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Three-dimensional finite element modelling of the fire behaviour of insulated RC beams strengthened with EBR and NSM CFRP strips

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ABSTRACT

This paper presents numerical simulations of the fire behaviour of reinforced concrete (RC) beams flexurally strengthened with carbon fibre reinforced polymer (CFRP) strips installed according to the externally bonded reinforcement (EBR) and near surface mounted (NSM) techniques. Three dimensional (3D) finite element (FE) models of the beams were developed, in which the temperature-dependent thermo-physical and mechanical properties of the constituent materials was considered. The CFRP-concrete interaction was modelled by means of bi-linear bond-slip laws previously calibrated by the authors for different temperatures. Comparisons between numerical and previous experimental results confirmed the accuracy of the models in predicting the thermo-mechanical response of insulated CFRP-strengthened RC beams exposed to fire. The results obtained highlight the possibility of exploring the CFRP mechanical contribution in fire through a "cable" behaviour by applying a thicker insulation in the CFRP anchorage zones. Moreover, the numerical results confirmed the better fire performance of the NSM strengthening technique when compared to EBR: with the latter technique CFRP debonding occurred after considerably shorter periods of fire exposure and for much lower average temperatures in the adhesive in the anchorage zones, from $1.2 \times T_g$ to $1.4 \times T_g$, with such range being $2.4 \times T_g$ to $4.2 \times T_g$ for the NSM system.

1. Introduction

Fibre reinforced polymer (FRP) composites are being increasingly used in civil engineering applications thanks to the advantageous properties they present when compared to traditional materials, such as very high strength-to-weight ratio, resistance to electrochemical corrosion and ease of installation. Among the most common applications of FRPs in structural rehabilitation is bonding or wrapping carbon fibre reinforced polymer (CFRP) strips or sheets to the surface of reinforced concrete (RC) members with epoxy-based adhesives to increase their strength, stiffness, and/or deformation capacity; this strengthening technique is known as externally bonding reinforcement (EBR). More recently, a different technique, known as near surfaced mounted (NSM), in which the CFRP reinforcement (strips or bars) is inserted and bonded into slits saw cut in the concrete cover, has been successfully introduced. Due to the higher bonding area and the confinement offered by the surrounding concrete, this method has proved to provide higher mechanical efficacy when compared to the EBR technique [1–3].

Since the beginning of the development of CFRP strengthening techniques, attempts to apply these materials in buildings have been hindered due to concerns (and uncertainty) about the reductions in their mechanical and bond properties at elevated temperatures. In fact, CFRP systems exhibit poor performance when exposed to elevated temperatures, because both the CFRP materials and the bonding adhesives are made from organic polymers, which soften around their glass transition temperature (T_g), that usually ranges between 45 and 120 °C [4]. When those temperatures are attained, not only the mechanical properties of the constituent materials decrease, but also the bond between CFRP and concrete is reduced, thus significantly reducing the effectiveness of the strengthening system. Such elevated temperature range can be easily attained in several civil engineering applications for both service conditions (e.g., outdoor applications, roof structures) and accidental events, such as fire or blast explosions [5–7].

Therefore, considerable experimental research has been undertaken in an attempt to better understand the response of CFRP materials and CFRP-strengthened RC elements at high temperatures and under exposure to fire [8]. The existing studies concern-

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ing the CFRP-concrete bond at high temperatures (e.g., [9–14]) showed remarkable bond strength reductions for temperatures above (and often below) the adhesive T_g. Fire resistance tests performed on CFRP-strengthened beams (e.g., [5,15–23]) and slabs (e.g., [24–27]) confirmed the susceptibility of CFRP systems when subjected to elevated temperature, but showed also that remarkable fire resistances can be achieved if supplementary fire insulation is applied over the strengthening systems. Additionally, some of those investigations empirically found that the presence of cold anchorages, either by extending the CFRPs to cold regions [5,18,21,22] or by applying thicker insulation at their extremities [15,17,19,23,24], allows for a further extension of fire resistance. It was reported that during fire exposure the CFRP transforms into a "cable" fixed at its extremities, where the CFRP-concrete bond retains most of its strength (due to the aforementioned insulation strategy).

Notwithstanding the considerable fire endurances reported in the studies mentioned above (in some case more than 2 h, e.g., [5,20,22]), only a few studies have provided useful data regarding the stress-temperature dependence of CFRP systems at elevated temperatures [5,15,18,19,23], and the majority of them have studied EBR-strengthened RC members in bending (beams or slabs). It has also been found that loss of composite action seems to occur when the temperatures at the EBR-CFRP-concrete interface are in the range of the adhesive's T_g. Much less information is available concerning the fire performance of NSM strengthening systems and a systematic comparison of the fire performance of both strengthening techniques is still needed.

2. Previous numerical studies on the thermo-mechanical response of CFRP-strengthened RC beams subjected to fire

The numerical studies available in the literature about the simulation of the thermo-mechanical behaviour of CFRP-strengthened RC structural members subjected to fire are relatively scarce, likely as a consequence of the considerable complexities involved. Hawileh et al. [28] developed a 3D FE model using a commercial finite element (FE) software of the EBR-CFRP-strengthened T-section RC beams tested by Williams et al. [16]. Although the variation with temperature of the thermophysical and mechanical properties of the constituent materials has been considered, the failure of the strengthening system (owing to either delamination or adhesive degradation) was simulated using a simplistic element-killing procedure that was applied when: (i) the temperature in the CFRP exceeded 250 °C (based on [29]) and (ii) the shear stress at the CFRP-concrete interface exceeded 4.5 MPa (based on [30]). The model agreed well with experimental temperatures, however it was not possible to validate the numerical procedure in terms of mechanical response (namely the ability to accurately predict CFRP debonding) because reliable experimental data were available only for a short duration of testing.

Kodur and Ahmed [31] and Ahmed and Kodur [32] presented similar numerical procedures capable of simulating the thermo-mechanical response of RC beams strengthened with EBR-CFRP strips under exposure to fire. The models consider the temperature dependent material properties (namely those of the CFRP and adhesive) and after performing a 2D heat transfer analysis of the cross-section they use moment-curvature relationships to trace the mechanical response of the beams. The main innovation of the work presented in [32] was that the model explicitly simulates the bond degradation at the CFRP-concrete interface, particularly the bond-slip as a function of temperature (in [31] no bond degradation was considered). Failure is evaluated through any of the following criteria (instead of a rational structural functional objective): (i) the applied moment exceeds the beam's capacity; (ii) the temperature in the internal steel rebar exceeds 593 °C; (iii) the beam deflection exceeds $L/20$ (L being the span); (iv) the rate of beam deflection exceeds $L^2/9000d$ (mm/min), where d (in mm) is the effective depth of the beam (with L in mm); and (v) the temperature in the FRP layer exceeds T_g. In spite of the simplifying assumptions, good agreement with experimental data was generally obtained in terms of temperatures, deflections and time to beams' failure.

Kodur and Yu [33] extended the previous numerical model to predict the fire response of RC beams strengthened with NSM-FRP materials. The model includes the same features as above; the main difference is that failure is now evaluated based only on criteria (i), (iii) and (iv). The bond-slip relationship proposed by Sena-Cruz and Barros [34] is incorporated into the numerical model and its variation with temperature is assumed to follow test data reported by Palmieri et al. [20,35]. After the successful validation of their model, the authors performed a parametric study to evaluate the influence of: (i) the strengthening technique (NSM *vs.* EBR); (ii) the position of the strengthening element in the cross-section; and (iii) the use and geometry of a thermal insulation layer. Results obtained suggested that the NSM technique is likely to lead to higher fire resistances as compared with EBR.

Dai et al. [36] developed the only 3D FE model to date that simulates the thermal and structural behaviour of insulated EBR-FRP-strengthened RC beams exposed to fire, accounting for the bond degradation with temperature of both internal steel and external FRP reinforcement. The model was developed using a commercial package and, as the numerical procedures described above, it considers the temperature-dependence of the thermophysical and mechanical properties of all constituent materials. The bond-slip model for the concrete-steel reinforcement interaction suggested in Model Code 90 [37] for ambient temperature was implemented; reductions in bond strength and interfacial fracture energy (calibrated by Gao et al. [38]) were then incorporated to reflect the bond degradation at elevated temperatures. For the FRP-concrete interface, the bond-slip model developed by Dai et al. [14] was implemented, representing the most innovative feature of this study. These FE models provided accurate predictions of both thermal and structural responses obtained in tests reported in the literature [15,16]. The authors concluded that the fire resistance of insulated EBR-CFRP-strengthened RC beams can be overestimated if the CFRP-concrete bond-slip relationships are not considered.

More recently, Firmo et al. [39] simulated the thermo-mechanical response of EBR-CFRP strengthened beams subjected to fire and protected with different insulation schemes with a thinner layer along the bottom soffit of the beams and a thicker one in the CFRP anchorage zones. Two-dimensional (2D) FE models of the beams were developed using a commercial software, where the CFRP-concrete interaction was modelled by means of bi-linear bond-slip laws previously calibrated up to 120 °C [13]. The numerical results presented good agreement with the experimental data, in terms of temperature distributions and mechanical response, including the CFRP debonding phenomenon; this study also confirmed that it is possible to exploit the CFRP mechanical contribution through a cable behaviour when a thicker insulation is applied in the anchorage zones of EBR-CFRP strips. Moreover, it provided useful data to understand in further depth the structural effectiveness of EBR-CFRP strengthening systems during fire (namely, the strains/stresses in the materials and at the CFRP-concrete interface during fire exposure).

3. Research significance and objectives

Numerical investigations can be developed as a complement to relatively expensive and time-consuming tests, providing further