Fire resistance behaviour of GFRP pultruded profiles

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Extended abstract

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FIRE RESISTANCE BEHAVIOUR OF GFRP PULTRUDED PROFILES

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Abstract: This paper presents experimental investigations on the behaviour of GFRP pultruded profiles exposed to fire. The feasibility and efficacy of using five different materials to provide fire protection to GFRP pultruded profiles were investigated. The experimental programme included differential scanning calorimetry and thermogravimetric analysis (DSC/TGA) experiments and fire resistance tests on GFRP tubular loaded beams. Fire resistance tests included different types of exposition to fire, regarding the number of surfaces exposed to heat, and different loading levels. The unprotected GFRP beam, exposed to fire only in one surface and subjected to a load corresponding to a midspan deflection of L/400, failed after about 36 min, while the five different passive protection systems provided a fire resistance between 51-83 min. The unprotected GFRP beam and one protected GFRP beam, exposed in three surfaces and subjected to the same service load, failed after about 8 and 46 min, respectively. An unprotected GFRP beam and one protected GFRP beam, exposed only in one surface and subjected to a load corresponding to a midspan deflection of L/250, failed after about 31 and 66 min, respectively. Failure occurred mostly in the upper part of the beams, due to compression and shear stresses.

Key-words: Glass fiber reinforced polymer pultruded profiles (GFRP), composite materials, experimental tests, behaviour of GFRP beams in a fire situation, fire protection systems.

1. Introduction

The most currently used material in civil engineering applications is reinforced concrete, which exploits the best features of steel and concrete materials. Fiber reinforced polymer (FRP) materials are being increasingly used in civil engineering applications due to their several advantages when compared to traditional materials, namely, the lightness, strength, good insulation properties, low maintenance and durability. At the same time, new design issues and challenges are inevitably encountered, among which are the legitimate concerns their performance when exposed to fire, especially in building applications [1].

When fiber reinforced polymer materials are exposed to moderate temperatures (100-200 °C), FRP materials soften, creep and distort, and such degradation of mechanical properties often leads to buckling failure mechanisms of load-bearing composite structures. When these materials are exposed to high temperatures (300-500 °C), the organic matrix decomposes, releasing heat, smoke, soot and toxic volatiles [2]. Glass is the most widely used reinforcement in FRP materials. For E-glass fibers, which are presently used in 80-90% of the commercially available FRP materials [3], softening and viscous flow start only when temperatures reach about 830 °C, and melting occurs at about 1070 °C [4].

Construction materials used in buildings are required to have adequate fire reaction behaviour, avoiding fire ignition, flame spreading and excessive smoke production and spreading. Additionally, structural elements are also expected to present sufficient fire resistance in order to prevent structural collapse under fire. Although these composite materials do not present
adequate fire reaction behaviour, composites are very good heat insulators, and this feature is important for slowing the spread of fire from room to room. Also when compared to steel, composites present better burn-through resistance, providing an effective barrier against flame, heat, smoke and toxic fumes. Furthermore, several measures can be applied to improve the fire performance of FRP materials [5].

Experiments reported by Wong et al. on the compressive strength of GFRP columns at high temperatures showed noticeable strength reductions already at 60 °C and 90 °C, with compressive strengths at those temperatures being 63% and 31%, respectively, of the ambient temperature strength [6].

Correia [7] investigated the behaviour of GFRP pultruded square tubular profiles exposed to fire. An unprotected GFRP beam, exposed only in one surface, failed after about 38 min, the three different passive protection systems provided a fire resistance between 65-76 min and the water cooling system provided a fire resistance of at least 120 min. In these tests the failure occurred in the upper part of the beams, due to compression and shear stresses.

Massot [8] investigated the behaviour of GFRP floors exposed to fire. An especially designed full scale test has been carried out on three beams laid adjacent to each other, loaded to rated stress during fire in three points bending. For comparison purpose, an equivalent steel flooring has been installed on the same oven, also loaded centrally to the same level. Load on the steel flooring has been withdrawn after about 15 min, due to slow sinking of the plate in fire. After that, steel flooring continued to sink under own weight. On the contrary, composite flooring sustained load all along the test which was stopped after 41 min, when smoke and flames began to propagate between beams.

The main objective of the experimental programme reported herein was to evaluate the fire resistance of GFRP beams and to evaluate the feasibility of different fire protection systems. The experiments were divided into three experimental series. In the first series seven beams were tested, two of them unprotected and five with fire protection systems, being exposed to fire only in one surface and subjected to a load corresponding to a midspan deflection of L/400. The second experimental series included three beams, two unprotected and one fire protected, all exposed in three surfaces and subjected to the same service load. The third series comprised two beams, one unprotected and the other with fire protection, both exposed to fire only in one surface and subjected to a service load corresponding to a midspan deflection of L/250. Differential scanning calorimetry and thermogravimetric analysis (DSC/TGA) tests were also performed. The DSC/TGA tests were performed to study the thermo-physical behaviour of both GFRP and fire protections materials at elevated temperature.

2. Materials

The GFRP material used in the fire experiments consisted of tubular pultruded profiles (100×100×8 mm) supplied and produced by Fiberline. This material is constituted by alternating layers of unidirectional E-glass fibre rovings and strand mats (69% in weight) embedded in an isophthalic polyester resin matrix. A dissection of a profile’s laminate showed that the rovings are positioned in the centre of the cross-section, while two mats are positioned next to the surface of the material, having continuity in the web-flange junctions.
Five different materials to be used as passive fire protection systems for GFRP pultruded profiles were investigated, namely, an agglomerated cork (AC) board, a rockwool (RW) board, a calcium silicate (SC) board, an intumescent mat (TEC) and an intumescent coating (TI). The AC board, produced by Robcork, is made of agglomerated cork. The RW board used in the experiments was produced by Rockwool and is constituted primarily by rock wool. The SC board, produced by Promatec (Type H), is made of agglomerated calcium silicate. The intumescent mat used in experiments (Tecnofire 60853A, thickness of 2 mm) was supplied by Technical Fibre Products Lda. The intumescent coating (C-THERM HB) was supplied by CIN.

2.1. DSC/TGA experiments

Differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) measurements were performed on the GFRP pultruded material and on the fire protection materials, in order to determine the mass variation and the energy changes as a function of temperature. These experiments allowed determining, in particular, the decomposition temperature of the polymer, \( T_d \). Experiments were performed at the Chemical Engineering Department of IST. Tests were run from a temperature of 30 ºC to about 800 ºC, in both air and nitrogen atmospheres, at heating rates of 5, 10, 15 and 20 ºC/min. Table 1 lists the experimental programme performed to study the thermo-physical behaviour of both GFRP and fire protection materials at high temperature.

<table>
<thead>
<tr>
<th>Material</th>
<th>Purge gas</th>
<th>Heating rate [ºC/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFRP</td>
<td>Air/Nitrogen</td>
<td>5, 10, 15 and 20 (in each atmosphere)</td>
</tr>
<tr>
<td>AC</td>
<td>Air/Nitrogen</td>
<td>10 (in each atmosphere)</td>
</tr>
<tr>
<td>RW</td>
<td>Air/Nitrogen</td>
<td>10 (in each atmosphere)</td>
</tr>
<tr>
<td>SC</td>
<td>Air/Nitrogen</td>
<td>10 (in each atmosphere)</td>
</tr>
<tr>
<td>TEC</td>
<td>Air/Nitrogen</td>
<td>10 (in each atmosphere)</td>
</tr>
<tr>
<td>TI</td>
<td>Air/Nitrogen</td>
<td>10 (in each atmosphere)</td>
</tr>
</tbody>
</table>

Results obtained from TGA measurements in air (GFRP-O) and nitrogen (GFRP-N) atmospheres are presented in Figure 1 (for the GFRP material) and allowed defining the decomposition temperature of the GFRP material at 370 ºC, based on the middle temperature of the sigmoidal mass change.

![Figure 1: DSC/TGA results in GFRP material: loss mass vs. temperature and heat flow/mass vs. temperature (O – Air; N – Nitrogen).](image-url)
The fire protection materials results obtained from TGA experiments in both atmospheres are presented in Figure 2. It can be seen that agglomerated cork presented a considerable mass loss, which is accompanied by the release of heat. Oppositely, rockwool presented a small mass loss releasing a small heat flow as well. Attending to TGA experiments, rockwool and calcium silicate were the two materials with better fire behaviour.

![Figure 2: DSC/TGA results in fire protection materials: loss mass vs. temperature and heat flow/mass vs. temperature (O – Air; N - Nitrogen).](image)

3. **Fire resistance test setup**

3.1. **Objectives**

Fire resistance tests were performed on loaded GFRP pultruded beams under a fire situation, either unprotected and protected with different fire protection systems, in order to determine the thermal response, the mechanical response, the failure modes and the fire resistance of the different systems. In particular, one aimed at evaluating the effects (i) applying fire protection materials, (ii) exposing the GFRP beams to 1 or 3 surfaces, and (iii) applying different load levels.

3.2. **Experimental programme**

Fire experiments were conducted in an oven and the experiments were divided into three experimental series. In the first series seven beams were tested, two of them unprotected and five with fire protection, being exposed to fire only in one surface (the bottom one) and subjected to a load corresponding to a midspan deflection of L/400. The second experimental series included three beams, two unprotected and one fire protected, all exposed in three surfaces (the bottom and the lateral) and subjected to the same service load. The third series was composed by two beams, one unprotected and the other with fire protection, both exposed to fire only in one surface and subjected to a service load corresponding to a midspan deflection of L/250. The five passive fire protection systems were applied on one surface (series 1 and 3) or three surfaces (series 2) and consisted of: (i) a 25 mm thick AC board (beam AC); (ii) a 25 mm thick RW board (beam RW); (iii) a 25 mm thick SC board (beams SC); (iv) a 2 mm thick intumescent mat layer (beam TEC); and (v) a 2 mm thick intumescent coating layer (beam TI). Table 2 presents the experimental programme performed.
The experimental programme included five unprotected beams, two of them with a cap (NPCT) and three without a cap (NPST). The cap was made in order to properly install thermocouples into the bottom and the lateral surfaces of the GFRP tubes. These beams (NPCT) were used only to measure temperatures, as they were not subjected to mechanical load.

### Table 2: Overview of fire resistance experiments.

<table>
<thead>
<tr>
<th>Experimental series</th>
<th>Specimen labelling</th>
<th>Fire protection</th>
<th>Fire exposure</th>
<th>Loading level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series 1</td>
<td>NPCT-1F</td>
<td>-</td>
<td>1 surface</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>NPST-1F</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>AC-1F</td>
<td>Agglomerated cork</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RW-1F</td>
<td>Rockwool</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SC-1F</td>
<td>Calcium silicate</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TEC-1F</td>
<td>Intumescent blanket</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TI-1F</td>
<td>Intumescent coating</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Series 2</td>
<td>NPCT-3F</td>
<td>-</td>
<td>3 surfaces</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>NPST-3F</td>
<td>-</td>
<td></td>
<td>L/400</td>
</tr>
<tr>
<td></td>
<td>SC-3F</td>
<td>Calcium silicate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Series 3</td>
<td>NPST-1F</td>
<td>-</td>
<td>1 surface</td>
<td>L/250</td>
</tr>
<tr>
<td></td>
<td>SC-1F</td>
<td>Calcium silicate</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 3.3. Specimen preparation

The preparation of the test specimens was carried out at IST and consisted of three main tasks: (i) cutting the GFRP profiles into the intended length (1.6 m); (ii) drilling holes at predetermined locations in the GFRP profile for installation of thermocouples; and (iii) application of the fire protection systems. In order to install the thermocouples for the measurement of temperature profiles throughout the GFRP tubes, 2.0 mm diameter holes were drilled at predetermined sections and depths in the tested beams at midspan section (see Figure 3). The thermocouples were then fixed with a polyester resin.

![Figure 3](image1.png)

**Figure 3:** Fire resistance tests setup – instrumentation at midspan section: (a) unprotected beams (series 1 and 3); (b) unprotected beam (series 2); (c) protected beams with protections systems (series 1, 2 and 3).

Figure 4 illustrates the thermocouples installation process in unprotected beams (NPCT (series 1) and NPCT (series 2)). In the unprotected beam from series 1 one cover was installed in the top surface, while in the unprotected beam from series 2 two covers had to be installed in the top surface and in one of the lateral surfaces.
Figure 4: NPCT (series 1) beams preparation: (a) removal of cover and (b) thermocouples installation process in bottom surface; NPCT (series 2) beams preparation: (c) thermocouples installation process in lateral and bottom surfaces and (d) sealing of the lateral cover.

Figure 5 illustrates the thermocouples installation process in protected and unprotected (NPST) beams.

Figure 5: Thermocouples installation process in (a) upper, (b) lateral and (c) bottom surfaces in protected and unprotected beams.

For the preparation of beams AC and SC, the AC and SC boards were fixed to the GFRP surfaces using a fire resistant mastic combined with mechanical system comprising thin metal handles. For the preparation of beam RW, the RW board was fixed to the GFRP surface using a mortar supplied by Rockwool. Figure 6 illustrates the preparation of these beams.

Figure 6: Preparation of beams (a) AC, (b) RW, (c) SC (series 1 and 3) and (d) SC (series 2).

For the preparation of beam TEC, the intumescent mat was cut with scissors and fixed to the GFRP surface using polyester resin (produced by Polyfix). For the preparation of beam TI, successive layers of intumescent coating were applied until the intended thickness of 2 mm was attained. Figure 7 illustrates the preparation of these beams.
3.4. Test setup, instrumentation and procedure

3.4.1. Oven

Fire resistance experiments were performed on a vertical oven, with external dimensions of 1,35 m long × 1,20 m wide × 2,10 m high, that presents an opening on the top surface to test horizontal elements (Figure 10). The oven is fired by six gas burners controlled by a computer, which reads the oven temperature from three internal thermocouples and is able to adjust the burners’ intensity in order to follow, as close as possible, a predefined time-temperature curve.

3.4.2. Fire loading

Fire resistance tests were performed with the fire exposure according to the ISO 834 [9] time-temperature curve, which is described by the following equation,

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

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

3.4.3. Test setup

In series 1 and 3, the tested GFRP profiles were placed over the opened top of the oven, positioned along its length. The top of the oven was covered with four modules, placed adjacently to the lateral surfaces of the GFRP profiles, as shown in Figure 8. Consequently, the lateral surfaces were protected from being directly exposed to the furnace heat and only the bottom surfaces of the profiles were directly exposed to heat.
The GFRP beams were supported on roller supports (12 cm long × 6 cm wide) placed over metallic plates, adjacently to the oven’s external walls. Beams were installed keeping a vertical distance of 5 cm between their bottom surface and the oven’s lateral walls, in order to allow for the deformation of the beams during the tests, without touching the oven’s walls, which was guaranteed in all tests.

In series 2, the top of the oven was covered with four modules, two of them in a high level, exposing the lateral surfaces of the GFRP profiles directly to the oven heat. Figure 9 illustrates the mentioned top cover of the oven used in the tests of series 2.

3.4.4. Structural loading

The GFRP beams, with a length of 1,60 m, were tested in four-point bending in a 1,30 m span. In series 1 and 2, a total load of 11,7 kN was applied in two sections, as shown in Figure 10, while in series 3 a total load of 18,7 kN was applied. Load was applied by means of concrete elements, suspended in a load transmission steel beam with pulley blocks, which facilitated the operations of loading/unloading. The applied loads of 11,7 and 18,7 kN, constant in all tests, corresponds to the serviceability load, for midspan deflections of L/400 and L/250, respectively, L being the span.

3.4.5. Instrumentation

One displacement transducers from TML (model CDP-500, with 500 mm stroke and precision of 0.01 mm), was used to measure deflections at midspan section, at the centre of the top surface. The beams were instrumented with sets of thermocouples type K, with twin wires enfolded by a thick glass fabric. As previously referred, the thermocouples were placed on holes drilled at predetermined depths and heights inside the GFRP profile. Temperatures throughout the top surface were measured with thermocouples T1–T3, placed at the depths of 2,0 mm (T1), 4,0 mm (T2) and 6,0 mm (T3), as shown in Figure 3. Throughout the lateral surface, temperatures were measured at a depth of 4,0 mm inside the material with thermocouples T4-T6, uniformly distributed across the height of the lateral surface. In the bottom surface of unprotected beams (NPCT), temperatures were measured with thermocouples T7 (at a depth of 1 mm), T8 (3,0 mm), T9 (5,0 mm) and T10 (7,0 mm). In the bottom surface of protected beams,
temperatures were measured with thermocouples T7 (at a depth of 0.5 mm), T8 (2.0 mm), T9 (4.0 mm), T10 (6.0 mm) and T11 (7.5 mm).

![Diagram of Fire resistance tests setup – frontal view (dimensions in meters).](image)

3.4.6. Test procedure

With the exception of unloaded beams, all tests started with the application of the structural loading. Following a recommendation of ISO 834 [9], measurements were performed for a period of 10 min without starting the fire exposure, in order to guarantee a stabilisation of deflections and deformations. 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 duration of 60 min in beams NPCT.

4. Fire resistance test results

4.1. Temperature profiles

4.1.1. Series 1

In the first series, to help comparing the fire resistance test results, average temperatures (T-m) for each surface were determined for all beams. Figures 11 and 12 show average the temperatures measured as a function of time at different depths inside the GFRP profile at the upper and lateral surfaces of midspan section, for both unprotected and protected GFRP profiles. Figure 12 also shows the progression of temperature of the air inside the oven for all tests of series 1.
In the unprotected beams (NPCT and NPST), the average temperatures followed very similar curves in each surface, increasing almost linearly with the exposure time and presenting the highest temperatures in this series. In beam NPST, the fire resistance test finished after 36 min of exposure, when the top surface attained the glass transition temperature ($T_g$), roughly 140 °C. The thermocouples placed throughout the bottom surface of beam NPCT did not seem to provide reliable temperature measurements taking into account the results obtained for the protected beams, as shown in Figure 12.

For the five beams with passive fire protection systems, when compared to the unprotected beams, and concerning the same duration of exposure, all temperatures throughout the GFRP profile present a quite significant drop, especially in beams AC, RW and SC. For the five beams (beams TI, TEC, AC, RW and SC) with passive fire protection systems, at the end of the fire exposure (after 51, 63, 75, 81 and 83 min), the average temperature of the top surface was near to $T_g$. Experimental curves of the oven temperature were in close agreement with the ISO 834 curve, as shown in Figure 12. Table 3 lists, for all tested beams in series 1, the average temperatures measured on the different surfaces of the profiles (top surface – FS, lateral surface – LS, and bottom surface – FI) at the end of fire exposure.
Table 3: Average temperatures at the end of fire exposure in each surface.

<table>
<thead>
<tr>
<th>Beam</th>
<th>Average temperatures at the end of fire exposure</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPST</td>
<td>131</td>
<td>289</td>
</tr>
<tr>
<td>AC</td>
<td>128</td>
<td>259</td>
</tr>
<tr>
<td>RW</td>
<td>136</td>
<td>217</td>
</tr>
<tr>
<td>SC</td>
<td>118</td>
<td>302</td>
</tr>
<tr>
<td>TEC</td>
<td>131</td>
<td>284</td>
</tr>
<tr>
<td>TI</td>
<td>145</td>
<td>272</td>
</tr>
</tbody>
</table>

4.1.2. Series 2

In the second series, to compare the fire resistance test results, average temperatures (T-m) for each surface were also determined, as mentioned previously. Figure 13 shows the temperatures measured at different depths inside the GFRP profile in midspan, as function of time, for both the unprotected and the protected GFRP profiles.

![Figure 13: Average temperatures measured at upper (T-m-FS), lateral (T-m-FL) and bottom (T-m-FI) surfaces and oven temperatures (T-oven) in series 2.](image)

In unprotected beam (NPCT), the average temperatures in both lateral and bottom surfaces followed very similar curves. In beam NPST, the fire resistance test finished after only 8 min of exposure. In this beam, the temperature measurements were not reliable, and were therefore discarded.

For the beam with passive fire protection system (beam SC), when compared to the unprotected beam (beam NPCT), all thermocouples throughout the GFRP profile presented a quite significant drop. In this protected beam, the fire resistance test finished after 46 min. In series 2, oven temperatures also followed those defined in the ISO 834 curve, as shown in Figure 13.

4.1.3. Series 3

In the third series, the average temperatures (T-m) for each surface were also determined, in order to compare the fire resistance test results. Figure 14 shows the temperatures measured at different depths inside the GFRP profile at midspan, as function of time, for both the unprotected and the protected GFRP profiles.
Figure 14: Average temperatures measured at upper (T-m-FS), lateral (T-m-FL) and bottom (T-m-FI) surfaces and oven temperatures (T-oven) in series 3.

For the beam with passive fire protection (beam SC), when compared to the unprotected beam (beam NPST), all thermocouples throughout the GFRP profile presented a quite significant drop. In beams NPST and SC, the fire resistance tests finished after 31 and 66 min, respectively.

4.2. Mechanical behaviour

4.2.1. Series 1

Figure 15 presents midspan deflections of all beams tested in series 1 as a function of time. Before fire exposure started, midspan deflection of the beams varied between 3.3 and 4.1 mm, which corresponds roughly to L/400 of the span (3.25 mm).

Figure 15 shows that during the first 30 s after burner ignition, midspan deflection of beam NPST remained constant. After 30 s of fire exposure, the unprotected beam suffered a rapid increase. However, only the beginning of the midspan deflection of beam NPST could be measured due to a problem in the connection of the displacement transducer to the data logger.

In the beams protected with passive systems, during most of the time of the tests, midspan deflection increased almost linearly with the exposure time, at variable rates among the different beams. At the end of the fire exposure, midspan deflection of protected beams suffered a rapid increase, as shown in Figure 15.
4.2.2. Series 2

Figure 16 presents midspan deflections as a function of time of beams tested in series 2, together with corresponding ones from series 1 to allow for a comparison between them. Before fire exposure started, midspan deflection of the beams varied between 2.5 and 3.6 mm, which corresponds roughly to L/400 of the span (3.25 mm).

![Figure 16: Midspan deflection vs. time in series 1 and 2.](image)

In beam NPST (series 2), after 20 s of fire exposure, the midspan deflection of the unprotected beam suffered a rapid increase, presenting a midspan deflection at a quicker rate comparing to beam NPST (series 1). For beam SC, midspan increase was similar for beams from series 1 and 2, most probably because unlike beam NPST from series 2, the lateral surfaces of beam from series 1 were thermally insulated.

4.2.3. Series 3

Figure 17 presents midspan deflections as a function of time of beams tested in series. Results obtained for corresponding beams from series 1 are also plotted to allow for a direct comparison. Before fire exposure started, midspan deflection of the beams varied between 6.3 and 6.8 mm, which is slightly higher than L/250 of the span (5.2 mm).

![Figure 17: Midspan deflection vs. time in series 1 and 3.](image)

In beam NPST (series 3), after 60 s of fire exposure, midspan deflection of the unprotected beam suffered a rapid increase, presenting a faster midspan deflection increase comparing to beam NPST (series 1). Beam SC (series 3) presented similar deflection increase compared to
beam SC (series 1) during most of the exposure, exhibiting only a much higher deflection variation at the end of its test.

4.3. Failure modes and post-fire assessment

All tested beams collapsed without any prior warning signs. The unprotected beam, exposed to fire in three surfaces, collapsed as a consequence of the resin softening in the lateral surfaces and presenting also a crack at the top surface, as shown in Figure 18.

![Figure 18: Beam NPST (series 2): (a) resin softening in lateral surfaces and (b) top surface cracked.](image)

The remaining beams collapsed due to compressive failure of the top surfaces and to shear failure of the lateral ones, as shown in Figure 19.

![Figure 19: Beams collapsed due (a) to compressive failure of top surfaces and (b) to shear failure of lateral surfaces.](image)

5. Discussion

5.1. Thermo-mechanical response

The evolution of both deflections and deformations is intrinsically related to the temperature variations throughout the depth of the GFRP profile during fire exposure and the consequent changes in the mechanical properties of the material.

The increase of deflections/deformations is attributed to the heating of the GFRP profile and the consequent loss of stiffness, which occurred cumulatively to the effect of the thermal elongation of the material. In the first series, the temperatures measured in the unprotected beam (NPST) were higher than those in the protected beams, therefore the former beam presented higher midspan deflections than the latter ones. The different heating rates observed in the protected beams and the consequent delay in loss of stiffness caused different midspan variations as a function of time.

In the second series, the heating of the unprotected beam (NPST), exposed to fire in three surfaces, induced a rapid increase of midspan deflection, causing a rapid structural collapse as well. Once again, temperatures measured in the protected beam were much lower than those in unprotected beam, and therefore not only its midspan deflections increase at a much slower rate but also it was able to sustain load for a much longer period.
In the third series, the temperatures of the tested beams followed very similar curves comparing to those tested in series 1. In this series, the midspan deflections of the tested beams were higher compared to series 1, due to the increase of the loading level, which caused them to fail for shorter periods of exposure to fire.

5.2. Temperatures and failure modes

For the seven beams tested in series 1, at the end of the fire exposure, the average temperatures of the top surfaces were similar to the glass transition temperature of the material determined from dynamic mechanical analyses (DMA), as shown in Table 3. In this experimental series, the tested beams collapsed without any prior warning signs, due to compressive failure of the top surface and to shear failure of the upper part of the lateral surfaces.

In the second series, the failure mode of beam NPST was different from the failure modes of the former beams. The unprotected beam collapsed as a consequence of the resin softening in lateral surfaces and presented a crack at the top surface. Due to difficulties in reliably measuring temperatures, it was not possible to associate the failure mode observed with material temperatures. The protected beam SC presented similar failure modes to that observed in series 1.

In the third series, at the end of the fire exposure, the average temperatures of the tested beams were lower than in those from series 1. As expected, collapse of the beams NPST and SC (series 3) occurred earlier than in beams NPST and SC (series 1), due to the increase of the loading level.

6. Conclusions

In spite of the smoothness of the GFRP profiles surfaces, all systems used as passive fire protection presented reasonable adherence to the bottom flange of the profile – therefore, from a technological point of view, it seems feasible to use those materials for the passive fire protection system of GFRP pultruded profiles.

All investigated fire protection systems were effective in reducing the temperatures throughout the depth of the GFRP profile, especially protection systems AC, RW and SC.

Under fire exposure, the GFRP pultruded profiles proved to be much more vulnerable under compression than under tension, which is a common feature of this type of materials. In all tests, although the bottom surface was submitted to temperatures well above $T_d$ for long periods of time, tensile failure of the bottom surface never occurred. Conversely, failure in most of the beams occurred due to compression of the top surface and to shear of lateral surfaces. Only unprotected beam, exposed to fire in three surfaces, collapsed as a consequence of the resin softening in lateral surfaces and presenting a crack at the top surface, thereby exhibiting a different failure mode.

For the GFRP tubular profile and fire protection systems used in the fire resistance tests, the comparison between the unprotected beam and the beams protected with passive systems, showed a significant correlation between: (i) the increase of fire resistance and (ii) the corresponding increase of time for the top surface to attain $T_g$.
The comparison between beams tested in series 1 and 2, showed a significant reduction of fire resistance owing to the increase of surfaces directly exposed to fire. In this study, as expected, fire resistance was also reduced, due to the increase of the loading level.

In terms of fire resistance, the beams NPST (series 1 and 2) were rated as REI 30, the beams TI and SC (series 2) were rated as REI 45 and beams AC, RW, SC (both series 1 and 2) and TEC were rated as REI 60. The above-mentioned fire ratings are valid for the simply supported tubular GFRP profile used in the present study.

7. **References**


