STRENGTH EVOLUTION AFTER HIGH TEMPERATURE EXPOSURE OF COATED CARBON FIBER ROVINGS USED FOR A FIBER-REINFORCED CEMENTITIOUS MATRIX (FRCM)

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ABSTRACT

This paper presents experimental results of the tensile strength decrease of coated Carbon Fiber rovings after high temperature exposure up to 1000°C. The composite material is used as a mesh reinforcement for various shotcrete applications (FRCM – Fiber Reinforced Cementitious Mortar) in structural retrofitting projects. In case of a fire accident, it is mandatory to dispose of a certain residual strength after high temperature exposure in order to guarantee structural safety.

The current investigation treats unidirectional tensile strength tests on Carbon Fiber rovings carried out at Empa. The investigation was performed at room temperature on Carbon Fiber rovings after having been thermally subjected to constant temperature of 300, 500, 700 and 1000°C in a tube furnace for 30 minutes. It can be observed that an exposure at 300°C for half an hour does not affect the mechanical properties of the analyzed reinforcement. However, a further increase in temperature starts seriously damaging the material’s ability at 500°C, whilst no residual strength is left at 700 and 1000°C, respectively.

Additionally, reinforced concrete plate strips were strengthened with a fiber-reinforced-cementitious-matrix (FRCM) layer and subsequently subjected to fire at the ‘Versuchsstollen Hagerbach’ (CH), temperature was controlled according to the European ETK-temperature curve. The measured temperature evolution on the Carbon Fiber rovings (under a total concrete/shotcrete cover of 40 mm for the steel reinforcement) together with the previously performed tensile tests lead to the conclusion that the inner steel reinforcement, for which temperature was also monitored, is partially protected by the FRCM layer and does not trespass 250°C in this case.

KEYWORDS

Fiber reinforced cementitious matrix (FRCM), carbon fiber rovings, high temperature exposure, residual tensile strength

INTRODUCTION

Fiber Reinforced Cementitious Matrix (FRCM), also known under the designation ‘Textile Reinforced Concrete’ (TRC) (see Curbach and Jesse (2011)) is known to be an efficient strengthening method for existing reinforced concrete structures. Schladitz et al. (2012) performed static loading tests on RC beams strengthened with an FRCM layer and demonstrated a uniform enhancement in the ultimate bearing capacity when increasing the number of reinforcement layers. Ehlig et al. (2010) present textile reinforced concrete plates tested after fire exposure under sustained load. It is shown that residual bearing capacity is considerable after one hour under high temperature.

The FRCM system presented in this manuscript is also used as a reinforcement technique for existing reinforced concrete structures (S&P Clever Reinforcement 2012). The present papers quantifies the reduction in tensile strength capacity of a specific composite reinforcement for FRCM application after high temperature exposure. In the end, a high temperature test with a RC beam element retrofitted with an FRCM layer aims at quantifying the temperature developments in the inner steel reinforcement, in the carbon fiber composite as well as on the interface concrete/shotcrete.
EXPERIMENTAL INVESTIGATION

Test specimens and heating configurations

A composite mesh type (L500, mechanical characteristics are summarized in Table 1) was tested in the current investigation. In longitudinal direction, 58.5 carbon strings per meter are used for tensile force transfer. Since one string is composed of two rovings, this implicates a total number of 117 rovings per meter. One roving has a density of 1.7 g/cm³ or 1’600 tex (1.6 g/m). In theory, the unidirectional tensile resistance is in the range of 500 kN/m, which gives an average value of 4.27 kN per roving. The roving specimens were cut form the original mesh structure, as shown in Figure 1. In transverse direction, E-glass fibers are used as a fixing element, but are not taken into account for any structural purposes.

As a coating, a compacted acrylic ester copolymer is used. The surface is finally sprinkled with an amorphous silica fume.

Figure 1. Composite mesh (L500)

<table>
<thead>
<tr>
<th>Mesh Structure</th>
<th>2 x 1600 tex/string - 58.5 strings/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (Carbon fiber) [g/cm³]</td>
<td>1.7</td>
</tr>
<tr>
<td>Theoretical strain at failure [%]</td>
<td>1.5</td>
</tr>
<tr>
<td>Theoretical force at failure [kN/m]</td>
<td>500</td>
</tr>
</tbody>
</table>

Table 1. Composite mesh configuration (L500) and characteristic material properties

 Tube furnace

For high temperature exposure, the specimens were installed in a tube furnace (see Figure 2) during 30 minutes or more. It is emphasized that the specimens had already entered the furnace during the heating-up period. Hence, a higher final temperature also involves a longer total temperature exposure and thus more conservative results. It is emphasized that only a central segment with an approximate length of 40 cm was submitted to the high temperatures, whereas the remaining roving ends were kept at room temperature (see Figure 2 b)).

Figure 2. a) Tube furnace, b) end closing of the tube
Clamping configurations and test setup

An initial specimen length of 1600 mm was considered. The rovings were revolved three times around the rolls at both ends and eventually fixed with a clamping device (see Figure 3 a)). This procedure was performed according to the ISO 3341 (2000) testing recommendation. As a comparison, the reference tests were repeated with an epoxy coating and a special metallic clamping (see Figure 3 b)). This procedure was expected to deliver higher tensile resistances, since the stress transfer can be achieved in a more homogeneous way. Extensometers with a base length of 150 mm were used to record the vertical displacement subsequently transformed into a tensile strain. A load cell measured the applied loading force. All the tests were conducted at room temperature (approx. 21°C) at a displacement velocity of 5 mm/min. An example of the test setup with roll clamping is given in Figure 3a.

RESULTS AND DISCUSSIONS

Tensile tests

The results in terms of force-strain behaviour are presented in Figure 4. Ultimate tensile forces of the different configurations are summarized in Table 2. All specimens revealed a more or less linear tensile behaviour up to failure, with the difference that the uncoated specimens need an initial time span before the real stiffness is developed. This is due to a relative slip of the two bundles against each other before the specimen is fully stretched.

It can be observed that an epoxy coating together with a metallic clamping configuration delivers higher tensile resistances and higher strains at failure than the roll clamping method, a relative increase of 85% in force is presented (average value rises from 2664 N to 4938 N). This clear enhancement is due to a more equal stress transfer in the rovings when an epoxy coating and metallic clamping are used. Additionally, the overall roving stiffness clearly shows less deviation in this case.

Exposure to an increased temperature up to 1000°C has a clearly decreasing effect on both ultimate tensile force and strain at failure. A temperature of 300°C does not seem to have any effect on the bearing capacity, the measured average ultimate force being even higher than the reference one (see Table 2.). A further increase to
500°C of exposure during 30 minutes involved an average reduced strength of 1542 N, corresponding to only 58% of the initial reference. Both series with 700°C and 1000°C heating temperature destroy the roving, leaving no noticeable remaining tensile capacity left. Average forces in function of the exposing temperature prior to testing are given in Figure 5. The following equation summarizes the dependence:

\[ F_e(T_e) = 2733.5 + \frac{2733.5 - 39.2}{1 + e^{-\frac{T_e - 300}{39.1}}} \] (1)

Figure 4. Force-strain curves for all the test specimens under different temperature configurations

Table 2. Summary of the failure forces for all the tested configurations

<table>
<thead>
<tr>
<th>Temperature exposure [°C]</th>
<th>Metallic clamp</th>
<th>Roll clamps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure force [N]</td>
<td>RT</td>
<td>RT</td>
</tr>
<tr>
<td></td>
<td>4938</td>
<td>2664</td>
</tr>
<tr>
<td>Standard deviation [N]</td>
<td>323</td>
<td>182</td>
</tr>
</tbody>
</table>

Figure 5. Left: Ultimate tensile resistance for the composite mesh in function of temperature exposure during 30 minutes (roll clamping) / Right: Temperature evolution in the steel, at the interface and in the mesh (L200) following a temperature exposure according to the ETK for 2 hours
Temperature tests in Hagerbach (CH)

In the testing gallery Hagerbach (Versuchsstollen Hagerbach (CH), www.hagerbach.ch), a RC slab (lower tensile reinforcement $5\phi 8$) with a similar composite mesh type (L200) (see S&P Clever Reinforcement AG (2013a)) was submitted to a fire exposure for a determined time span. The L200 mesh is a two-directional carbon-roving grid with a theoretical failure force of about 200 N/m.

Figure 6 presents the retrofitted concrete element. Two cm of the initial cover of 30 mm is hydro-mechanically removed, the remaining reinforcement cover of 1 cm was subsequently enhanced to two cm by applying a first layer of wet shotcrete. Afterwards, two layers of an L200-mesh are introduced on the first shotcrete layer. Finally, a second shotcrete layer with a thickness of 2 cm is put in place. Hence, the total concrete/shotcrete cover thickness with respect to the steel bars is 4 cm. At ultimate state, the strengthening ratio $M_{R,new}/M_{R,old}$ is 1.3.

The strengthened RC slab under service load is subsequently submitted to a high temperature exposure from below (against the lower shotcrete surface) as presented in Figure 7. The goal of this investigation was to assess the temperature evolution in the inner steel reinforcement, in the composite reinforcement as well as on the interface concrete/shotcrete. Several temperature exposure procedures are possible; in the current test the European ‘Einheits-Temperatur-Kurve’ (ETK), generally applied in Europe in structural engineering design, was chosen. Its evolution is presented in Figure 5 (right). The slabs with a width of 0.95 m (see Figure 6) and a span of 2 m was simply supported and tested under two point loads of each time 24 kN (see Figure 7). In this state, the strain in the composite reinforcement is approximately 0.17 %. Temperature is monitored with thermocouples. According to the graph presented in Figure 5 (right), the temperature in the end in the mesh is approximately 440°C and 250°C in the steel reinforcement. Only minor cover spalling at the border regions was visible. Visual inspection after the test revealed that both composite layers were still in place and that a certain residual tensile capacity is likely. Exact values would have to be determined in analogy to the previously presented tensile tests in order to establish a force-temperature relation for the measured temperature profile similar to Eq. (1). Earlier research by Ehlig et al. (2010) on retrofitted concrete plates with TRC has shown that after one hour of fire
exposure (ETK), the residual bearing capacity was still 80% of the initially determined bearing capacity after strengthening.

Eventually, one can conclude that, in addition to the structural strengthening effect, the applied composite mesh and shotcrete layer can act as a temperature protection for the inner steel reinforcement in case of a fire situation for instance. Further experimental investigation should be carried out in order to quantify residual structural safety after such a fire exposure.

CONCLUSIONS

Out of the presented results, the following conclusions can be drawn:

• In case of a two-carbon-string roving, both the coating and the clamping type play a major role with regard to a proper stress transfer and eventually the resulting tensile capacity. An epoxy coating and a metallic clamping allowed obtaining an increase of 84% in ultimate loads on average.
• A temperature exposure diminishes the residual tensile resistances. Whereas an exposure to 300°C during a bit more than 30 minutes has no effect on the measured forces, an increase to 500°C halves the initial tensile strength. Even higher temperatures in the range between 700 and 1000°C completely destroy the composite.
• The application of an additional shotcrete layer containing a composite reinforcement can act as a fire protection for the inner steel reinforcement. Tests following the European ETK-curve revealed a steel temperature of 250°C after two hours. Further tests on the overall structural residual capacity should be performed.

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REFERENCES


