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Heat transfer modelling of CFRP strengthened and insulated steel tubular columns

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HIGHLIGHTS

- Conducted elevated temperature thermal property tests of construction materials.
- Obtained temperature dependent variations of four important thermal properties.
- Developed heat transfer models of CFRP strengthened and insulated steel columns.
- Validated the heat transfer models with experimental results.
- Developed an approach to determine the FRL.

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ABSTRACT

The lack of knowledge of the fire performance of CFRP strengthened and insulated steel tubular columns has hindered the CFRP usage in steel columns, which require certain structural fire ratings. In this research, a numerical modelling approach was used to investigate the heat transfer behaviour of CFRP strengthened and insulated steel columns, and thus to enhance the knowledge of their fire performance characteristics. For this purpose, an experimental investigation was also conducted to determine the thermal properties of carbon fibre, adhesive, CFRP and insulation materials at elevated temperatures. These thermal properties were idealized and used to develop heat transfer finite element models in ABAQUS/CAE to simulate the behaviour of CFRP strengthened and insulated steel columns exposed to fire. The developed models were validated by using experimental results and a parametric study was then conducted to investigate the influence of insulation thickness on the heat transfer behaviour. This paper presents the details of this research and the results. It provides the details of the validated heat transfer finite element models and the important thermal properties of CFRP and insulation materials. An approach to determine the fire resistance level of CFRP strengthened and insulated columns is also presented in this paper.

1. Introduction

Carbon Fibre Reinforced Polymers (CFRP) have been increasingly used in steel column strengthening applications in recent times due to the many advantages they possess, such as high strength to weight ratio, high stiffness and durability (Fig. 1a-b). However, CFRPs are combustible and vulnerable to strength and stiffness deterioration at elevated temperatures, which raises concerns over their fire performance [1,2]. Therefore, an external insulation layer is necessary to protect the CFRP strengthened columns in fire and to achieve certain fire ratings [3] (Fig. 1c). Hence the fire performance of these CFRP strengthened and insulated steel columns should be evaluated by means of determining their fire resistance levels (FRL) to confidently use CFRP strengthening in steel column applications.

Conventionally, a prescriptive approach is used to quantify the FRL, where a column is pre-loaded and exposed to standard fire (ISO 834) until failure. In recent years, fire safety design approach is being transformed from conventional prescriptive approach to performance based approach. Performance based approach is cost effective, flexible and provides designers multiple pathways to achieve the desired FRL [4]. Finite Element (FE) modelling has been widely used as a performance based tool for this purpose and FRL of a CFRP strengthened steel tubular column can be determined by performing sequentially coupled thermo-mechanical FE analyses. Such a modelling approach has been used by Lu et al. [5], Dai et al. [6] and Firmo et al. [7]. In this approach, initially heat transfer

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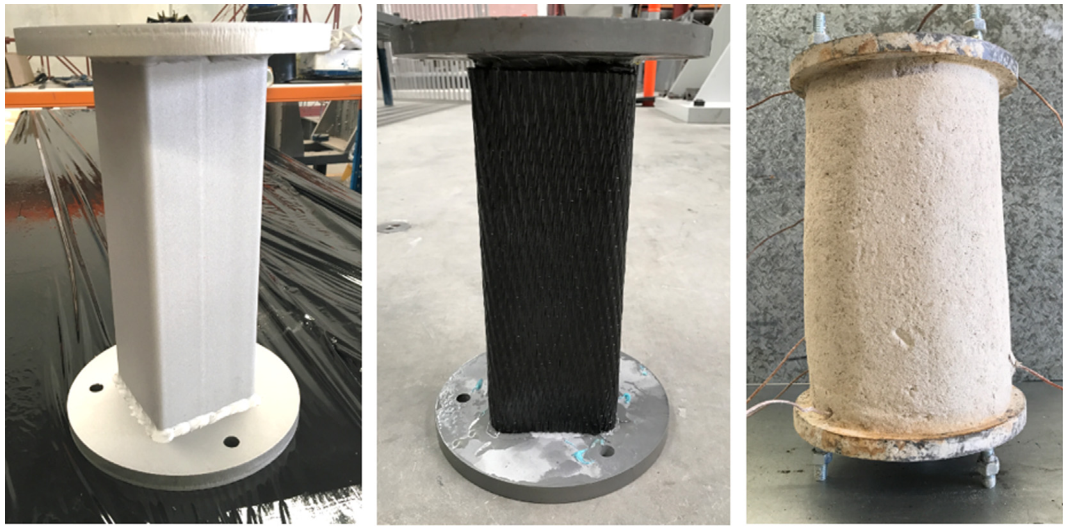

(a) Bare steel column (b) CFRP strengthened steel column (c) CFRP strengthened and insulated steel column

Fig. 1. Process of CFRP strengthening and insulating a steel column.

modelling is performed and the results are transferred to the structural model to analyse the thermal-structural response.

Structural modelling of CFRP strengthened steel members has been carried out by many researchers and different modelling techniques are available in the literature [8–11]. However, heat transfer modelling studies of CFRP strengthened steel members are scarce in the literature even though heat transfer modelling studies of CFRP strengthened and externally insulated concrete members are available [6,7]. Hence this paper attempts to address this knowledge gap.

To determine the thermal response of CFRP strengthened and insulated cold-formed steel tubular columns in fire using heat transfer FE modelling, accurate elevated temperature thermal properties (specific heat, thermal conductivity and density) of steel, CFRP and insulation material are essential. Extensive research carried out over the past decades has led to a good understanding of thermal properties of steel at elevated temperatures and such data can be found in Eurocode 3 Part 1-2 [12].

Griffis et al. [13] provides temperature dependent thermal properties of graphite epoxy laminates while Bai and Keller [14] provides temperature dependant thermal properties of Glass FRP laminates. In addition, Chowdhury et al. [15] provides temperature dependent mass variation of Glass FRPs. Nonetheless, a recent comprehensive study on the elevated temperature thermal properties of CFRP composites, carbon fibres and adhesives is lacking in the literature.

Spray applied insulation materials, insulation boards and intumescent paints are often used to protect steel columns in industrial applications. Spray applied insulation materials are relatively cheap, easy to apply and require less labour and skill compared to other alternatives. In addition, thickness restrictions do not apply and insulation thicknesses can be varied within a wide range. Because of these advantages, spray applied insulation materials are preferred in the protection of CFRP strengthened steel tubular columns. They maintain the CFRP surface temperature below the glass transition temperature of the adhesive for an extended period of time, and thus allow the achievement of higher FRLs. The thickness of insulation and its thermal properties greatly influence this thermal response and thus precise thermal properties of these insulation materials are essential for accurate heat transfer modelling. Recent studies carried out by Kodur and Shakya [16], and Zhang and Li [17] provide elevated temperature thermal properties of some commercial and innovative spray applied insulation materials.

As disscussed above, it was evident that a comprehensive study of the thermal properties of CFRP and insulation material is lacking, which are invaluable for the analysis of thermal and fire response of CFRP strengthened and insulated cold-formed steel tubular columns. Hence an experimental investigation was undertaken to determine the elevated temperature thermal properties of carbon fibre, adhesive, CFRP and spray applied insulation materials.

3D heat transfer models using ABAQU/CAE [18] were then developed and used with the measured thermal properties to simulate the thermal response of CFRP strengthened and insulated steel tubular columns. They were then validated by comparing the thermal responses obtained from the models with experimental results obtained from an ongoing study. This paper provides the details of this research study and its results.

2. Experimental investigation

An experimental investigation was conducted to measure the elevated temperature thermal properties of CFRP and their individual constituents: carbon fibre and adhesive. In addition, two commercialy available spray applied insulation materials (CAFCO 300 and CAFCO FENDOLITE) were investigated. The study was focused on measuring the specific heat, mass retention, linear thermal expansion, thermal diffusivity and conductivity at various elevated temperatures.

2.1. Specific heat capacity (C_p) and mass retention

Specific heat capacity and mass retention with temperature were measured using the Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA) techniques, respectively. Simultaneous thermal analyser (NETZSCH STA 449F3 Jupiter) was used for this purpose with type S sample carrier as it provides high sensitivity in high temperature ranges (Fig. 2). Initially, the instrument was calibrated for temperature and enthalpy using a melting point method and Au, Ag, Al, Sn, In, and Zn were used for this