FIRE PROTECTION SYSTEMS FOR REINFORCED CONCRETE BEAMS STRENGTHENED WITH CFRP LAMINATES

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Summary: This paper presents experimental and numerical investigations on the fire behaviour of reinforced concrete (RC) beams flexurally strengthened with carbon fibre reinforced polymer (CFRP) laminates. The main objective was to assess the efficacy of different fire protection systems and to evaluate the viability of their use in floors of buildings. Fire resistance tests were conducted on an intermediate scale oven to investigate the behaviour under fire (ISO 834) of loaded CFRP-strengthened RC beams. The fire protection systems comprised calcium silicate boards and layers of vermiculite/perlite cement based mortar, with thicknesses of 25 mm and 40 mm, applied along the bottom soffit of the beams that was directly exposed to fire. In addition, the anchorage zones of the CFRP laminates were highly thermally insulated in order to evaluate the benefits of this particular constructive detail. Member deflection and temperatures throughout the midspan section were measured and recorded during the tests. When the strengthening system was left unprotected in the exposed length of the beam, the CFRP laminate anchorage debonded after about 23 min. When the above mentioned fire protection materials were applied in the exposed length of the beams, the fire resistance of the strengthening system varied between 60-89 min (25 mm thickness) and 137-167 min (40 mm). Two-dimensional finite element thermochemical models of all tested beams were also developed in order to predict the evolution of temperatures in the materials. The calculated temperatures compared reasonably well with those measured in the tests.

1 INTRODUCTION

Fibre reinforced polymers (FRPs) are being increasingly used in civil engineering applications due to their advantages over traditional materials, such as high strength, lightness and corrosion resistance [1,2]. One of the most common applications involves externally
bonding carbon fibre reinforced polymer (CFRP) laminates or sheets to reinforced concrete (RC), steel or timber members using epoxy resins [3].

CFRP strengthening systems are being essentially used in bridge structures, in which fire resistance is not usually a primary design consideration. For buildings, although CFRP systems also present great potential, widespread application is being delayed due to concerns regarding their performance at elevated temperature - several researchers have recently identified the fire behaviour of FRPs as one of the top priorities in terms of critical research needs [4,5].

The above mentioned concerns are legitimate since the organic matrix of FRPs decomposes when exposed to 300-500 °C, releasing heat, smoke, soot and toxic volatiles [6-9]. Furthermore, the strength, stiffness and bond properties of FRPs are severely deteriorated at moderately elevated temperatures [8-10], namely when approaching the glass transition temperature (T_g) of the polymer matrix, which is typically in the range of 65-120 °C. In particular, the bond between CFRPs and concrete, which is critical to maintain the effectiveness of the strengthening systems, is also severely reduced at temperatures above T_g.

Little research was reported in what concerns the bond between concrete and externally bonded FRP systems at high temperature. Single shear tests carried out by Gamage et al. [11-12] on CFRP-strengthened concrete members showed a rapid loss of strength when epoxy adhesive temperature increased beyond 60-70 °C. Similar results were reported by Klamer et al. [13] based on double lap shear tests and three-point bending tests. Based on temperature measurements and numerical simulation, Gamage et al. [12,14] suggested the use of vermiculite cement based mortar thermal insulation to extend the fire endurance of CFRP strengthening systems.

Regarding the performance of full-scale FRP-strengthened concrete members exposed to fire, studies reported in the literature are also relatively scarce [15]. Results of fire tests on FRP-strengthened RC beams [16-19], slabs [20-21] and columns [22] (some of which are discussed next in further detail) point out the need to develop adequate fire protection systems and confirm the effectiveness of using thermal insulation (passive protection) in extending the fire resistance of strengthened RC members. However, the degradation mechanisms and the definition of the actual “critical” temperature, above which the effectiveness of FRP strengthening systems is lost, remain unclear. According to Kodur et al. [23] the T_g of the bonding resin is a conservative lower bound of the actual critical temperature - for currently used epoxy adhesives the upper bound would probably be as much as 250-300 °C.

Williams et al. [18] investigated the fire performance of two CFRP-strengthened RC T-beams (3.9 m long, 0.4 m deep) protected with VG insulation (vermiculite/gypsum fire resistant lightweight cementitious plaster), applied on the lateral and bottom faces of the beams in thicknesses of 25 mm or 38 mm. The CFRP strengthening system (100 mm wide) was anchored at both ends with 600 mm wide GFRP U-wraps to prevent premature debonding. The specimens were exposed to ASTM E119 standard fire curve and subjected to a sustained uniformly distributed service load (48% of the failure load) applied to the top surface of the beam. Strengthened beams protected with both insulation thicknesses (25 mm and 38 mm) achieved 4 hours of fire endurance. In addition, the 38 mm-thick VG insulation maintained the
average FRP temperature below the matrix $T_g$ for 54 minutes and below the ignition temperature for more than 4 hours.

Deuring [16] tested a series of 5 m span externally-strengthened concrete beams (0.3 m deep, 0.4 m wide) under ISO 834 standard fire conditions. The beams were strengthened with CFRP strips, some of them being protected with a 40 mm thick calcium silicate (CS) board, and loaded to approximately 55% of their theoretical load capacity. The FRP-strengthened beam without protection achieved a fire endurance of 81 minutes, whereas an identical beam with a 40 mm thick CS board presented a fire endurance of 146 minutes.

Blontrock et al. [17] tested a series of 10 CFRP-strengthened RC beams, some of which were protected with U-shaped CS boards. The authors reported considerable reductions of temperature in the CFRP strip and steel reinforcement and, consequently, in the member deformation. The loss of composite action between the CFRP strip and concrete occurred when the strengthening material reached approximately 66 to 81 °C, which is in the range of the $T_g$ used in this system. According to the authors, when the insulation was applied only within the anchorage zones of the FRP, with the middle portion of the FRP left directly exposed to fire, the bond was preserved and the CFRP strip was able to maintain its contribution as tensile reinforcement during the test.

Burke et al. [24] also reported a similar behavior during an experimental program where they submitted near surface mounted (NSM) CFRP-strengthened concrete slabs at elevated temperatures. In this study, due to an error in the testing procedures, one specimen was inadvertently tested with approximately 50 mm of the bond unheated at the unloaded end. As a result, this specimen was able to hold the sustained load for a much longer period than the other identical strengthened specimens.

This paper presents further investigations on the fire behaviour of reinforced concrete beams flexurally strengthened with CFRP laminates [25]. The main objective was to study the viability of their use in floors of buildings and to assess the efficacy of different fire protection systems - in addition to insulating the bottom surface of the beams, the present study aimed at evaluating in further depth the potential beneficial effect of thermally insulating the anchorage zones of the strengthened beams. Dynamic mechanical analyses and differential scanning calorimetry and thermogravimetric measurements were first performed in order to determine the thermo-physical properties of the strengthening and fire protection materials. Subsequently, fire resistance tests were conducted to investigate the behaviour in a fire situation (simulated by the ISO 834 time-temperature curve) of loaded RC and CFRP-strengthened RC beams, unprotected and protected with CS boards and vermiculite/perlite (VP) cement based mortars. These tests investigated (i) the feasibility of applying the investigated fire protection systems to CFRP-strengthened RC beams, (ii) the thermal response, (iii) the mechanical response and (iv) the failure modes of the beams when exposed to fire, and (v) the fire resistance provided by the different fire protection systems. Finally, two-dimensional finite element thermochemical models of all tested beams were developed in order to simulate the evolution of the temperature fields.
2 EXPERIMENTAL INVESTIGATIONS

2.1 Test programme

Six fire resistance tests were conducted in an intermediate scale oven to investigate the fire behaviour of loaded CFRP-strengthened RC beams, either unprotected (beam CFRP) or protected with two different passive fire protection systems: CS boards and layers of VP mortar. The fire protection systems were applied on the bottom surface of the beams and consisted of 25 mm or 40 mm thick CS boards (beams CS25 and CS40, respectively) and 25 mm or 40 mm thick layers of VP mortar (beams VP25 and VP40, respectively). As a reference, an unstrengthened RC beam (beam RC) was also tested.

2.2 Fire protection materials

The CS board is made of agglomerated calcium silicate and has a dry density of $\rho = 870$ kg/m$^3$ and a thermal conductivity of $\lambda = 0.164$ W/mK. The VP mortar is composed of lightweight expanded vermiculite and perlite aggregates, refractory compounds and cementitious binders, mixed with water (0.67-0.80 l/kg), presenting a dry density of $\rho = 450-500$ kg/m$^3$ and a thermal conductivity of $\lambda = 0.0581$ W/mK. The above mentioned properties, reported in the technical sheet of the supplier [26], are at ambient temperature.

2.3 Strengthening materials

The CFRP laminates used as externally bonded reinforcement, with the commercial designation S&P Laminates CFK 150/2000, have a cross-section of 50 mm × 1.2 mm. This material is constituted by unidirectional carbon fibers (about 70% in weight) embedded in an epoxy resin matrix. The average tensile properties of the CFRP laminates, determined according to ISO 527 [27] by Dias and Barros [28], are as follows: tensile strength of $\sigma_{fu} = 2741.7$ MPa; Young’s modulus of $E_f = 170.9$ GPa; and ultimate strain of $\varepsilon_{fu} = 16.0$ %. The epoxy adhesive used to bond the CFRP laminates, with the commercial designation S&P Resin 220, is supplied in two components, mixed in a ratio of 4:1, both with a density of $\rho = 1750$ kg/m$^3$. Tensile tests performed on adhesive specimens according to ISO 527, reported in [25], provided average values of tensile modulus and strength of 8.8 GPa and 17.3 MPa, respectively.

Dynamic mechanical analyses (DMA) were performed on the CFRP laminate and on the epoxy adhesive, according to ISO 6721 [29], in order to determine their glass transition temperature ($T_g$). Experiments were performed on a Q800 dynamic mechanical analyzer from TA Instruments, using a dual-cantilever flexural test setup to impose the cyclic loads. Experiments were conducted on 3 CFRP specimens (60 mm long × 15 mm wide, 1.2 mm thick) obtained from sawing the laminate in the longitudinal direction, and on 3 epoxy adhesive molded specimens (60 mm long × 10 mm wide, 4 mm thick). Tests were run at a frequency of 1 Hz from about 25 °C to approximately 250 °C in air atmosphere, at heating rate of 2 °C/min. The values of $T_g$ were defined as being 138 °C and 54 °C for the CFRP laminate and the epoxy adhesive, respectively.
Thermogravimetric (TGA) and differential scanning calorimetry (DSC) measurements were performed on the strengthening materials as well as in the fire protection materials, according to ISO 11357 [30], in order to determine the mass variation and the energy changes as a function of temperature. Experiments were performed on a SDT2960 Simultaneous thermogravimetric analyzer from TA Instruments. Tests were run from ambient temperature (approximately 25 ºC) to about 1000 ºC, in air atmosphere, at a heating rate of 10 ºC/min. Based on the middle temperature of the sigmoidal mass change, the T_d of both the CFRP laminate and the epoxy adhesive was defined as being approximately 380 ºC.

2.4 Test specimens

The tested beams were 2.10 m long, 0.10 m wide and 0.12 m deep (Figure 1). The internal reinforcement consisted of four φ6 mm steel bars as longitudinal reinforcement and φ5 mm/0.06 m steel bars as transverse reinforcement. The CFRP laminate was installed in the bottom face of the beams according to the externally bonded reinforcement (EBR) technique. The laminate was 1.35 m long - such distance corresponded to the external width of the oven used in the fire resistance tests (Figure 2), guaranteeing that the anchorage zones were thermally insulated in a length of 0.20 m (thickness of the oven walls). In real applications, such insulation can be provided by inserting the CFRP laminates in the partition walls or by applying very thick insulation layers in the anchorage zones.

Four point bending tests (without thermal load) showed that this strengthening system provided a flexural strength increase of approximately 94%. The concrete mixture, incorporating limestone aggregates, was identical for all 6 beams and provided an average 28 day cube compressive strength of f_cm = 32 MPa. The steel reinforcement used presents an elasticity modulus of E_s = 200 GPa, a yield stress of f_sym = 542 MPa and an ultimate tensile strength of f_sum = 582 MPa.

In beams CS25 and CS40, the CS boards (1.40 m long × 0.10 m wide, 25 mm or 40 mm thick) were mechanically fixed to their bottom soffit using four U-shaped thin steel plates. These plates were fixed to the lateral faces of the beams with small metallic screws. For the application of the VP mortar (beams VP25 and VP40), a water content of 0.67 l/kg was used in the mixture and, to improve the adherence between the concrete and the VP mortar and also the mechanical resistance of the latter, a 0.10 m wide steel wire netting was fixed to the bottom surface of the beams with small metallic screws. The VP mortar was then cast and cured for a period of 20 days.

Figure 1: Geometry of the beams flexurally strengthened with a CFRP laminate (before the installation of the fire protection system).
2.5 Test setup, instrumentation and procedure

2.5.1 Oven

The fire resistance tests were performed on a vertical oven, with external dimensions of 1.35 m (length) × 1.20 m (width) × 2.10 m (height), which presents an opening on the top surface to test horizontal elements (Figure 2). The oven is fired by six gas burners controlled by a computer that reads the oven temperature from three internal thermocouples and is able to adjust the burners intensity in order to follow as closely as possible a predefined time-temperature curve. The burners are distributed by two facing walls of the oven, lined with ceramic wool, each one having three burners with a vertical spacing of about 0.60 m.

2.5.2 Beam supports and sealing of the oven

The tested beams were placed over the opened top of the oven, positioned along its length, with their axes aligned with the centre of the oven. In order to seal the lateral openings of the
oven, two mineral wool panels coated with a thin layer of intumescent paint and a total thickness of 0.10 m were placed adjacently to the beams (Figure 3) and fixed with fire resistant mastic. In the tests of beams CS40 and VP40 (40 mm thick protection), the above mentioned lateral sealing was complemented with two CS boards with a total thickness of 0.05 m. Consequently, in all tests, only the bottom face of the beams was directly exposed to heat – these test conditions actually simulate the behaviour of one-way slabs.

The beams were supported on rollers (8 cm long × 10 cm wide) placed over metallic plates, adjacent to the oven’s external walls. Those metallic plates were suspended with four φ24 mm steel rods on a steel reaction frame, which was erected surrounding the oven (see Figure 2). Beams were installed keeping a vertical distance of 3.5 cm between their bottom surface and the oven’s lateral walls in order to allow for the free deformation of the beams during the tests without touching the oven’s walls.

2.5.3 Fire loading

Fire resistance tests were performed with the fire exposure according to the ISO 834 [31] time–temperature curve,

\[ T = T_0 + 345 \times \log_{10}(8 \times t + 1) \]  

(1)

where \( T \) is the oven temperature (in °C), \( t \) is the time (in minutes) and \( T_0 \) is the initial oven temperature (in °C), which was approximately 20 °C.

2.5.4 Structural loading

All beams, with a 2.10 m length and a simply supported span of 1.5 m, were tested in four point bending. A total load of 10.2 kN (unstrengthened beam RC) or 16.3 kN (all 5 strengthened beams) was applied in two sections, positioned at a distance of 0.475 m from the support sections and symmetric relative to midspan (Figure 2). Load was applied by means of two sets of weights, suspended at the ends of a load transmission steel beam with pulley blocks (Figure 3), which guaranteed a constant load during the test. The load transmission beam, placed over
the tested beams, transferred the load to the top surface of the concrete beams through two tubular steel profiles, 10 cm high × 5 cm long. The applied loads correspond to a serviceability load of the beams tested, causing a midspan deflection of 1/250 of the span (about 6 mm).

2.5.5 Instrumentation

Deflection at midspan of all tested beams was measured with an electrical displacement transducer from TML model CDP-500 with 500 mm stroke (δ in Figure 2). In order to measure temperature distributions all tested beams were also instrumented with 8 thermocouples (type K), placed inside the concrete at midspan section (T1 to T6). In beam CS40 two additional thermocouples were placed at one of the anchorage zones of the CFRP laminate (TAE and TAI). Figure 4 shows a scheme of the thermocouples and their nomenclature.

![Figure 4: Position of thermocouples: midspan section of all beams (left) and anchorage zone of beam CS40 (right) (dimensions in cm).](image)

2.5.6 Test procedure

All tests started with the application of the structural loading. Measurements were performed for a period of about 30 min without starting the fire exposure, in order to guarantee a stabilization of deflections and deformations, although this condition was observed after a much shorter period of time. The fire exposure started with the ignition of the burners, after which specimens started to be thermally loaded according to ISO 834 time–temperature curve. Specimens were thermally loaded up to structural collapse or up to a maximum duration of 210 min, after which the burners were turned off.

In the tests of beams RC, CS25 and CS40, it was not possible to follow exactly the above mentioned test procedure - in fact, in those tests it was decided to extinguish the burners prior to collapse (and before 210 min) when the lateral sealing of the oven started to become less effective. However, it is worth mentioning that the lateral sealing was still completely effective when the strengthening system failed and the determination of its fire endurance was the main objective of these experiments.
3 FIRE RESISTANCE TEST RESULTS AND DISCUSSION

3.1 Temperature profiles

Figure 5 shows the temperatures measured as a function of the time at different depths of midspan section of both the unprotected beams (RC and CFRP) and the four protected beams (VP25, VP40, CS25 and CS40). In Figures 7b) to 7f), the instant corresponding to the failure of the CFRP strengthening system is marked. Table 1 lists for all strengthened beams (i) the time for the temperature at the CFRP-concrete interface (at midspan section) to reach the epoxy adhesive $T_g$ (54 ºC), (ii) the time for the CFRP strengthening system to fail (failure modes are discussed in 3.3.) and (iii) the average temperature at the CFRP-concrete interface (also at midspan section) at such instant.

Although experimental curves of the oven temperature ($T_{oven}$) do present some differences compared to ISO 834 curve ($T_{ISO}$), especially in the first moments of fire exposure (yet, well within the deviation bounds established in the test standard), in general, experimental curves approach quite closely the nominal curve. With the exception of thermocouple T5 in beam CS40 (that was damaged during the fabrication of the beam), all temperature measurements were successful.

In the unprotected beams (RC and CFRP), the bottom surface temperatures ($T_{1_{av}}$, average of thermocouples T1 and T1’) followed a similar pattern to that of the oven temperature, approaching it with increasing time. Temperatures throughout the cross section increased at a much slower rate. For the same time of exposure, temperatures reached in beam RC are higher than those measured in beam CFRP. This difference can be explained by a certain thermal insulation provided by the strengthening system in beam CFRP. In this latter beam, when the bond between the CFRP laminate and the concrete soffit was lost (after 23 min of exposure), the temperature at the bottom surface of the beam at midspan (414 ºC) was considerably higher than the $T_g$ of the adhesive; in fact, it was even higher than the $T_d$ of the adhesive.

For all strengthened beams with passive fire protection systems (beams VP25, VP40, CS25 and CS40), when compared to beam CFRP and considering the same duration of exposure, all temperatures throughout the cross sections present a quite significant drop, especially those at the bottom face. As expected, for both fire protection materials, thicker insulations were more effective in reducing temperature distributions and, consequently, in extending the fire endurance of the CFRP strengthening system. For both insulation thicknesses, the fire protection provided by the CS board at midspan section was slightly more effective during the first 60 min of fire exposure, after which temperature distributions at the CFRP-concrete interface became roughly similar. However, as discussed next, for both insulation thicknesses, the strengthening system of beams with VP protection maintained its effectiveness for considerably longer periods of time. This result may due to the fact that CS boards were not adhered to the soffit of the beams – due to the gaps, the thermal insulation along the edges may not have been as effective as in the centre. Further investigations are needed to confirm this possibility.
Results listed in Table 1 show that when the strengthening system failed the average temperature at the CFRP-concrete interface (midspan section) of beams with passive protection varied between 119 °C and 187 °C - this temperature range is well above the T_g of the epoxy adhesive. Thermocouples TAE and TAI installed along one of the anchorage zones of beam CS40 (c.f. Figure 4) indicate that when the bond between the CFRP laminate and the soffit of the concrete beam was lost, temperatures were 26 °C and 78 °C, respectively. Therefore, the average temperature along the insulated length (20 cm) of the CFRP laminate was 51 °C, which is roughly the T_g of the resin. These results confirm that the bond between the strengthening system and the beam was much less affected in a small length of the anchored zones, and may explain why the temperatures at midspan section of all strengthened beams were much higher than the T_g of the adhesive and the CFRP strengthening system was still effective.

Table 1: Time for the temperature at the CFRP-concrete interface at midspan section to reach T_g, time for the CFRP system to fail and corresponding average temperature at CFRP-concrete interface at midspan.

<table>
<thead>
<tr>
<th>Beam CFRP</th>
<th>Beam VP25</th>
<th>Beam VP40</th>
<th>Beam SC25</th>
<th>Beam SC40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time for the temperature at the CFRP-concrete interface (at midspan) to reach T_g [min]</td>
<td>1</td>
<td>24</td>
<td>24</td>
<td>17</td>
</tr>
<tr>
<td>Time for the CFRP strengthening system to fail [min]</td>
<td>23</td>
<td>89</td>
<td>167</td>
<td>60</td>
</tr>
<tr>
<td>Average temperature at CFRP-concrete interface (midspan section) when the CFRP system failed [°C]</td>
<td>414</td>
<td>176</td>
<td>187</td>
<td>119</td>
</tr>
</tbody>
</table>

3.2 Mechanical behavior

Figure 6 presents the midspan deflection variation of all tested beams as a function of time, where the origin of the time scale (t = 0 min) corresponds to the ignition of the burners.

In the unstrengthened beam (beam RC) the midspan deflection increased almost linearly until 50 min of exposure; subsequently, the deflection increase rate increased considerably, indicating that failure of the beam would be imminent. As already mentioned, due to the progressive loss of effectiveness of the lateral sealing of the oven during a late stage of this test (which also occurred in the tests of beams CS25 and CS40), the burners had to be extinguished prior to the beam’s collapse. The deflection in beam CFRP increased at a lower rate than in beam RC until the bond between the CFRP laminate and concrete was lost. At that moment, the midspan deflection suffered an instantaneous increase (due to the loss of stiffness), after which, the mechanical properties of beam CFRP became roughly similar to those of beam RC. As the applied load in the strengthened beam was higher, its failure happened after a shorter period of exposure. In the protected beams, as expected, the deflection increase rate was lower than that observed in beam CFRP (both before and after the failure of the strengthening system). As mentioned above, the temperatures registered in those
beams were considerably lower and so was the stiffness loss. Consequently, the CFRP-concrete bond was lost after a longer period of exposure.

Figure 5: Measured temperatures vs. time: a) beam RC; b) beam CFRP; c) beam VP25; d) beam CS25; e) beam VP40; f) beam CS40.
3.3 Fire resistance, failure modes and post-fire assessment

In beam CFRP, the strengthening system failed after 23 min of exposure. As presented in Figure 7a), the CFRP laminate debonded from the concrete at the left anchorage zone. Figure 7b) shows that at the right anchorage zone, in a length of approximately 20 cm, the strengthening system showed no visible signs of thermal degradation after the fire resistance test, owing to the additional thermal insulation provided by the oven walls (Figure 7c). As mentioned above, at midspan section of beam CFRP, where there was no thermal insulation, the temperatures exceeded the adhesive $T_g$ only after 1 min of exposure. Consequently, the bond between the laminate and the concrete was lost in an early stage of the test. Figure 7d) shows that the length of the CFRP laminate which was directly exposed to the thermal action was completely detached after the test. Figure 7 shows that the laminate in its heated length was transformed into a “cable” fixed at the anchorage zones, where the CFRP-concrete bond remained relatively undamaged. As temperatures increased, the stiffness properties of the beam deteriorated and, as a consequence, the beam deflection increased as well as the tensile force in the “cable”. The failure of the strengthening system occurred (after 23 min) when one of the anchorage zones lost its bond strength. After 1 hour of fire exposure, beam CFRP collapsed at midspan section due to tensile rupture of the steel bottom reinforcement, and the burners were then extinguished.
In all protected beams, the failure mode of the CFRP system was identical to that described for beam CFRP, but it took place after a much longer period of exposure: after 89 min and 60 min in beams VP25 and CS25, respectively; and after 167 min and 137 min in beams VP40 and CS40, respectively. As already mentioned, for similar insulation thicknesses, the VP mortar was more effective in protecting the CFRP strengthening system. In beams VP25 and VP40, collapse occurred at midspan section due to tensile rupture of the steel bottom reinforcement. In beam VP25, the loss of bond between the CFRP system and the concrete was immediately followed by the failure of the beam (tensile rupture of the rebars) at midspan section. This result must be attributed to the dynamic effect caused by the failure of the strengthening system – because the strengthening ratio was relatively high, the “residual” (unstrengthened) cross-section was not able to sustain the load transfer.

4 NUMERICAL THERMOCHEMICAL MODELLING

4.1 Description of the models

Two-dimensional (2D) finite element (FE) thermochemical models of all tested beams were developed, using commercial package ANSYS [32], in order to predict the evolution of temperatures within the cross-sections during the fire exposure. The FE models developed have the same geometry, configuration and dimensions of the specimens tested. However, the steel reinforcement bars were not modelled, due to their reduced influence in the evolution of temperatures in the CFRP-concrete interface, which was the region where the highest modelling accuracy was needed. A mesh of quadrangular finite elements with variable dimensions was defined. Smaller elements (maximum mesh size of 2.5 mm) were used to model the CFRP system, the protection materials and the air in beams CS25 and CS40, while bigger elements (maximum mesh size of 15 mm) were used to model the concrete near the
upper face of the beams. The mesh used in the FE models allowed to obtain nodal temperatures coincident with the thermocouples positions at midspan section (c.f. Figure 4). The mesh was created using mostly quadrilateral elements (triangular elements were used only in transition zones). As an example, Figure 8 shows the mesh used in the FE model of beam CS25.

![Figure 8: Finite element mesh and materials of beam CS25.](image)

The 2D element PLANE55 (2D thermal solid), with thermal conduction capacity, was used in the modelling of all materials. The surface element SURF151 (2D thermal surface effect) was also used - it can be associated to an extra node which simulates the heat transfer by radiation and convection between the beam and (i) the oven and (ii) the laboratory’s environment. Two extra nodes were considered in the model associated to the bottom and top surfaces of the beams: the one at the bottom simulated the ISO 834 time-temperature curve, while the one at the top defined a constant temperature of 20 °C (ambient temperature). The lateral surfaces were defined as adiabatic boundaries because they were thermally insulated. After thorough parametric studies, a better accuracy was obtained in the modelling of the unprotected beams (RC and CFRP) when a constant convection coefficient at the hot face of $h_c = 50$ W/m²K was considered, with the heat exchanges by convection and radiation at the cold face being neglected. On the other hand, in all protected beams (VP25, VP40, CS25 and CS40), a better accuracy was obtained when the temperature-time curve was directly applied to the hot face nodes and heat exchanges at the cold face were neglected.

The FE models took into account the variation of the thermal conductivity ($K$), specific heat ($C_p$) and density ($\rho$) with temperature of all materials – table 2 provides a listing of the thermal-physical properties at room temperature and their normalized properties with temperature are plotted in Figures 9 to 11. Thermo-physical properties were defined using bibliographic data [33-38], with the exception of the density of the CFRP and that of the fire protection materials, for which results of TGA experiments were used. It was considered that the adhesive properties followed the same relation with temperature that was defined for the CFRP material. The emissivity of both VP mortar and concrete [34] was considered as $\varepsilon = 0.7$, constant with temperature. For the CFRP laminate, based on [39,40], an emissivity of $\varepsilon = 0.875$ was adopted, also constant with temperature. For the CS boards material, based on
[41], the emissivity was considered as $\varepsilon = 0.75$ at $T = 20$ ºC and $\varepsilon = 0.95$ at $T = 1000$ ºC (linear variation).

Table 2: Thermal-physical properties at room temperature [33-38].

<table>
<thead>
<tr>
<th>Material</th>
<th>$C_p$ [J/Kg.ºC]</th>
<th>$K_o$ [W/(m.ºC)]</th>
<th>$\rho_o$ [Kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>900</td>
<td>1.642</td>
<td>2400</td>
</tr>
<tr>
<td>CFRP</td>
<td>1287</td>
<td>1.364</td>
<td>1550</td>
</tr>
<tr>
<td>Air</td>
<td>1005</td>
<td>0.026</td>
<td>1.2</td>
</tr>
<tr>
<td>VP mortar</td>
<td>712</td>
<td>0.058</td>
<td>500</td>
</tr>
<tr>
<td>CS board</td>
<td>687</td>
<td>0.164</td>
<td>870</td>
</tr>
</tbody>
</table>

Figure 9: Normalized specific heat vs. temperature for all modelled materials [32-37].

Figure 10: Normalized thermal conductivity vs. temperature for all modelled materials [32-37].

Figure 11: Normalized density vs. temperature for all modelled materials [32-37].

4.2 Results and comparison with experiments

Figure 12 shows the comparison between experimental (E) and numerical (N) temperatures as a function of time at different depths in all beams tested. Overall, the models provided a good estimate of the temperatures evolution in the beams - the global average errors varied between 12% and 21%.
In beam CFRP (Figure 12b) the calculated temperatures present a reasonable agreement with measured values, in particular for thermocouples $T_{1av}$ and $T_{2av}$. The time for the CFRP-concrete interface to reach $T_g$ was overestimated by the model (40 s against 198 s), but the calculated time for the CFRP-concrete interface to reach $T_d$ (1200 s) matched exactly the experimental measurement. As mentioned above, in the first moments of fire exposure, the nominal curve is steeper and therefore more difficult to be rigorously followed by the burners, which may explain the difference in estimating the time to reach $T_g$. In the other thermocouples located above in the cross section, the model slightly underestimated the measured temperatures – relative errors may stem from differences between the modelled and actual thermophysical properties of concrete. In beam RC (Figure 12a), although the agreement in thermocouples $T_{1av}$ and $T_{2av}$ was not as good as that obtained in beam CFRP, the average global error was very similar (21% in beam RC against 19% in beam CFRP).

In what concerns the protected beams (Figures 15c to 15f), the global errors were 19% and 13%, for beams VP25 and VP40, respectively, and 14% and 12% for beams CS25 and CS40, respectively. When compared to beams RC and CFRP, in the protected beams a better agreement was obtained for the thermocouples located at the upper part of the cross-section. However, at the CFRP-concrete interface ($T_{1av}$ and $T_{2av}$) the agreement was worse than that obtained in beam CFRP.

Numerical time-temperature curves obtained from the models of beams VP25 and VP40 increase almost linearly, while experimental curves have a more irregular behaviour – relative differences may stem from the fact that modelled properties may not accurately reproduce the sequence of dehydration reactions that took place in the VP material. Figures 12c and 12e show that at the end of the tests of beams VP25 and VP40, temperature increased at a higher rate than that measured during the earlier stages of the tests. This situation most likely stems from the thermal and physical degradation suffered by the lateral sealing and also from the lost of insulation capacity of the VP mortar itself. Consequently, the lateral faces of those beams were no longer adiabatic boundaries and the thermal insulation in the bottom face also decreased. This behavior was not modelled, which also helps explaining the relative differences between numerical and measured temperatures at that test stage.

In what regards beams CS25 and CS40, Figures 12d and 12f show that the experimental curves corresponding to thermocouple $T_{1av}$ are slightly above the corresponding calculated curves during almost the entire test duration. As for beams VP25 and VP40, such deviations are also likely to result from differences between actual and modelled thermophysical response of the materials (data from the literature was used). Consequently, in beam CS25 the predicted time for the temperature at the CFRP-concrete interface to reach $T_g$ was 830 s, instead of 1000 s observed in the fire resistance test of this beam. In beam CS40 those numbers were 1920 s and 2290 s, respectively.
Figure 12: Predicted and measured temperatures vs. time: a) beam RC; b) beam CFRP; c) beam VP25; d) beam CS25; e) beam VP40; f) beam CS40.
5 CONCLUSIONS

This paper presented the results of experimental and numerical investigations into the fire performance of loaded, intermediate-scale, RC beams flexurally strengthened with CFRP laminates. The anchorage of the CFRP strengthening system was highly thermally insulated in a length of 0.20 m – in practical applications, such insulation can be provided by applying very thick insulation layers in the anchorage zones or by inserting the CFRP laminates in the partition walls. Based on the results obtained, the following main conclusions can be drawn from this study:

1. The fire resistance test of the unprotected beam CFRP confirmed the susceptibility of externally bonded CFRP strengthening systems when exposed to high temperatures - although the anchorage zones of the laminate were thermally insulated by the oven walls in a length of 0.20 m, the CFRP laminate debonded after only 23 min of fire exposure.

2. When the strengthening system of beam CFRP failed, the average temperature at the CFRP-concrete interface (midspan section) was 414 ºC, which is considerably higher than the $T_g$ of the adhesive (about 54 ºC). Such difference must be associated with the above mentioned thermal insulation of the anchorage zones. In fact, when the strengthening system of beam CS40 failed, the average temperature in the first 0.20 m of the anchorage zone was 51 ºC.

3. The post-fire assessment of beam CFRP demonstrated that the CFRP laminate in its heated length transforms into a “cable” fixed at the anchorage zones, where the CFRP-concrete bond remained relatively undamaged. As temperatures increased, the overall stiffness of the beam deteriorated and, consequently, the beam deflection increased together with the tensile force at the “cable”. The strengthening system failed when one of the anchorage zones lost its bond strength.

4. In beam VP25, the failure of the strengthening system immediately triggered the collapse of the beam due to tensile rupture of the steel reinforcement - this failure mechanism was caused by the relatively high cross-section of the CFRP laminate used in these experiments, confirming the importance of limiting the strengthening ratio (a recommendation that is already given in most design documents).

5. Both protection materials, used together with the thermal insulation of the anchorage zones, allowed the CFRP strengthening system to be effective during a considerably longer period of fire exposure. Such extension of fire endurance, which increased for thicker protections, was obtained due to considerable reduction of the temperature fields, particularly at the concrete-CFRP interface. To some point, this result differs from previous observations made by Blontrock et al. [17].

6. For similar insulation thicknesses, the VP mortar was considerably more effective than the CS boards in protecting the CFRP strengthening system. For 25 mm of insulation, the VP mortar and the CS board provided 89 min and 60 min of protection to the CFRP system, respectively, while for 40 mm thick insulation, those figures increased to 167 min and 137 min.

7. Temperature distributions calculated by the finite element thermochemical models developed within this study compared reasonably well with measured data, as attested by the
average global relative errors that varied between 12% and 21%. Although there may be some inaccuracy in the modeling of the actual material properties used in the beams tested (most of the thermo-physical properties were modelled based on values from the literature), the models provided reliable results and useful information about the fire resistance of the tested beams. In the future, such models can be used for the selection and design of passive fire protection measures for RC beams flexurally strengthened with CFRP laminates.

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