INTRODUCTION

As fibre reinforced polymer (FRP) materials are starting to be increasingly used in civil engineering applications due to their several advantages when compared to traditional materials (Keller 2003), new design issues and challenges are inevitably encountered, such as their long-term performance (Kharbari & al. 2003). Among these issues, there are legitimate concerns regarding the performance of FRP materials when exposed to fire, especially in building applications. 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. However, when FRP materials are exposed to high temperatures (300-500°C) their organic matrix decomposes, releasing heat, smoke, soot and toxic volatiles. Also when heated to moderate temperatures (100-200°C), FRP materials soften, creep and distort, and this degradation of the mechanical properties often leads to buckling failure mechanisms of load-bearing composite structures (Mouritz & Gibson 2006).

This paper presents results of an experimental study on the fire behaviour of GFRP pultruded profiles, whose main objective was to study the viability of their use in floors of building, as structural elements. The feasibility and efficacy of using different protective coatings/layers and a water cooling system to provide fire protection to GFRP pultruded profiles was investigated. Dynamic mechanical analysis (DMA) and differential scanning calorimetry (DSC) and thermogravimetric (DSC/TGA) measurements were first performed in the GFRP material and also in the fire protection materials in order to determine their thermo-physical and thermo-mechanical properties. Fire resistance tests were then conducted on an intermediate scale oven to investigate the behaviour of loaded GFRP pultruded beams in a fire situation (unprotected and protected), simulated by the ISO 834 time-temperature curve. These tests allowed to investigate the thermal response of the GFRP material when exposed to fire, the mechanical response and the failure modes of the beams under a simulated fire and the fire resistance of the beams with the different fire protection systems, allowing to define the field of application of each investigated solution, according to standards’ requirements.

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As fibre reinforced polymer (FRP) materials are starting to be increasingly used in civil engineering applications due to their several advantages when compared to traditional materials (Keller 2003), new design issues and challenges are inevitably encountered, such as their long-term performance (Kharbari & al. 2003). Among these issues, there are legitimate concerns regarding the performance of FRP materials when exposed to fire, especially in building applications.

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This paper presents results of an experimental study on the fire behaviour of glass fibre reinforced polymer (GFRP) pultruded profiles, whose main objective was to study the viability of their use in floors of building, as structural elements. The feasibility and efficacy of using different protective coatings/layers (intumescent coatings, calcium silicate boards and vermiculite/perlite based mortars, often used to protect structural steel) and a water cooling system to provide fire protection to GFRP profiles was investigated.

Dynamic mechanical analyses (DMA) and differential scanning calorimetry (DSC) and thermogravimetric (DSC/TGA) measurements were first performed in the GFRP material and also in the fire protection materials in order to determine their thermo-physical and thermo-mechanical properties.
Subsequently, fire resistance tests were conducted on an intermediate scale oven to investigate the behaviour of loaded GFRP pultruded beams in a fire situation (unprotected and protected), simulated by the ISO 834 time-temperature curve. These tests allowed to investigate (i) the feasibility of applying the investigated fire protection systems to GFRP pultruded profiles; (ii) the thermal response of the GFRP material when exposed to fire; (iii) the mechanical response and failure modes of the beams under a simulated fire; and (iv) the fire resistance of the beams with the different fire protection systems, allowing to define the field of application of each investigated solution, according to standards’ requirements.

2 MATERIALS

The material used in the fire resistance tests consisted of tubular pultruded GFRP profiles (100 mm × 100 mm, 8 mm thick) 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. The longitudinal flexural modulus (E_p = 31.0 GPa) and the shear modulus (G_p = 3.6 GPa) of the GFRP profile were determined in a full-scale three-point flexural test (Correia 2008).

In the fire resistance tests, the efficacy of three different materials to be used in passive fire protection systems was investigated, namely (i) a calcium silicate (CS) board; (ii) a vermiculite/perlite (VP) based mortar; and (iii) an intumescent coating. These materials were chosen because they have been successfully used in the past to protect structural steel. The CS board, produced by Promatec (Type H), is made of agglomerate calcium silicate, presenting a dry density of ρ = 870 kg/m³ and a thermal conductivity of λ = 0.164 W/mK (at ambient temperature). The VP mortar, produced by TRIA, is composed by 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 ρ = 450-500 kg/m³ and a thermal conductivity of λ = 0.0581 W/mK (also at ambient temperature). The solvent based intumescent coating used in the experiments (UNITHERM 38091) was produced by DuPont Performance Coatings and has a density of ρ = 1240 kg/m³, a solid weight of 69% and a volatile organic compound content of 400 g/l.

3 DMA AND DSC EXPERIMENTS

Dynamic mechanical analysis (DMA) experiments (ISO 6721) were performed in the GFRP pultruded material in order to determine the glass transition temperature, T_g, which marks the transition from a glassy state to a rubbery solid state, being associated with a material stiffness reduction. 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 2 specimens (60 mm long × 15 mm wide × 4 mm thick) obtained from sawing the tubular profile in the longitudinal direction. Tests were run from about -60ºC to approximately 250ºC in a nitrogen atmosphere at a heating rate of 2ºC/min. A strain amplitude of 0.05% was adopted. Results obtained for a dynamic oscillation frequency of 1.0 Hz are presented in Figure 1 and allowed defining the T_g at 140ºC (based on the peak value of the loss modulus curve) and the T_g,onset at 82ºC (based on the middle temperature of the sigmoidal change presented by the storage modulus curve).

Thermogravimetric (TGA) and differential scanning calorimetry (DSC) measurements (ISO 11357) were performed in the GFRP pultruded material and in the fire protection materials in order to determine the mass transition 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 on a SDT2960 Simultaneous thermogravimetric analyzer from TA Instruments. Specimens were produced by rasping the original material into powder (VP mortar and CS board) or by cutting them into small parallelepipeds (GFRP profile and intumescent coating), and placed in the oven inside a platinum pan. Tests were run from ambient temperature (approximately 25ºC) to about 1000ºC, in both air and nitrogen atmospheres, at a heating rate of 10ºC/min. Time, temperature, specimen mass and heat flow were measured and registered during the tests. One specimen was tested for each material and gas type. Results obtained from TGA measurements in air atmosphere are presented in Figure 2 (for both the GFRP
and the fire protection materials) and allowed defining the decomposition temperature of the GFRP material at 356°C, based on the middle temperature of the sigmoidal mass change.

Figure 1. DMA results for 1.0 Hz frequency: storage modulus and loss modulus vs. temperature.

Figure 2. TGA results in air atmosphere: remaining mass vs. temperature.

4 FIRE RESISTANCE TESTS

4.1 Experimental programme

Five experiments were conducted in a furnace in order to determine the fire resistance of GFRP beams, either unprotected or protected with three different passive fire protection systems and one active fire protection system.

The three passive fire protection systems were applied on the profile’s bottom flange and consisted of (i) a 2 mm thick intumescent coating layer; (ii) a 15 mm thick layer of VP mortar; and (iii) a 15 mm thick CS board. The active fire protection system consisted of a water circuit, in which a 0.11 l/s flow of water, controlled by a flow-rate meter, cooled the internal surface of the bottom flange. This type of fire protection system had already been successfully tested in GFRP pultruded slab panels (Keller et al. 2006).

4.2 Test setup

Figure 3 illustrates the test setup used in the fire resistance tests. The five GFRP beams, with a 2.00 m length, were placed on the top surface of a vertical furnace (external dimensions, 1.35 m long × 1.20 m wide × 2.10 m high), whose burners are controlled by a computer, which reads the furnace temperature from internal thermocouples and is able to adjust the burners intensity in order to follow the ISO 834 time-temperature curve as close as possible. Two mineral wool panels were placed adjacent to both webs of the GFRP profile, protecting them from being directly exposed to the heat. Therefore, only the bottom flange of the profile was directly exposed to heat.

The supports of the GFRP beams were placed adjacent to the furnace external walls, on the top of metallic plates, which were suspended on a reaction frame with four steel rods. The GFRP elements were tested in four-point bending in a 1.51 m span. A total load of 8 kN was applied in two sections, 0.55 m apart and symmetric relative to midspan, by means of two water containers suspended in a load transmission steel beam. The applied load corresponds to the serviceability load, for which the midspan deflection is considered to be 1/400 of the span, about 3.8 mm. The above mentioned load value was defined in a flexural test performed in a beam from the same batch of those used in the fire resistance tests, with the same span and load arrangement.

At midspan section (section S4), deflections were measured with a 500 mm stroke displacement transducer and longitudinal strains at the top flange were measured with strain gauges. At a distance of 5 cm from midspan section (section S5), the beams were instrumented with sets of thermocouples type K, placed on holes drilled at predetermined depths and heights inside the GFRP profile and fixed with a polyester resin.
4.3 Results and discussion

Figures 4 and 5 show the temperature profiles evolution at midspan section of the unprotected profile and the CS board protected profile, respectively. In the unprotected profile, it can be seen that the centre of the bottom flange attained $T_g$ after about 90 s and reached $T_d$ after approximately 260 s, while the centres of the web and the top flange attained $T_g$ after 1720 s and 1940 s, respectively. In the CS board protected profile, it can be seen that, for the same fire duration, temperatures in the GFRP profile were significantly lower: the bottom flange centre attained $T_g$ only after about 600 s and reached $T_d$ after 1370 s; the centres of the web and the top flange attained $T_g$ only after 2650 s and 3650 s, respectively.

Overall, when compared to the unprotected profile, all fire protection systems led to a considerable drop of the temperatures throughout the depth of the GFRP profile. While the passive fire protection systems led to higher downfalls of bottom flange temperatures, the water cooling system provided much higher temperature reductions at both the webs and the top flange.

Figure 6 presents the midspan deflection of all tested beams. During the first 8-10 min after furnace ignition ($t = 0$ s), midspan deflection of all beams suffered a rapid increase, especially in...
the unprotected and water-cooled beams. Subsequently, in the unprotected beam, midspan deflection continued to increase (but at a lower rate) up to failure, which occurred 38 min after furnace ignition, therefore being classified as REI 30 according to the European classification system (EN 1363-1). In the three GFRP beams protected with passive systems, after the initial period of rapid deflection increase, midspan deflection stabilized for a certain period (which was longer for the beams protected with the intumescent coating and the VP mortar), after which it increased again quite rapidly up to failure. In all these beams protected with passive systems, failure occurred between 65-75 min (REI 60) after furnace ignition. In the water cooled beam, after the initial deflection increase, midspan deflection stabilized and exhibited only a very slow and almost linear increase. Test was interrupted after 120 min, and the beam did not collapse, therefore, being rated as REI 120 (at least). Figure 6 presents also the field of application of the tested beams according to the Portuguese regulation for fire safety in residential houses (Coelho 1998). Considering the fire resistance requirements for beams and slabs, it is shown that the unprotected solution can be only used in buildings up to 3 storeys. All solutions with passive fire protection systems can be used in buildings up to about 9 storeys, while the water cooling system can be used regardless of the number of storeys. Figure 7 presents, for all tested beams, the axial strains of the top flange measured at midspan section (average value from the two strain gauges), which present a similar tendency to the corresponding midspan deflection curves, both being intrinsically related to the temperature variations throughout the depth of the GFRP profile during fire exposure and the consequent changes in the mechanical properties.

Regarding the failure modes, the unprotected beam (Fig. 8) and the VP mortar protected beam presented a top flange compressive failure in the vicinity of midspan section, while the CS board and the intumescent coating protected beams presented a web compressive failure under the applied load (Fig. 9 shows the failure sequence of the beam protected with the intumescent coating). Tensile failure of the bottom flange did not occur in any case, although temperatures in the bottom flange were much higher than those observed in the top flange/upper part of the web.

Figure 6. Midspan deflection vs. time. Figure 7. Top flange axial strains vs. time.

Figure 8. Unprotected GFRP beam: top flange compressive failure in the vicinity of midspan. Figure 9. Failure sequence of the beam protected with the intumescent coating under the applied load section.
5 CONCLUSIONS

The following main conclusions can be drawn from this study:

1. In spite of the smoothness of the GFRP profile’s surfaces, all systems used as passive fire protection presented a reasonable adherence to the bottom flange of the profile. Therefore, from a technological point of view, it seems feasible to use those materials, usually applied to protect steel structures, for the passive fire protection system of GFRP pultruded profiles.

2. All investigated fire protection systems were effective in reducing the temperatures throughout the depth of the GFRP profile. The passive fire protection systems were more effective in protecting the bottom flange, while the water cooling system provided the lowest temperatures at the webs and top flange.

3. 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 flange was submitted to temperatures well above $T_d$ for long periods of time, tensile failure of the bottom flange never occurred. Conversely, failure always occurred due to compression, precisely where temperatures were lowest: either at the top flange, in the vicinity of midspan, or at the upper part of the webs, under the applied load sections.

4. Although the number of performed experiments was rather limited, the comparison between the unprotected beam and those protected with passive systems showed a significant correlation between the fire resistance increase ($\Delta FR$) and the corresponding increase of the time to attain $T_g$ ($\Delta t$) at the top flange. In fact, the relative differences between the fire resistance increase and the increase of the time to attain $T_g$ at the top flange [(AFR-$\Delta t$)/AFR] were 7.3% (CS board protected), -11.4% (VP mortar protected) and -8.4% (intumescent coating protected).

5. In terms of fire resistance, the unprotected GFRP profile collapsed after 38 min of fire exposure and was consequently rated as REI 30. The passive fire protection systems guaranteed a fire resistance of 65-76 min (REI 60), which corresponds to an increase of 27-38 min relatively to the unprotected profile. The water cooling system guaranteed a fire resistance of at least 120 min (REI 120).

6. Consequently, with regard to the fulfilment of fire resistance requirements, and according to the Portuguese fire safety regulation for residential houses, the unprotected GFRP profile can be used in residential houses up to 3 storeys; all solutions with passive fire protection systems can be used in buildings up to 9 storeys; and the water cooled solution can be used regardless of the number of storeys.

Numerical investigations are currently being undertaken in order to simulate the fire resistance tests. In parallel, the fire reaction behaviour of the material (both protected and unprotected) was also experimentally investigated (Correia 2008), in order to assess the fire reaction properties of the GFRP material (such as the ignition time, the rate of heat release, the smoke and toxic gas evolution), to measure the benefit of using the different fire protection systems on those properties and to define the fire reaction related restrictions for building applications.

6 REFERENCES