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Thermal performance of modular GFRP multicellular structures assembled with fire resistant panels

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ABSTRACT

Modular glass fibre reinforced polymer (GFRP) multicellular structures were formed using pultruded GFRP box sections incorporated between two GFRP flat panels by adhesive bonding. Three types of fire resistant panels, namely glass magnesium (GM) board, gypsum plaster (GP) board and lightweight calcium silicate (CS) board, were installed at the outer face of the lower GFRP flat panel using screws. The lower surfaces of the built-up specimens were then exposed to fire. The thermal responses of the GFRP multicellular specimens assembled with different fire resistant panels were measured and comparatively analysed, in association with the damage patterns observed. It was found that the fire resistant panels effectively mitigated the temperature progressions developed in the GFRP components, thereby improving the fire insulation performance of those structural assemblies. The GM board provided the best fire insulation performance, with the highest temperature at the outer face of the upper GFRP flat panel (the surface unexposed to fire) being less than 120 °C after 90 min of fire exposure. Further, the effects of cavities and end closure configurations of the multicellular assemblies on the heat transfer were evaluated and highlighted.

1. Introduction

Glass fibre reinforced polymer (GFRP) composites provide favourable properties such as high strength, light weight and corrosion resistance for civil structural applications. They usually have relatively low elastic modulus values of approximately 10–20% of steel [1]. GFRP multicellular and sandwich structures, made through the pultrusion process or consisting of box or I sections as webs between two flat panels, show enhanced shear transfer through web sections or additional core materials and improved structural stiffness through adequate sectional inertial moment. Such GFRP multicellular and sandwich structures have attracted considerable attention for applications in bridge and building construction [2–5].

As an important design concern, especially in building applications specified in many fire standards, certain fire insulation performance is required for structural elements in use. For example, according to ISO 834 [6], fire insulation is one of three failure criteria for structural elements in fire performance evaluation. That criterion determines that a structural element fails in fire if the temperature at any location on the fire unexposed surface of the structural element exceeds the initial temperature by more than 180 °C, or if the average temperature of the fire unexposed surface increases above the initial temperature by more than 140 °C. Such specifications are also taken into account in relevant standards in China and Australia [7,8]. For GFRP composites under elevated temperature or fire scenarios, complex changes of physical and mechanical properties were well identified and reported [9–11]. Their glass transition temperatures are generally around 100–120 °C [12], levels that can easily be achieved in fire scenarios, and above which the material elastic modulus and strength begin to degrade significantly. Furthermore, most polymeric matrixes of GFRP materials thermally decompose at temperatures between about 300 and 600 °C [13]. This decomposition entails several fire reaction characteristics, such as heat release rate, smoke production, flame spread and oxocarbon release that are also considered in fire design, especially for buildings. Therefore, the fire insulation performance of GFRP structural elements for potential building applications is important, in order to maintain the temperatures of structural materials unexposed to fire at levels satisfying the fire insulation requirements.

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GFRP multicellular and sandwich structures exhibit advantageous thermal insulation characteristics. In addition to the low thermal conductivity of GFRP materials [9,12], the structural sections generally contain a large volume of cavities due to their multi-cellular sectional configuration, as commonly seen in hollow bricks. At room temperature, such cavities usually offer energy-saving, taking advantage of the low thermal conductivity of the cavity air, and are therefore beneficial for building external roof and wall applications. When such a GFRP structure is exposed to fire from one side, its polymer matrix is consumed and a char layer at the fire exposed surface grows (a process more remarkable in phenolic resin than in polyester or vinyl ester resins [13]). This charring process slows down the decomposition rate in the underlying virgin layers and, more importantly, in the webs and the fire unexposed side, resulting in reduction in temperature development, smoke density, etc. [14]. In fire scenarios, it has been shown that pultruded multicellular structures under service loading conditions with no protective measures at the fire side provided about 40 min [15] or 60 min [16] fire-resistance times for slab applications and about 50 min [17] for column applications. The integration of a water cooling system through the cellular sections could considerably extend the fire-resistance time [16,17], where water circulation and control systems needed to be properly installed as an active fire protection measure.

To mitigate temperature progression at structural surfaces and interiors for enhancing their fire insulation performance, passive fire protection solutions can also be considered for GFRP structural elements. Fire resistant panels, composed of non-combustible materials such as gypsum, magnesium oxide, calcium silicate and mineral wool, are often used as passive fire protection solutions because of their low thermal conductivity [18]. These fire resistant panels have been used in steel structures and are among the popular fire protection methods [19,20] due to their prefabricated and modular nature for convenient installation. Satisfactory improvement in structural fire performance has been reported for cold-formed steel (CFS) structures with fire resistant gypsum plasterboard (GP) boards [21–24]. The fire-resistance time of such CFS wall systems lined with one or two layers of GP boards on both sides was experimentally evaluated in [23]. The temperature of steel studs in the wall protected by one layer of GP board exceeded 300 °C (at this temperature the yield strength of the used steel began to drop considerably) at 43 min; while double layers of GP boards provided 94 min fire protection before the wall studs reached the same temperature. These results corresponded to 48 min as the fire-resistance time (when structural failure occurred) for the single-layer configuration and 111 min for the double layer configuration. The fire insulation effects of several types of fire resistant panels, including GP boards, glass magnesium (GM) boards, CS boards and autoclaved lightweight concrete boards were further examined by Chen et al. [25,26] for improving the fire-resistance time of CFS wall systems. It was shown that the fire-resistance time of the wall lined with double GP boards on both sides was 71 min. Replacement of the base layer of GP board by CS board or GM board resulted in improved fire-resistance times of 92 min or 94 min respectively.

Passive fire resistant panels were introduced for improving the fire performance of GFRP structural elements by Correia et al. [27]. In that study, the lower flanges of pultruded GFRP box beams (100 × 100 × 8 mm) were installed with 15 mm thick CS board using bolts, or with 15 mm thick vermiculite/perlite (VP) based mortar through casting. The lower surface was then exposed to ISO 834 fire. It was found that the centre of the upper flange of the specimen with CS board reached the glass transition temperature at 61 min, 180% longer than that of the unprotected specimen. The temperature at this location for the specimen with VP mortar was kept below glass transition temperature until 74 min of fire exposure. Similar box GFRP columns (1.5 m high) installed with 25 mm thick CS boards on one or three sides were investigated by Morgado et al. [28]. These fire resistant boards were bonded to the GFRP surface through a thin layer of fire resistant mastic. Subjected to the exposure to ISO 834 fire on one or three sides of the specimens, the fire-resistance times achieved were 51 min or 39 min respectively. Significant improvements were identified in comparison to unprotected GFRP columns which demonstrated fire-resistance times of 16 min (one side fire exposure) or 5 min (three sides exposure) under the same fire conditions.

It appears that results for fire resistant panels for improving the fire insulation performance of GFRP multicellular structures are very limited, although such structures have shown great potential for building applications. Moreover, very few types of fire resistant panels have been introduced to GFRP structures. Understanding of the fire insulation performance of GFRP multicellular structures assembled with different fire resistant panels is important and necessary. In this study, four GFRP multicellular assemblies, each consisting of three pultruded GFRP box sections in parallel between two GFRP flat panels, were fabricated using adhesive bonding. Then, three types of fire resistant panels, namely GM board, GP board and lightweight CS board, were installed on the outer surface of the lower GFRP flat panel. These formed three built-up fire protected specimens in comparison to the fourth specimen, which lacked a fire resistant panel. The lower surfaces of the specimens were exposed to the ISO 834 fire curve to evaluate their fire insulation performance. The temperature progressions were measured at different locations through the depth direction of the specimens during fire exposure. Based on the measured temperature responses, the efficiency of different fire resistant panels for improving the fire insulation performance of the GFRP multicellular assemblies was analysed in detail. The damage patterns were compared and the effects of cavities and end closure configurations of the GFRP multicellular assemblies on heat transfer were also evaluated.

2. Experimental investigations

2.1. GFRP materials

The pultruded GFRP flat panels and GFRP box sections used in this study consisted of glass fibres and polyester resin with aluminium trihydrates as fire retardant. The flat panels were 580 mm wide and 8 mm thick and the box sections were 100 × 100 mm with wall thickness of 10 mm. Microscopy was performed to understand the material architecture details. As shown in Fig. 1, the flat panel consisted of 5 mat layers and 7 roving layers (0°/90°) and the box section consisted of 4 mat layers and 5 roving layers (0°/±45°/90°) in the through-thickness direction.

Thermogravimetric analysis (TGA), a widely accepted method of determining mass loss at elevated temperature [29], was conducted using STA8000 from PerkinElmer for both the flat panels and the box sections. The test materials were prepared by grinding powders through the entire thickness. The temperature in the TGA tests was increased from room temperature to 600 °C at a heating rate of 5 °C/min in an air atmosphere with a flow rate of 50 ml/min. The results presented in Fig. 2 indicate that the onset of decomposition temperature $T_{d,onset}$ (at which 5% of the mass was lost) were 275 °C for the flat panels and 296 °C for the box sections. Furthermore, the decomposition temperature T_d (at which the mass decreased at the highest rate based on the derivative mass curve) of the flat panels and the box sections was identified to be close to 350 °C. The residual mass fraction of the flat panels was 63.3% of the original material, while that of the box sections was 69.5%. The detailed results from the TGA are summarised in Table 1.