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TRM versus FRP in flexural strengthening of RC beams: Behaviour at high temperatures

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ABSTRACT

The flexural behaviour of RC beams strengthened with TRM and FRP composites was experimentally investigated and compared both at ambient and high temperatures. The investigated parameters were: (a) the strengthening material, namely TRM versus FRP, (b) the number of strengthening layers, (c) the textile surface condition (dry and coated), (d) the textile material (carbon, basalt or glass fibres) and (e) the end-anchorage of the flexural reinforcement. A total of 23 half-scale beams were constructed, strengthened in flexure and tested to assess these parameters and the effectiveness of the TRM versus FRP at high temperatures. TRM exhibited excellent performance as strengthening material in increasing the flexural capacity at high temperature; in fact, TRM maintained an average effectiveness of 55%, compared to its effectiveness at ambient temperature, contrary to FRP which totally lost its effectiveness when subjected to high temperature. In specific, from the high temperature test it was found that by increasing the number of layers, the TRM effectiveness was considerably enhanced and the failure mode was altered; coating enhanced the TRM effectiveness; and the end-anchorage at high temperature improved significantly the FRP and marginally the TRM effectiveness. Finally, the formula proposed by the *fib* Model Code 2010 was used to predict the mean debonding stress in the TRM reinforcement, and using the experimental results obtained in this study, a reduction factor to account for the effect of high temperature on the flexural strengthening with TRM was proposed.

1. Introduction and background

Due to the continuous deterioration of RC structures, both in seismic and non-seismic areas, the need for upgrading the existing concrete structures has become very important. Ageing, degradation due to environmental conditions, inadequate maintenance, increase of applied permanent or earthquake loads, and the need to meet the requirements of modern design codes (i.e. Eurocodes) are the main reasons which advocate for the urgent need of structural strengthening the existing RC structures. The use of Fibre Reinforced Polymer (FRP) as a means of external reinforcement for RC structures has gained popularity due to the favorable properties of FRP such as the high strength to weight ratio, ease and speed of application, resistance to corrosion, and minimal change in the geometry of structural elements. Nevertheless, FRP has some disadvantages such as high costs, incompatibility with concrete surfaces, difficulty to apply on wet surfaces or low temperatures, and poor performance at high temperature. The latter is due to epoxy resins used in FRP which lose their tensile capacity under high temperature. Therefore, unless protective (thermal insulation) systems are provided [1], the effectiveness of TRM will be extremely low due to the deterioration of bond at the concrete-adhesive interface when the interface temperature is above the glass transition temperature (T_g). A state-of-the-art review on the fire performance of reinforced concrete (RC) members strengthened with FRP and subjected to fire and high temperatures was recently presented by Firmo et al. 2015 [2].

In an attempt to overcome such drawbacks, a new generation of composites combining high strength textile fibres with inorganic matrices have been recently proposed as a structural retrofitting material for the deficient RC members namely the textile reinforced mortar (TRM) [3], identified in the literature also as TRC [4] or FRCM [5]. In comparison with FRP, TRM is a relatively low cost strengthening material, safer for manual workers, compatible

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with concrete and masonry substrates and can be applied on wet surfaces or at low temperatures.

Bond between TRM and concrete substrate has been addressed in several studies [i.e. 6,7]. TRM has also been investigated as a means of external reinforcement for strengthening RC members, namely in flexural reinforcing of RC beams [i.e. 8–11], one way [12,13], and two way slabs [14,15]; the shear upgrading of RC elements [i.e. 16–20]; the seismic retrofitting of RC columns [21-26]; and the seismic reinforcing of infilled RC frames [27]. The experimental results demonstrated the effectiveness of TRM as a retrofitting solution. TRM has been successfully used worldwide in the construction field. Selected case studies can be found in [28].

TRM could outperform FRP systems at high temperatures or fire due to the breathability, non-combustibility, and non- flammability offered by mineral-based cement mortars used as binding materials. In general, the research on the performance of TRM systems at high temperature or fire and the comparison between TRM and FRP systems at high temperature or fire is extremely limited [29–33]. This is attributed to the experimental difficulties associated with applying simultaneously loading and high temperatures. For this reason, the past studies were mainly focused on evaluating the residual strength of TRM after being exposed to high temperatures and cooled down. Particularly, in [29–31] uniaxial tensile tests were conducted on TRM coupons made of glass [29], carbon [30], and basalt [31] textile fibres. The specimens were exposed to different level of high temperature varied between 20 and 1000 °C, cooled down and then subject to tensile loading up to failure. The main conclusion of these studies was that the TRM coupons maintained their ambient tensile strength up to 200 °C [29,30], and 150 °C [31], but for higher temperatures the residual tensile strength was gradually decreased.

The only studies reported in the literature on the effectiveness of TRM versus FRP as strengthening materials at high temperature are those of Raoof and Bournas 2017 [34], Tetta and Bournas 2016 [35], and Bisby et al. 2013 [36].

In [34] the authors investigated the bond behaviour between TRM vs. FRP and concrete at high temperatures, whereas [35] studied the effectiveness of TRM vs. FRP in shear strengthening of concrete members subjected to high temperatures. In both studies, specimens were heated up to predefined temperatures equal to 20, 50, 75, 100, 150, 300, 400 and 500 °C in [34] and 20, 100, 150 and 250 °C in [35], and then subjected to double-lap shear test [34] and three point-bending test [35], demonstrating superior performance for TRM over FRP at high temperature. In particular, in [34], it was found that TRM specimens maintained an average of 85% of their ambient bond strength up to 400 °C, contrary to FRP which kept only 17% at 150 °C. Similarly, in [35] it was shown that TRM maintained 60% of its ambient temperature shear strengthening effectiveness at 150 °C, contrary to FRP which totally lost its effectiveness when subjected to temperature above the T_g.

Finally, in [36], FRP and TRM flexurally retrofitted beams were subjected to a sustained load and then exposed to increasing temperature up to failure, keeping however the end anchorage TRM and FRP zones cold. It was concluded that both TRM and FRP can have the same performance at high temperature when their anchorage is kept cold. However, in that study, the effect of high temperature on the FRP/TRM debonding mechanism was not addressed because the bond condition was not realistically simulated due the cold anchorage zones.

From the literature survey, it is clear that the subject of TRM vs. FRP in flexural strengthening of RC beams subjected to high temperature has not covered and needs to be studied in realistic bond conditions for the externally bonded reinforcement. This paper investigates for the first time the effectiveness of TRM vs. FRP in flexural strengthening of RC beams subjected to simultaneous high temperature and loading, without protecting the TRM and FRP anchorage zones. The parameters investigated include the number of FRP/TRM layers (1, 3, and 7), the textile surface condition (dry and coated), the textile fibre materials (carbon, basalt, and glass), and the end-anchorage system of the flexural reinforcement.

2. Experimental programme

2.1. Test specimens and investigated parameters

The main objective of the current study was to compare the performance of TRM versus FRP in enhancing the flexural capacity of RC beams at high temperature. A total of 23 half-scale rectangular section RC beams (dimensions of 101 × 202 mm) were constructed, strengthened and tested under 4-point bending load. The total length of the beams was 1675 mm, whereas the effective and shear span were 1500 mm, 580 mm, respectively (Fig. 1a).

All beams were intentionally designed with a low amount of longitudinal reinforcement so as to have low flexural capacity. The reinforcement ratio (ρ_s) was equal to 0.56%, simulating flexural-deficient beams as a result of corrosion of rebars or increase of the applied load. As shown in Fig. 1b, the longitudinal reinforcement comprised two 8 mm diameter rebars at the bottom (tension zone) and two 12 mm diameter deformed rebars at the top (compression zone) of the beams. The tensile rebars were bent at their ends over 180 degrees to provide proper anchorage. As shown in Fig. 1a, 8 mm-diameter shear links were placed at 80 mm distances along the two clear shear spans of the beams (expect for the constant moment zone) resulting – by design – to a shear resistance seven times higher than the shear force corresponding to the predicted flexural capacity of the unstrengthened beam.

Several parameters were investigated in this study including: (a) the strengthening system (TRM versus FRP), (b) the number of strengthening layers (one, three, and seven), (c) the material of the textiles fibres (carbon, glass and basalt), (d) the textile surface condition (coated versus dry) of carbon-fibre textiles, and (e) the end-anchorage of the main FRP/TRM reinforcement using 2-layers U-shaped jacketing made of FRP/TRM. All these parameters were investigated at ambient (20 °C) and high (150 °C) temperatures.

Table 1 supporting by Fig. 2a, provide description of the tested specimens and strengthening configurations. The strengthened specimens were named following the notation BN_F_T, where B denotes the type of bonding agent (M for cement mortar and R for epoxy resin); N the number of TRM or FRP layers; F the type of textile fibres material (C for dry carbon fibres, CCo for coated carbon fibres, BCo for basalt fibres and G for glass fibres); and T denotes the temperature at which the specimens were exposed (20 °C or 150 °C). For the specimens receiving U-jackets at their ends (Fig. 2b), an additional suffix (EA-End anchorage) is added to the notation. For example, 'M3_C_20' refers to a beam strengthened with 3 layers of dry carbon TRM and tested at 20 °C, whereas 'R3_C_EA_150' refers to a beam strengthened with 3 layers of carbon FRP, anchored at its ends using two layers of U-shaped jacket, and tested at temperature of 150 °C. It is noted that the axial stiffness of seven layers of glass or basalt-fibre textile are approximately equivalent to one layer of carbon-fibre textile. Table 1 gives the normalized axial stiffness of the textile reinforcement used in all specimens (normalized to one layer of carbon-fibre textile).

2.2. Materials and strengthening procedure

The beams were cast in four different groups using the same concrete mix-design. The concrete compressive and splitting