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Experimental study on the fire resistance of GFRP pultruded tubular columns

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ABSTRACT

This paper presents experimental investigations about the fire behaviour of GFRP pultruded columns with square tubular cross-section. The objectives of the study were to evaluate (i) the efficacy of passive (calcium silicate (CS) boards) and active (water-cooling) systems in providing fire protection to GFRP pultruded columns; and the effects of (ii) the number of sides exposed to fire; and (iii) the service load level on the GFRP columns' fire response. To this end, fire resistance tests were performed on 1.5 m long GFRP columns, subjected to two different load levels corresponding to axial shortenings of $L/1500$ and $L/750$ (L being the span), and simultaneously exposed to fire, in either one or three sides, according to the time–temperature curve defined in ISO 834. Results obtained were analysed regarding the thermal and mechanical responses of the GFRP columns (unprotected and protected), namely in terms of the evolution of axial and transverse displacements, the failure modes and the fire resistance. It was possible to conclude that for one-side exposure, water-cooling is the most effective protection, particularly with flowing water, providing more than 120 min of fire resistance. For three-sides exposure, the fire resistance of the different solutions tested was severely reduced, namely that of the water-cooling systems, which provided fire resistances of only about 20 min, regardless of using flowing water; for this type of exposure, the best performance was provided by the CS board protection, with about 40 min of fire resistance. The results obtained in this study draw the attention to the technical advantages of adopting a building architecture in which the GFRP columns are integrated in the façades and embedded in partition walls, preventing the columns from being exposed to fire in three sides. As expected, the load level increase caused a reduction of fire resistance, due to the higher stresses developed in the sections' walls and to the GFRP strength decrease with temperature.

1. Introduction

Glass fibre reinforced polymer (GFRP) pultruded profiles are finding an increasing interest for civil engineering applications, in both new construction and rehabilitation. When compared with more traditional materials, the main advantages of GFRP pultruded profiles are the lightness, the ease of installation, the non-corrodibility and the reduced maintenance requirements. In opposition, their most important drawbacks are the relatively high initial costs, the reduced elasticity modulus and the behaviour at elevated temperatures, which raises legitimate concerns, particularly for building applications [1].

In fact, modern codes specify requirements for the fire reaction and fire resistance behaviour of construction materials used in different parts of a building. In particular, materials must present adequate fire reaction behaviour, avoiding fire deflagration, flame spreading and excessive smoke production and spreading. Additionally, structural elements are also expected to present sufficient fire resistance, depending on the building type and geometry, in order to prevent structural collapse under fire and allow for the safe evacuation of occupants [2].

When fibre reinforced polymer (FRP) materials are exposed to high temperatures (300–500 °C), their organic matrix decomposes, releasing heat, smoke, soot and toxic volatiles [3,4]. Also when heated to moderate temperatures (100–200 °C), the stiffness and strength of FRP materials are remarkably reduced [5,6], particularly in what regards the properties that are more matrix-dependent, *i.e.* in compression and shear [7,8], which are more affected that those in tension [5,6].

The fire behaviour of GFRP pultruded profiles is critical for their widespread acceptance. Despite all the accomplished advances in the last decades on the numerical simulation of structural models, the study of this problem still remains a considerable challenge,

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involving heat transfer, fluid dynamics, radiation between the walls of closed cavities and physically and geometrically nonlinear structural analysis. Moreover, the thermal and mechanical material properties are anisotropic and nonlinearly dependent on the temperature. Therefore, at the present stage, it is natural to resort to experimental tests. Even so, there are only a few experimental studies at a full-scale level reported in the literature about this issue, most of which addressing the response of horizontal members, either floor/deck panels [9–11] or beams [12]. These studies have shown that GFRP horizontal members, when exposed to fire from the bottom, are able to sustain service loads for relatively long periods, even without any fire protection (30–60 min of fire resistance were reported). This is basically due to (i) the high residual strength in tension (the stress state in the side exposed to fire for members in bending), provided that the glass fibres remain anchored/unexposed at the support sections, and (ii) the low thermal conductivity of GFRP. In fact, failure of such members was generally seen to be triggered in their upper side, due to compressive stresses. With passive (coatings, boards) [12] and active (water-cooling) [10–12] protection, fire resistance increased considerably, with ratings of 60–120 min being attained.

Although GFRP material properties in compression are much more susceptible to elevated temperature than those in tension, there are only a few studies in the literature about the response of intermediate- or full-scale GFRP pultruded columns subjected to fire or elevated temperature [13–15]. These studies are described next.

Wong and Wang [13] performed compressive tests on pultruded GFRP channel (100 mm × 40 mm × 4 mm) columns with different lengths (500 mm, 900 mm and 1350 mm) and rotational restraints (around the minor and major axis) at temperatures varying from 20 °C to 120 °C. At the maximum tested temperature of 120 °C, the strength of the shorter columns was significantly reduced (40% retention for minor axis tests), whereas that of the medium length and longer columns was either moderately affected (strength retentions of 62% and 66%, respectively) or remarkably affected (26% and 38%), for minor axis and major axis tests, respectively. For minor axis tests, all columns failed due to global buckling. For major axis tests, the longer columns failed due to buckling, while the shorter columns collapsed due to a combination of buckling and material crushing. The authors attributed the different rates of strength reduction with temperature to the different failure modes for varying column lengths, arguing that the reduction in compressive strength of the GFRP material with temperature should be faster than that experienced by the compressive stiffness.

Bai and Keller [14] studied the efficacy of using internal water-cooling to provide thermal protection to 300 mm long GFRP pultruded tubes (outer diameter of 40 mm, wall thickness of 3 mm). Water-flow rates of 8 cm/s and 20 cm/s (average speed in the cross-section cavity) were used (slightly higher than those used in the mentioned deck panels [10,11]). Specimens were loaded up to different fractions of the serviceability load (50%, 75%, and 100%) and then exposed to elevated temperature using a thermal chamber set to a target temperature of 220 °C and heated at a rate of 5 °C/min. For the test conditions used in this study, it was shown that water-cooling was very effective in improving the fire endurance of GFRP columns. The authors also concluded that, differently from what had been observed in deck panels with higher wall thickness (15 mm, [11]), the efficacy of water-cooling in GFRP columns with low thickness walls is highly dependent on the water flow. In fact, for the columns subjected to the full service load, the following times to failure were obtained: 7 min without protection, 72 min with the lower flow-rate, and 164 min with the higher water-flow rates.

Bai et al. [15] then investigated this water-cooling concept on full-scale GFRP columns, loaded and exposed to fire from one side. Two columns with multi-cellular cross-section (195 mm high, flange thickness varying between 15.2 and 17.4 mm), 2805 mm of length and 609 mm of width, were subjected to an axial load of 145 kN (causing a relatively low axial stress of about 5 MPa) and then exposed to the ISO 834 fire curve. One column was tested without protection and the other was protected with water-cooling (2.5 cm/s). The unprotected column failed after 49 min due to a global buckling mechanism, which, according to the authors, was most like caused by a series of preceding local failures. The protected column was able to sustain the applied load for 120 min without collapsing. The authors acknowledged the contribution of the multicellular cross-section for these positive results: in fact, since it comprised 4 cells, the 3 inner webs were prevented to heat more rapidly, as they were not directly exposed to heat.

The pioneering studies reviewed above, although providing very relevant information, do not allow for a complete understanding about the fire response of GFRP pultruded columns. Only the study of Bai et al. [15] was performed for actual fire exposure conditions (the maximum temperatures in the preceding works of Wong and Wang [13] and Bai and Keller [14] were below the glass transition and decomposition temperatures of GFRP, respectively). In addition, in the study of Bai et al. [15] the exposure conditions were relatively favourable, not only due to the multi-cellular geometry, but also because the columns were exposed to fire only in one surface. Finally, none of the studies reported above investigated the effect of using passive fire protection, which was seen to be effective in extending the fire endurance of GFRP pultruded beams [12].

This paper presents results of an experimental study about the fire resistance behaviour of GFRP pultruded columns with square tubular cross-section. The main objective was to study the viability of their structural use in buildings. The efficacy of (i) applying calcium silicate boards, and (ii) using water-cooling systems, with either stagnant or flowing water, in providing fire protection to GFRP columns was investigated. The effect of exposing the columns to fire in either one or three faces was also assessed, as well as the effect of varying the service load.

2. Experimental programme

2.1. Materials

The GFRP pultruded profiles used in the fire resistance tests have a square tubular cross-section – 100 mm × 100 mm, 8 mm thick – and were produced by *Fiberline*. The profiles are constituted by an isophthalic polyester resin matrix reinforced with alternating layers of unidirectional E-glass fibre rovings (located mostly in the centre of the section's walls) and perimetral (inner and outer) strand mats and surface veils (69% of inorganic content in weight). The most relevant mechanical properties of the GFRP material in tension, compression, flexure and shear were determined by means of coupon tests and are summarized in Table 1. The full-section longitudinal (E_L = 31.0 GPa) and shear (G_{LT} = 3.6 GPa) moduli of the GFRP profiles were determined from three-point bending tests (EN 13706) performed on 1.5 m long beams. Full-scale compressive tests up to failure (caused by material crushing) were also carried out on 1.5 m long non-braced tubular columns, which allowed determining the longitudinal elasticity modulus ($E_L = 30.6 \pm 0.4$ GPa, in agreement with that obtained from flexural tests) and the full-section axial compressive strength ($\sigma_{L,c} = 280.6 \pm 24.0$ MPa).

The glass transition process of the GFRP material was assessed by means of dynamic mechanical analysis (DMA) experiments (dual-cantilever flexural setup, from −60 °C to 250 °C, heating rate of 2 °C/min); the glass transition temperature (T_g) was set at 140 °C