the linear elastic and strain hardening behaviour. The compression part will be calibrated by two parameters.

### 2.2 FEM model

Two material models were selected in Abaqus to model the behaviour of the TRC. In the first computation an elastic-plastic material model is used. The elastic part is defined by a Young’s modulus ($E_{c1} = 17.07$ GPa) and a Poisson’s ratio (0.3). The plastic behaviour was obtained by computing the plastic strain from the average experimental stress-strain data. The model uses the same stress-strain relation in compression and tension, which is a serious drawback for the material under study. The second model is based on hyperelasticity “Marlow” and enables the user to define a different behaviour in compression and tension. The tensile stress strain data was taken by averaging the experimental data obtained from 10 samples. The compressive behaviour is assumed linear with a composite stiffness $E_{c1} = 17.07$ GPa, until collapse at 80MPa, while the tensile behaviour will be nonlinear. Several strain energy potential forms are available in Abaqus; for the current study, the Marlow model is chosen for its ability to reproduce an asymmetric material behaviour.

### 3 Modeling TRC in bending (ACK)

Since the tensile behaviour of TRC shows three stages, three expressions are needed to define the equilibrium of forces and moments if a cross section is loaded in bending. By expressing the equilibrium of forces and moments, the position of the neutral axis (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 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 occurring tensile stress. As long as the composite behaves linear elastic along the whole beam section the following expressions can be used, with $M_e$ defined as external moment:

$$M_e = \frac{2}{3} a^2 E_{c1} \varepsilon_t$$  \hspace{1cm} (5)

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

By expressing the equilibrium of forces (7) and moments (8), the position of the neutral axis and the maximum occurring tensile strain ($\varepsilon_t$) in the section can be calculated for each cross section along the beam [6].

$$E_c t E_1 \frac{a^2}{2(h-a)} = \delta \frac{\sigma_{mc}}{2} + \delta^{*} \sigma_{mc}$$  \hspace{1cm} (7)

$$E_c t E_1 \frac{a^3}{3(h-a)} + \delta^{*} \frac{\sigma_{mc}}{2} + \sigma_{mc} \delta^{*} \left( \delta + \frac{\delta^{*}}{2} \right) = M_e$$  \hspace{1cm} (8)

With

$$\delta = \frac{\varepsilon_{mu}}{\varepsilon_t} (h-a) \text{ and } \delta^{*} = h - a - \delta$$

Finally the composite maximum tensile strain will be reached in the post-cracking stage.

By expressing the equilibrium of forces (9) and moments (10), the position of the neutral axis and the maximum occurring tensile strain ($\varepsilon_t$) in the section can be calculated for each cross section along the beam.

$$E_c t E_1 \frac{a^2}{2(h-a)} = \delta \frac{\sigma_{mc}}{2} + \delta^{*} \sigma_{mc}$$  \hspace{1cm} (9)

$$+ \left( \varepsilon_t - \varepsilon_{stage (II)} \right) E_f V_f \frac{\delta^{**}}{2}$$

With

$$\delta^{**} = (h-a) - \frac{\varepsilon_{stage (II)}}{\varepsilon_{mu}} \delta$$

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

### 4. Experiments and Discussion

#### 4.1. 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. A total of 8 chopped E-glass fibre mats 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 of 20%. Laminates are cured under ambient conditions for 24 hours. Post-curing is performed at 60°C for 24 hours and both sides are covered with plastic to prevent early evaporation of water. The plates of 500 x 500 mm were cut with a water cooled diamond saw. Specimens with a width of 25 mm were used for tensile testing, while specimens with a width of 50 mm were tested in bending. After cutting the specimens will be dried for 24h at 60°C. In order to examine the effect of elevated temperature the specimens will be thermally loaded at 105°C, 200°C or 300°C for 1h.

#### 4.2. Test Setup

In total 10 specimens for each thermal load were tested in order to obtain the stress-strain
curves using a testing machine (INSTRON 5885H) with a capacity of 100 kN. The rate of crosshead 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. For each laminate either heated or not, 10 specimens were loaded in a four-point bending test according to the dimensions shown in figure (4). The testing machine recorded the force on the crosshead. The displacement in the centre of the laminate was measured using a linear variable differential transformer (LVDT). The tests were displacement controlled with a loading rate of 1 mm/min.

4.3. Results and discussion

4.3.1. Tensile testing

Figure (5) shows the average stress strain curves obtained from 10 tested samples, either thermally loaded or not, including the indication of the standard deviation. The last point in the curves is defined by failure of the weakest specimen. By observing these plots, one can see the influence of the elevated temperature on the tensile behaviour of the TRC specimens. At room temperature, the specimens have an average maximum tensile strength of 63.92 MPa (stdev 2.48 MPa) with a maximum strain of 1.55%. After heating the specimens to 300°C, the maximum tensile strength will drop to 23.03 MPa (stdev 2.09MPa) and the ultimate strain is reduced to 0.6%. By heating the specimens the maximum tensile strength is thus reduced by 64%. It is also shown that the curves change their shape: the curves at ERT and 105°C have two well defined different slopes, showing the difference between the uncrazed and cracked composite. This difference gradually disappears with heating.

4.3.2. Bending testing

The force-deflection curve is the average of 10 experimental data sets. The maximum load obtained by testing virgin specimens is 400N, while after heating the specimens at 300°C this will be reduced to 100N, occurring also at a lower strain. Increasing the temperature load on the specimens leads to a more linear force-deflection behaviour, for similar reasons as for tension.

5. Modelling

5.1. ACK model

5.1.1. Calibrating stress strain ACK model

In figure (1) the average experimental data of 10 specimens is combined with the calibrated ACK model using the parameters presented in table (1). Only three parameters, fibre efficiency, matrix efficiency and ultimate matrix cracking stress, needed to be calibrated. The stiffness of the matrix and fibre are kept constant. The apparently very low value for the fibre efficiency is mainly attributed to their random orientation in the plane, where a theoretical value of 1/3 is proposed in literature by Cox [9]. When the specimens are exposed to the effect of elevated temperature the calibration parameters will change. The efficiency of fibre and matrix and the according composite uncrazed and crazed stiffnesses are shown in table (2). It can be noticed that after temperature loading, the fibre efficiency remains almost constant, while there is a significant drop in the efficiency of the matrix. This results in a significant drop in the uncrazed stiffness, but a fairly constant crazed stiffness. It can be assumed that the temperature load causes a significant degradation of the matrix by introducing micro cracks, which can indeed be remarked visually. At temperatures above 100°C, the matrix loses gradually its adsorbed water, resulting in a single but pronounced shrinkage of the order of 1%. The presence of the glass fibres, which are not shrinking, restrains this shrinkage and leads to internal matrix stresses which are exceeding its cracking stress. Thus the contribution of the
matrix to the composite stiffness is reducing, after temperature loading even in the first “uncracked” stage.

5.1.2 Bending model ACK

After calibrating the analytical bending model based on ACK, it is possible to compute the force-deflection curve in the absence of thermal loading, which is shown in figure (7).

By using the mean tensile stress strain data of specimens after thermal loading at 300°C for calibrating the analytical bending model, the force-deflection curve was computed as shown in figure (8). In both cases the calculated force-deflection curve using the ACK model resulted in good similarity between the experimental data and the absence of a correction for the maximum stress after temperature loading.

5.2 Model Soranakom and Mobasher

5.2.1 Calibrating stress strain behaviour

This model also uses experimental data for calibration but in this case 8 parameters ($E$, $\varepsilon_{cr}$, $\eta$, $\alpha$, $\mu$, $\beta_{tu}$, $\omega$, $\lambda_{cu}$) need to be determined. Figure (9) shows the calibrated stress strain behaviour fitted on the average experimental data.

5.2.2 Bending model

The model proposed by Soranakom and Mobasher was also capable of computing accurately the force-deflection curve in the absence of thermal loading, as shown in figure (7). But calibrating the model with 8 parameters is more complex.

5.3 FEM model results

5.3.1. Tension and compression behaviour

A 1D simulation of a tension and compression test was performed using the elastic-plastic and hyperelastic material models. The results are presented in figure (10). In this case the specimens are only cured and post cured at 60°C, no temperature load was applied. The stress and plastic strains is computed as shown in table (3). By observing the results in tension one can obtain a good fit of the computed stress strain behaviour with the experimental data. In compression however a large difference between the two models can be observed: only by using an the asymmetrical hyperelastic MARLOW material model the TRC material can be accurately described. When exposing the specimens to 300°C the stress strain curve can be fitted using the hyperelastic material model, as depicted in figure (11).

5.3.2. Bending behaviour

By knowing the compression and tensile behaviour of the material it is possible to generate the force deflection curves due to four point bending. The force deflection curves in figure (12) show the bending behaviour of specimens which were not heated to an elevated temperature after curing. As can be expected the elastic-plastic material model used in Abaqus is not able to simulate accurately the experimental bending behaviour. The elastic-plastic model in Abaqus indeed assumes a symmetrical material model. When the choice is made to use the tensile stress strain behaviour also in the compression part, as shown in figure (10), this underestimates the stiffness of the compression zone and thus of the specimen in bending. By using the hyperelastic asymmetric material model the full stress behaviour in compression an tension can be implemented in the material model, taking in account the asymmetry. The results in an accurate prediction of the bending behaviour. By exposing the specimens to 300°C the force deflection curves will change and become more linear as illustrated in figure (13).

6 Conclusions

Modelling textile reinforced cementitious composite taking in account the effect of elevated temperatures is possible using an
analytical model or a FEM program. Nevertheless the choice and calibration of the material model will influence the prediction. Accurate modelling can only be performed when compression and tension can be independently defined. When using the analytical ACK based bending model only 3 parameters are needed to calibrate the tensile stress strain behaviour. The calibration procedure uses experimental stress strain data. Once the model is calibrated the force deflection curves can be computed within the standard deviation of the average experimental curve. The analytical model proposed by Soranakom and Mobasher could also calculate the force displacement curves, but the calibration of 8 parameters was more complicated.

Due to the different behaviour in compression and tension of the TRC an asymmetrical is needed in order to model the material accurately. By using the hyperelastic model with the MARLOW option it was possible to define the stress strain behaviour in tension and compression as directly obtained from the experimental data. When computing the force deflection curve the hyperelastic model was able to reproduce the behaviour within the standard deviation of the average experimental curve. By using an elastic plastic model the force deflection curve cannot be reproduced.

Temperature load causes a significant decrease of the composite stiffness $E_{c1}$. The stiffness of the cracked composite $E_{c3}$ is less affected by the thermal load. Heating up the specimens to 300°C will reduce tensile strength and strain by 64%. If the temperature stays below 105°C, the effect on the mechanical properties is limited.

By heating the specimens above 200°C the material will lose its nonlinear behaviour because only the post cracking stiffness will determine the behaviour.

| $E_{m}$ | 18 GPa |
| $E_{f}$ | 72 GPa |
| $\sigma_{mu}$ | 10 MPa |
| $\eta_{f}$ | 0.28 |
| $\eta_{m}$ | 0.90 |

Table 1: Calibration data to model ACK curve.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>$\eta_{f}$</th>
<th>$\eta_{m}$</th>
<th>$E_{c1}$</th>
<th>$E_{c3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERT</td>
<td>0.28</td>
<td>0.90</td>
<td>17.1</td>
<td>4.4</td>
</tr>
<tr>
<td>105.0</td>
<td>0.28</td>
<td>0.80</td>
<td>15.7</td>
<td>4.6</td>
</tr>
<tr>
<td>200.0</td>
<td>0.30</td>
<td>0.40</td>
<td>10.3</td>
<td>4.6</td>
</tr>
<tr>
<td>300.0</td>
<td>0.20</td>
<td>0.40</td>
<td>8.9</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Table 2: Evolution of fibre and matrix efficiency and stiffness due to temperature load.

<table>
<thead>
<tr>
<th>Yield stress MPa</th>
<th>Plastic Strain %</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.63</td>
<td>0.00</td>
</tr>
<tr>
<td>10.20</td>
<td>0.03</td>
</tr>
<tr>
<td>13.72</td>
<td>0.07</td>
</tr>
<tr>
<td>17.58</td>
<td>0.14</td>
</tr>
<tr>
<td>25.10</td>
<td>0.29</td>
</tr>
<tr>
<td>29.82</td>
<td>0.38</td>
</tr>
<tr>
<td>55.62</td>
<td>0.87</td>
</tr>
</tbody>
</table>

Table 3: Plastic stress strain behaviour obtained from experimental data.

Figure 1: Experimental and theoretical stress-strain curve, according to the ACK theory [3]
Figure 2: distribution of stress strain over cross section in the multiple cracking stage

Figure 3: distribution of stress strain over cross section in the post cracking stage

Figure 4: 4 point bending test geometry and setup with LVDT

Figure 5: Stress strain curves obtained from tensile tests on 8 layer TRC specimens with different thermal loadings.
Figure 6: Force deflection curves obtained from 4 point bending tests on 8 layer TRC specimens with different thermal loadings.

Figure 7: Force deflection curves obtained by ACK and Soranakom-Mobasher bending models (ERT).

Figure 8: Force deflection curves obtained by ACK bending model (300°C).

Figure 9: Calibrated stress strain curve according to Soranakom-Mobasher (ERT).
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Figure 10: Stress strain curves obtained by Abaqus using an elastic-plastic and hyperelastic material model.

Figure 11: Comparison of experimental and computed stress strain curves for specimens heated at 300°C using Abaqus hyperelastic material model.

Figure 12: Force deflection curves obtained analytical ACK and Mobasher bending models.

Figure 13: Force deflection curves of specimens heated at 300°C obtained with hyperelastic FEM model using Marlow energy potential option.

References


