FIRE PROTECTION SYSTEMS FOR REINFORCED CONCRETE BEAMS AND SLABS STRENGTHENED WITH CFRP LAMINATES

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Abstract
This paper presents experimental and numerical investigations on the fire behaviour of reinforced concrete (RC) beams and slabs flexurally strengthened with carbon fibre reinforced polymer (CFRP) laminates. The first part of this paper summarizes the main results obtained from fire resistance tests on loaded CFRP-strengthened RC beams with fire protection systems, which included relatively thin layers of calcium silicate boards or vermiculite/perlite cement based mortar applied along the bottom soffit of the beams; in addition, the anchorage zones of the CFRP laminates were highly thermally insulated and this constructive detail allowed extending considerably the fire endurance of the CFRP strengthening systems. The numerical study, described in the second part of this paper, included the development of (i) 2D finite element (FE) models of the tested beams, which were validated based on the agreement between calculated temperatures and those measured in the tests; and (ii) 3D FE models of CFRP-strengthened RC slabs, which were used to assess the efficacy of different fire protection system configurations, with particular relevance being given to the geometry of the thermal insulation applied at the anchorage zones.

Keywords: reinforced concrete; strengthening systems; carbon fibre reinforced polymer (CFRP) laminates; fire; anchorage zones; protection systems.

1. Introduction
One of the most common applications of fibre reinforced polymer (FRP) composites in civil engineering applications involves externally bonding carbon fibre reinforced polymer (CFRP) laminates or sheets to reinforced concrete (RC), steel or timber members using epoxy resins [1]. Such strengthening systems offer several advantages over traditional solutions, owing to their strength, lightness and corrosion resistance.

When CFRP strengthening systems are used in bridge structures, fire resistance is not usually a primary design consideration. For building applications, although CFRP systems also present great potential, widespread application is being delayed due to concerns regarding their performance at elevated temperature. In fact, the strength, stiffness and bond properties of FRPs are severely deteriorated at moderately elevated temperatures [2], namely when approaching the glass transition temperature (T_g) of the polymer matrix, which typically varies between 55 °C and 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.

Results of fire tests on FRP-strengthened RC beams [3], slabs [4] and columns [5] 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, presently, there are neither guidelines nor any reliable models able to design fire protection systems for FRP strengthened RC members. With this regard, in addition to heat transfer models developed by Williams [6], a 3D thermomechanical model (comprising a relatively simplistic interface failure criterion) by Hawileh et al. [7] and a recent comprehensive model by Ahmed and Kodur [8], very little research has been done.

This paper presents further experimental and numerical investigations on the fire behaviour of reinforced concrete beams and slabs flexurally strengthened with CFRP laminates. The main objectives were (i) to assess the potential beneficial effect of thermally insulating the anchorage zones of CFRP-strengthened beams and slabs; and (ii) to evaluate the influence of the geometry of the fire protection system at the anchorage zones in extending the fire endurance. The first part of this paper briefly describes previous experiments on CFRP-strengthened beams comprising fire protection systems applied along their bottom soffit with very high insulation at the anchorage zones (for full details, cf. [9,10]). The numerical study, described in the second part of this paper, included the development of (i) 2D finite element (FE) models of the tested beams, which were validated based on the agreement between calculated temperatures and those measured in the tests; and (ii) 3D FE models of CFRP-strengthened RC slabs, which were used to assess the efficacy of different fire protection system configurations, with particular relevance being given to the geometry of the thermal insulation applied over the anchorage zones.

2. Previous experimental study

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: calcium silicate (CS) boards and vermiculite-perlite (VP) based 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). An unstrengthened RC beam (beam RC) was also tested. The tested beams were 2.10 m long, 0.10 m wide and 0.12 m deep. The CFRP laminate (with a cross section of 50 × 1.2 mm) was installed in the bottom surface 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, 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. The aforementioned strengthening system provided a flexural strength increase of approximately 94%, which is higher than the limits established in most design recommendations (that normally indicate an upper limit ranging from 40% to 60% [1]); however, in several CFRP strengthening applications, namely those that are prior to the most recent design guidelines, the above mentioned limits were not respected.

All beams, with a simply supported span of 1.50 m, were tested in a four point bending configuration. A total load of 10.2 kN (unstrengthened beam RC, about 58% of its ambient temperature strength) or 16.3 kN (all 5 strengthened beams, about 47% of their ambient temperature strength) was applied (previously to the thermal loading). In all tests, only the bottom surface of the beams was directly exposed to heat in a length of 0.95 m; the lateral faces were thermally insulated with mineral wool/calcium silicate panels; the top face was exposed to ambient temperature – these test conditions actually simulate the behaviour of one-way slabs. The thermal loading followed the ISO 834 time-temperature curve (see figure 6a). Deflection and temperature distributions of all tested beams were measured at midspan.

Figure 1 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 beginning of the thermal loading. The
midspan deflection of 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 increased suddenly (due to the loss of stiffness), and 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 occurred after a shorter period of exposure. As expected, in the protected beams the deflection increase rate was lower than that observed in beam CFRP (both before and after the failure of the strengthening system). The temperatures registered in those beams (cf. section 4) were considerably lower and so was the stiffness loss.

Post-fire assessments (figure 2) showed that the heated length of the CFRP laminate transformed into a “cable” fixed at the anchorage zones (figure 2c), where the CFRP-concrete bond remained relatively undamaged (figure 2a and 2b). 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, which could be associated to the average temperature in such zones attaining the adhesive T_g.

Figure 1: Increase of midspan deflection vs. time [9].

Figure 2: (a) anchorage zone of CFRP laminate; (b) internal view of the thermal insulation provided by the oven walls; (c) CFRP laminate detached from RC beam [9].

3. Description of the models

3.1 Numerical model

Numerical models were developed with ADINA-T [11] software. A combination of the finite element and the finite difference methods were used to solve the time-dependent temperature field. This scheme involves two essential procedures: (i) a finite element space discretization to transform the first-order system of differential equations into an algebraic system of equations, and (ii) a finite difference time discretization to find the transient response. A non-linear transient simulation was used in all models in order to consider the thermal properties material variation with the temperature.

3.2 Models geometry and boundary conditions

3.2.1 2D model

2D FE thermal models were developed to simulate the evolution of temperatures within a cross-section and to compare numerical and experimental results obtained in beams CFRP and VP25. The FE models developed have the same geometry, configuration and dimensions of the corresponding beams tested. 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 studied region. Furthermore, the epoxy adhesive properties were assumed to follow the same relation with temperature that was defined for the CFRP material.
A mesh of quadrangular elements with nine nodes and maximum length side of 2.5 mm was defined (see figure 5 in Section 4). Transient temperature fields were calculated using a semi-implicit scheme (Crank-Nicholson method) and a time step of 10 seconds. The lateral surfaces were defined as adiabatic boundaries. For the hot face, the thermal boundary condition was established as being the temperature progression of the ISO fire curve, while the one at the cold face was defined as an adiabatic boundary, with an initial temperature of 20ºC (ambient temperature). After the validation of these models with the experimental results, the 2D geometry was generalised to 3D in order to study the efficacy of different fire protection system configurations at the anchorage zones.

3.2.2 3D model

3D models were developed to simulate the fire behaviour of an RC slab sector flexurally strengthened with CFRP laminates, namely to obtain the temperature distribution in a critical zone (anchorage) and to study the effect of the VP protection geometry, with particular attention being given to temperature evolution at the CFRP-concrete interface.

The RC slab sector is 5.20 m long, 0.50 m wide and 0.12 m deep. The CFRP laminate has a cross section of 50 × 1.2 mm and is 4 m long. Due to the double symmetry of the geometry, only a quarter of the slab was modelled (figure 3). The VP insulation has a general thickness of 0.02 m but, in the anchorage zones, its geometry was considered variable in the three space dimensions and the influence of parameters \(d_1\) and \(d_2\) (figure 4) was analysed. One study was carried out to obtain the influence of parameter \(d_1\) - the developed models were designated by \(S_2\), \(S_4\), \(S_4\_N\) and \(S_4\_D\). Another studied was carried out in order to obtain the influence of the parameter \(d_2\) - the models developed are denominated by S2, S4, S6, S8 and S10. Slab dimensions models are given in Table 1.

A mesh of 10 nodes tetrahedral elements was used in all models. The maximum side length of the elements was 0.05 m in concrete, 0.02 m in VP and 0.005 m in CFRP/adhesive (where the highest modelling accuracy was needed). The details of the slab meshes are given in Table 2. As in 2D models, transient temperature fields were calculated using a semi-implicit scheme (Crank-Nicholson method) and a time step of 10 seconds. The lateral surfaces were defined as adiabatic boundaries. For the hot face (identified in grey in figure 4), the thermal boundary condition was established as being the temperature progression of the ISO fire curve, while the one at the cold face was defined as an adiabatic boundary, with an initial temperature of 20ºC (ambient temperature).

### Table 1. Slab models dimensions

<table>
<thead>
<tr>
<th>MODELS</th>
<th>(d_1) (m)</th>
<th>(d_2) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>S4_N</td>
<td>0.02</td>
<td>0.04</td>
</tr>
<tr>
<td>S4</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>S4_D</td>
<td>0.06</td>
<td>0.04</td>
</tr>
<tr>
<td>S6</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>S8</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>S10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
</tbody>
</table>

(*) N and D stand for None and Double, respectively; the number following the slab identifies the protection width and height (in cm).

![Figure 3. A quarter of the modelled slab.](image3)

![Figure 4. VP anchorage protection system (Detail 1).](image4)
Table 2. Generated meshes on the 3D models (number of elements and nodes).

<table>
<thead>
<tr>
<th>NUMBER OF ELEMENTS</th>
<th>S2</th>
<th>S4_N</th>
<th>S4</th>
<th>S4_D</th>
<th>S6</th>
<th>S8</th>
<th>S10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>32 498</td>
<td>33 249</td>
<td>33 662</td>
<td>32 691</td>
<td>33 033</td>
<td>32 730</td>
<td>33 659</td>
</tr>
<tr>
<td>CFRP</td>
<td>15 090</td>
<td>15 090</td>
<td>15 090</td>
<td>15 090</td>
<td>15 090</td>
<td>15 090</td>
<td>15 090</td>
</tr>
<tr>
<td>VP</td>
<td>31 556</td>
<td>32 889</td>
<td>33 462</td>
<td>31 600</td>
<td>32 284</td>
<td>32 704</td>
<td>33 788</td>
</tr>
<tr>
<td>Total elements</td>
<td>79 144</td>
<td>81 228</td>
<td>82 214</td>
<td>79 381</td>
<td>80 407</td>
<td>80 524</td>
<td>82 537</td>
</tr>
<tr>
<td>Total nodes</td>
<td>111 199</td>
<td>114 153</td>
<td>115 460</td>
<td>111 414</td>
<td>112 803</td>
<td>112 995</td>
<td>115 933</td>
</tr>
</tbody>
</table>

Figure 5. Calculated temperature distribution after 60 minutes in (a) Beam CFRP and (b) Beam VP25.

Figure 6. Measured and predicted interface temperatures in (a) Beam CFRP and (b) Beam VP25.

4. Results and discussion

4.1 Verification of minimum protection in the span

In order to guarantee that the 2 cm thick VP protection within the span is enough to guarantee that the tensile strength of the CFRP laminate is not exceeded, a temperature verification was performed at the midspan of model S2 up to 120 minutes of fire exposure. Figure 7(a) illustrates the temperature distribution at the CFRP laminate’s centre, showing that after 120 minutes of fire exposure, temperature in the CFRP cross section is within the range 530-600°C. Therefore, according to Feih and Mouritz [12], after 120 min the CFRP laminate retains at least 45% of its ambient temperature tensile strength. Since the design recommendations limit the CFRP stress to 50% of its tensile strength, and the tensile stress installed in the CFRP in a fire situation is lower than that value (the applied load in a fire situation is similar to that applied in a
serviceability state), one can expect it not to break.

### 4.2 Influence of the VP protection basic geometry

Models S4_N, S4 and S4_D were developed to obtain the temperature distribution in the anchorage zone by varying $d1$ parameter from 0.00 m to 0.08 m. Figure 7(b) shows the temperature distribution in the anchorage length (20 cm, identified as $la$ in figure 4) along both the extreme (E, $z=0.025$ m) and middle (M, $z=0$) fibres after 120 min of exposure. Model S4 ($d1=0.04$ m), compared with model S4_N ($d1=0.02$ m), provided an average temperature reduction along the anchorage length that varied between 5.4% (middle fibre) and 5.8% (extreme fibre). Model S4_D ($d1=0.06$ m), compared with model S4, provided an average temperature reduction along the anchorage length that was lower, varying between 2.2% (middle fibre) and 2.2% (extreme fibre). Based on these results, it was decided to consider $d1=d2$ in the study conducted to analyse the influence of the VP protection depth at the anchorage zone ($d2$).

![Figure 7](image.png)

**Figure 7.** (a) Average temperature at the CFRP laminate depth at midspan as a function of time and (b) temperature distribution along the anchorage length after 120 min (M and E-middle and extreme fibres).

### 4.3 Influence of the VP protection depth

Models S2, S4, S6, S8 and S10 were developed in order to study the influence of the thermal insulation thickness of the anchorage zone (parameter $d2$) in the temperature distribution of the CFRP-concrete interface, particularly at the anchorage zone (located between $x=0$ and $x=0.2$ m). Figure 8 shows the numerical results obtained which indicate that, for the different fire exposures, the influence of the increased insulation thickness at the anchorage zone becomes negligible between $x=0.3$ m and $x=0.4$ m, depending on the insulation thickness. Models S6 to S10 ($d2$ varying between 0.06 m and 0.10 m) were able to maintain the average temperature at the interface below $T_g$ for 30 min, while only model S10 ($d2=0.10$ m) was able to guarantee such thermal insulation for 60 min.

### 4.4 Influence of the adhesive glass transition temperature

Numerical results were used to determine the time for the $T_g$ of the epoxy adhesive to be reached along the length of anchorage. In addition to the value $T_g=55$ °C (that corresponds to the adhesive used in the tests), two additional values of $T_g= 65$ °C and $T_g= 75$ °C were considered. Figure 9 and Table 3 show the results for each model and the corresponding thermal insulation durations.
Figure 8. Numerical results after (a) 30 minutes, (b) 60 minutes, (c) 90 minutes and (d) 120 minutes.

Figure 9. Time for the $T_g$ to be attained along the length of the anchorage for different models.

### Table 3. Time for the $T_g$ to be attained along the length of the anchorage for different models.

<table>
<thead>
<tr>
<th>Model</th>
<th>$T_g = 55^\circ C$</th>
<th>$T_g = 65^\circ C$</th>
<th>$T_g = 75^\circ C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2</td>
<td>7.3</td>
<td>8.5</td>
<td>9.8</td>
</tr>
<tr>
<td>S4</td>
<td>17.8</td>
<td>20.3</td>
<td>22.3</td>
</tr>
<tr>
<td>S6</td>
<td>30.8</td>
<td>35.3</td>
<td>39.3</td>
</tr>
<tr>
<td>S8</td>
<td>47.3</td>
<td>53.8</td>
<td>60.0</td>
</tr>
<tr>
<td>S10</td>
<td>66.3</td>
<td>75.3</td>
<td>83.5</td>
</tr>
</tbody>
</table>

5. Conclusions

Based on the results presented in this paper, the following conclusions can be drawn:

- The fire resistance tests on CFRP-strengthened RC beams showed that it is possible to attain considerable fire endurances, provided that adequate fire protection systems are used, including a thick thermal insulation of the anchorage zones.

- The numerical models developed were capable of predicting the thermal response of CFRP-strengthened beams with fire protection systems made of VP mortar. The models, which account for temperature-dependant material properties, provided reasonably accurate temperature distributions in the elements and, therefore, were used to optimize the fire insulation schemes in the anchorage zones.

- The numerical study showed that a 2 cm thick VP protection maintains the CFRP laminate temperature below 600ºC after 120 min of fire exposure. For such temperature, one can expect it to retain 45% of its ambient temperature tensile strength, which should prevent it from rupturing.
• Three numerical models were set up in order to access the influence of \( d1 \) dimension. It was verified that the section with the maximum temperature response occurred along the extreme fibres at \( x=0 \) cm. The model with \( d1=d2 \) provided a 20% temperature reduction compared to the model with \( d1=0 \) and its average interface temperature was only 8% higher than that of the model with \( d1=2 \ d2 \). Therefore, it was concluded that a cost-effective fire protection scheme should have \( d1=d2 \).

• Five numerical models were developed to evaluate the influence of \( d2 \) dimension. Models S6 to S10 (\( d2 \) varying between 0.06 m and 0.10 m) were able to maintain the average temperature at the interface below \( T_g \) for 30 min, while model S10 (\( d2=0.10 \) m) was able to guarantee such thermal insulation for 60 min. The model with maximum thickness protection (S10) caused a temperature reduction of 80% compared with the model with the minimum protection (S2).

• The numerical results described in this paper confirm the potential of fire protection systems in extending the fire endurance of CFRP strengthening systems used in RC beams/slabs, provided that adequate thermal insulation is applied at the anchorage zones.

6. References