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Finite element modelling of CFRP jacketed CFST members under flexural loading

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ABSTRACT

In this era, using concrete filled steel tubular (CFST) members has become very popular in the construction industry; at the same time, ageing of structures and deterioration of members are often reported. Therefore, actions like implementing strengthening techniques with the new materials become essential to combat this problem. Due to their in-service and superior mechanical properties, carbon fibre reinforced polymer (CFRP) composites make an excellent candidate after upgrading. The aim of this study is to experimentally investigate the suitability of CFRP in strengthening of CFST members under flexure. Among eighteen beams, nine beams were strengthened by full wrapping (fibre bonded at the bottom throughout the entire length of beam) and the remaining nine beams were strengthened by partial wrapping (fibre bonded in-between loading points at the bottom). The effect of CFRP layers on the moment carrying capacity of CFST beams was investigated. Also a nonlinear finite element model was developed using the software ANSYS 12.0, to validate the analytical results such as load–deformation and the corresponding failure modes. The experimental results revealed that beams strengthened by partial wrapping failed by delamination of fibre, even before attaining the ultimate load of control beam but the beams strengthened by full wrapping exhibited more enhancements in moment carrying capacity and stiffness. From the numerical simulation and experiments, it is suggested that if any appropriate anchorages are provided in partial wrapping scheme to avoid delamination of fibre, then it will be turned into a fine and economical method for strengthening of CFST members.

1. Introduction

Engineers are faced with rising levels of ageing infrastructure which has, in turn, led them to implement new materials and techniques to efficiently combat this problem. For a variety of reasons such as fire, ageing, environmental degradation and overloading, reinforced concrete, steel, cast iron and cold-formed metal structures may be found to be structurally inadequate. The use of FRPs as external reinforcement of concrete structures has shown itself to be a successful method of repair/upgrade in the last 20 years [3]. FRP has high strength to weight ratios, and excellent resistance to corrosion and environmental degradation. It is very flexible and can be formed into any kind of shape, and is easy to handle during construction. Although the composite industry was introduced in 1909 [3,4], it was not until the 1940s that the composite industry began to bloom. The use of composite technology in aircraft applications flourished and, by the 1950s, FRP boat hulls and FRP car bodies were developed with glass fibres as the major reinforcement [5]. As a non-conductive material, glass was used as an insulator to prevent galvanic corrosion of metals [6]. However, under certain conditions of exposure, glass fibres proved to be sensitive to alkaline environments and moisture attack [7]. In addition, creep affected glass fibres more than any other types of fibres [8]. The higher performance carbon fibre reinforced polymers (CFRPs) were developed in 1963 for specialised applications.

Unlike glass, carbon is an electrical conductor and hence galvanic corrosion could take place if fibres are placed in direct contact with metals [9], but such fibres behave very well against creep deformation and relaxation [10]. Also resistant to creep and fatigue, aramid fibres were first developed in 1965 and found acceptance in aerospace and marine applications [3] despite their anisotropic mechanical behaviour [11]. In the last 30 years there have been considerable advancements in the use of FRP composites in civil infrastructure, and this trend will continue. Externally bonded FRP composites applied to reinforced concrete (RC) structures have been used around the world since the mid-1980s. Since then, the application of FRP reinforcement has expanded to include masonry structures, timber and, to a lesser degree,

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metals [12,13]. However, research related to FRP applications to steel structures has started only recently despite the urgent need for the rehabilitation of structural steel components such as bridges, offshore platforms, large mining equipment and buildings. Traditionally, the most common method to repair and/or rehabilitate a steel structure has been by welding additional steel plates. This not only adds weight to the structure, but also the heat involved in welding can affect the stress distribution and may be critical for structures exposed to fatigue loads. In addition, steel plates would be exposed to corrosion damage and frequently this repairing method requires the use of scaffolding and heavy machinery as well as long periods of service interruption. In contrast, rehabilitation methods using FRP composites do not exhibit any of these drawbacks. Other advantages of FRP over steel plates are the low weight of the bonded material, easy applicability and the capacity to cover areas with limited access, where the use of traditional techniques would be impractical [5]. High stiffness fibres, such as carbon fibres, can effectively enhance the structural properties of steel structures; additionally, composites could also enhance the fatigue life of steel structures. However, there has been limited research in this area. There are uncertainties concerning the long term behaviour of these applications and the bonding between the composite materials and steel [5]. One useful application of FRP composite materials is for concrete filled structural steel section, and this is the focus of this study.

In an investigation using CFRP for concrete filled steel tubular (CFST) sections, Zhao et al. [14] carried out tests on CFRP strengthened concrete-filled steel hollow section short columns. The increase in load-carrying capacity was found to be 5–22% and 20–44% when one and two layers of CFRP were applied. The load capacity enhancement increased with increasing diameter-to-thickness ratio. Tao et al. [15] also carried out tests on concrete-filled steel hollow section short columns strengthened by CFRP. They found that a lower increase in load-carrying capacity due to CFRP strengthening was achieved for concrete-filled rectangular hollow sections, although a similar increase in ductility was found for both the circular and rectangular sections. Tao et al. [16] presented the results of axial compression and bending tests of fire-damaged concrete-filled steel tubes repaired using unidirectional carbon fibre reinforced polymer composites. Both the circular and square specimens were tested to investigate the repair effects of CFRP composites on them. Repair of the specimens was achieved by the external wrapping of unidirectional carbon fibre sheets, with their fibres oriented in the lateral direction. The test results showed that the load-carrying capacity and the longitudinal stiffness of CFRP-repaired CFST stub columns increase with the increasing number of CFRP layers, while their ductility decreases with the increasing number of CFRP layers. Tao et al. [17] and Tao and Han [18] conducted a research project on fire-exposed concrete-filled steel tubular beam—columns repaired with CFRP wraps. Test results showed that the load-bearing capacity of fire-exposed CFST columns is enhanced by the CFRP jackets to some extent, while the influence of CFRP repair on stiffness was not apparent. However they did not consider long members in their research. Haedir et al. [19] conducted tests on class-4 CHS beams strengthened by CFRP sheets. They showed that a class-4 section can be upgraded to a class-2 section if CFRP strengthening is applied in both the longitudinal and hoop directions. It was found that the hoop layers played a more important role in restraining or delaying the local buckling which is often in the form of an ovalisation for CHS. The longitudinal layers played a more important role in increasing the moment capacity, due to the contribution of CFRP in the tension zones.

From the past research, it was observed that investigation on strengthening of CFST members using fibre is not widespread and also more tests are required to derive an optimal combination of fibre orientation, number of layers and sequence in applying CFRP layers. Also, research on repairing or strengthening of CFST members using CFRP under flexure is required. This research work investigated the use of an innovative FRP technology for concrete filled steel tubular beams under flexure and aimed to develop optimum wrapping schemes that can be used to repair these structures. The main parameter in this study was fibres wrapping scheme. Two types of wrapping scheme were used such as full wrapping and partial wrapping at the bottom. In full wrapping, the fibres were bonded at the bottom throughout the full length of the steel tube and in partial wrapping, the fibres were bonded in-between loading points at the bottom. Furthermore, to eliminate the galvanic corrosion between steel tube and CFRP, a thin layer of glass fibre mat was introduced between steel and CFRP. The new retrofitting technology could simplify the complicated and costly retrofitting methods used at present. By promoting the use of such a composite material in the retrofitting of steel structures, it leads to considerable short term and long term benefits.

Since the Finite Element Method has reached a state of maturity, numerical simulation is an alternative method to validate with the experimental results and understand the behaviour of CFRP strengthened CFST members. As a result, the present investigation also focused on modelling of CFRP strengthened beams using ANSYS 12.0. On the basis of experimental observations, a three-dimensional finite element model was developed to predict the load–deformation behaviour of CFRP strengthened CFST members in which all the structural parameters and nonlinear properties of concrete, steel and FRP composites were included.

2. Materials

2.1. Concrete

The concrete mix proportion designed by the IS method to achieve the strength of 30 N/mm^2 was 1:1.39:2.77 by weight. The designed water cement ratio was 0.35. Three cube specimens were cast and tested when they aged 28 days to determine the compressive strength of concrete. The average compressive strength of the concrete was 38.5 N/mm^2.

2.2. Carbon fibre

The unidirectional carbon fibre called MBrace 240, fabricated by BASF India Inc., was used in this study. It is a low modulus CFRP fibre having the modulus of elasticity 240 kN/mm^2 and the tensile strength was 3800 N/mm^2. The thickness and the width of the fibre were 0.234 mm and 600 mm, respectively. It is fabric type and can be tailored into any desired shape.

2.3. Adhesive

The MBrace saturant supplied by BASF India Inc. was used in this study to get the good bonding between steel tube and carbon fibre. It is a two-part system, a resin and a hardener and the mixing ratio was 100:40 (B:H).

2.4. Steel tube

The square hollow steel tube confirming to IS 4923-1997 and IS 1161-1998 having a dimension of 91.5 mm $\times$ 91.5 mm was used in this study. The thickness and the length of the square hollow steel tube were 3.6 mm and 1500 mm, respectively. The yield strength provided by the manufacturer was 240 N/mm^2.