Composite Structures 100 (2013) 71–78

Contents lists available at SciVerse ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Numerical investigation of FRP-strengthened tubular T-joints under axial compressive loads

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ARTICLE INFO

Article history:
Available online 3 January 2013

Keywords:
Tubular T-joints
FRP
Ultimate strength
Axial compression
Finite element method
Strengthening

ABSTRACT

This paper presents the failure pattern, ultimate static strength and detailed behavior of steel tubular T-joints strengthened by fiber reinforced polymer (FRP) obtained from numerical investigations under an axial brace compressive loading. The joints were analyzed in two cases in which FRP was included and excluded considering typical glass/epoxy composite. The results obtained from the numerical modeling revealed the influence of the FRP wrap in joint ultimate capacity enhancement. In addition, the state of stresses and deflections of the steel substrate were all improved as a result of FRP application which clearly showed an upgrade in overall joint behavior. The orientation and extent of FRP reinforcement has been proposed based on practical applications. The modes of failure observed throughout the numerical analysis were local bending of the chord member, punching shear due to ovalization and plastic failure of the chord. The FRP-Strengthened joint hindered the occurrence of these failure modes. The FRP plies were capable to withstand a minimum of 50% of the joint ultimate load with no sign of failure. The critical regions of the plies were around the saddle point and the adjacent ovalized area of the chord shell.

1. Introduction

Fiber reinforced polymer (FRP) composites applied by surface attachment have been widely used for the strengthening and retrofitting of various types of structures. The FRP composites as structural reinforcing materials offer superior performances in terms of corrosion resistance, environmental durability, and stiffness-to-weight ratio over steel plates or alternate materials used for strengthening. Moreover, ease of application makes FRP extremely attractive for usage in civil infrastructure applications, especially in cases where dead weight, space, access constraints and/or time limitations exist.

Research over the last few decades reveals that the application of non-metallic fiber composite materials for strengthening and retrofitting of reinforced concrete structures has proved to be of economic and engineering advantages [1]. In recent years, there has been an intense interest towards the use of externally applied FRP on steel members in which the union of FRP and steel leads to improved structural performance [2–4]. In order to improve the characteristics of steel members, several external reinforcing methods have been investigated. The majority of these studies have focused on reinforcing open-section steel beams and girders with FRP mostly emphasizing on flexural strengthening [5–9]. More recently, research on strength enhancement of hollow steel sections strengthened with FRP has been performed.

Circular hollow sections (CHS) subjected to tension and confined by CFRP sheets were investigated [10]. The study proposed four CFRP layers and a suitable epoxy for strengthening. Short CFRP strengthened hollow steel columns with different section slenderness ratios were experimentally investigated and the possibility to restrain the steel wall with the high modulus reinforcing fibers was shown [11]. Moreover, increased capacity for crippling-sensitive, thin walled rectangular hollow sections (RHS) reinforced by CFRP sheets was reported [12]. Possibility to develop strengthening schemes for thin-walled steel sections composed of non-compact plate elements with focus on orthogonal (longitudinal and hoop) fiber orientation has also been carried out [13]. A Study on the flexural behavior of steel tubular poles with mono-symmetric cross-sections and externally bonded with high modulus CFRP sheets revealed the importance of considering the ultimate strain of the reinforcing elements in compression [14]. Artificially damaged steel RHS beams in pure flexure with an eye towards implementation of two types of fiber configurations were tested [15]. The results illustrated that extending the fiber perimeter up

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0263-8223/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compstruct.2012.12.020

to the webs of the beam provides a significant level of composite action between the two materials, which ensures improved post-yield performance. Results of bending tests on composite tubular steel sections utilizing different types of fiber, epoxy components and curing methods were also performed [16]. The study revealed that the capacity of the tube wrapped and cured in air was 1.3 times higher than the bare steel counterpart. Circular and square CFRP-repaired steel tubular stub columns with concrete infill have been tested [17] and the results showed that the CFRP wraps provided better confinement of the circular steel and concrete than its square counterpart, and this confinement enhanced the load-carrying capacities and the longitudinal stiffness of the composite columns. Strengthening technique of externally bonding FRP sheets to selected sides of steel T-sections to enhance the compressive buckling behavior has also been employed [18]. Unlike steel, the properties of FRP can be adapted to different directions by altering the fiber orientation and amount of fiber sheet in any specific direction. The effects of fiber orientation (longitudinal, hoop and inclined) and strengthening configuration on the buckling mode of lipped channel columns and of square hollow section (SHS) columns were examined [19,20]. The key role of fiber composites on circular steel tubes reinforcement and the restraining effect of external glass FRP composites in steel tubes against significant axial displacement mainly in the post-failure regime were assessed [21]. Buckling behavior of carbon composites externally reinforced circular steel tubes under pure compression was explored [22] which revealed that the amount of fiber reinforcement had a significant effect in delaying local buckling of the steel tube, which led to the improved capacity for the steel component. Techniques of jacketing which can effectively augment the deformation capacity with nominal increase in strength were applied to investigate the influence of FRP sheets on the static behavior of axially loaded steel tubes [23]. Ductility of glass FRP-jacketed circular steel tubes due to axial compression was investigated theoretically and experimentally and test results showed that the axial load–strain relationships of composite tubes were almost elastic–plastic, with a marginal strain hardening depending on the number of fiber jackets. Rehabilitation of cracked aluminum overhead truss-shaped sign structures composed of tube members with GFRP and its effect to improve strength and fatigue load resistance has been proved [24,25]. Whilst the previously mentioned and further studies demonstrate the efficacy of applying external FRP composites to single hollow section members, practically no research has been conducted on the influence of FRP for improving the structural performance of tubular joints which consists of a branch/brace member welded to the exterior surface of a main/chord member with different angles.

It is worth to mention that there were several reported strengthening methods for tubular joints in the literature. These methods could be generalized as external reinforcement and internal reinforcement. Both methods were metallic-based strengthening schemes and were distinguished upon the placement of the reinforcement. In the internal reinforcement, i.e., stiffened internal ring and inner plate were typically used in tubular structures. The study on the reinforcement of tubular joints using internally stiffened rings and by increasing chord thickness was carried out by some researchers [26–28]. From the reported research, it was found that a tubular joint strengthened by internal reinforcement could remarkably improve the load bearing capacity. However, the disadvantage of the internal reinforcing methods was the difficulty to place the reinforcement inside the tube during fabrication. In addition, it was impossible to be used for strengthening an in service tubular joint specially where inside of the member is also occupied by thru member elements such as piles. In the external reinforcement, i.e., doubler plate and collar plate were welded onto the outer surface of the chord. It was also proved by some researchers [29–32] that these methods were effective to increase the static strength of a tubular joint. However, doubler plate reinforcement could still not be used in the servicing period of a tubular joint but collar plates were convenient for strengthening a tubular joint in its servicing period.

In this paper, a new non-metallic reinforcing technique which lies in the external reinforcement category is proposed. Using the finite element method (FEM), the static strength of an FRP-reinforced tubular joint was analyzed. It has been revealed that this method was efficient and suitable for in-service tubular joint reinforcement catering all advantages of FRP application over traditional metallic reinforcements.

This paper presents numerical investigations on a typical T-joint under compressive loading selected from an available experimental database. Model of the joints with and without reinforcement have been investigated. Monitoring the joint behavior along the crown and hoop lines such as state of stress, displacements, ovalization and composite failure has been performed in all cases. The findings of this study have shown the effectiveness of the FRP reinforcement to enhance the ultimate strength of the joints. Also, the FRP wrap helped to improve joint behavior in comparison with joints without such reinforcement.

2. Tubular T-joint properties

From the available experimental-based tubular joint databases, a typical joint under axial compression loading was selected for numerical investigation throughout this paper. The properties of this joint are indicated in Table 1.

For steel, a Young's modulus of 210 kN/mm^2 and a Poisson's ratio of 0.3 were used throughout the analyses. It was generally assumed that steel material would obey the von-Mises yield criterion and the associated flow rule as the classical plasticity model.

3. FRP Properties

Fiber reinforced polymers are composed of two distinguishable parts namely fibers and matrix. Therefore, various compositions could be selected. In this study, glass/epoxy composite was used as the reinforcement due to its popularity. Also, epoxy putty was applied to the joint to create a smooth transition from the larger tube (chord) to the smaller tube (brace) at the joint intersection.

Table 2 demonstrates the properties of the FRP and putty used in the analyses.

In this table, subscripts "1" and "2" stand for the fiber longitudinal and transverse directions while subscripts "c" and "t" represent compression and tension relatively.

For the FRP, the "Hashin" damage criteria was utilized for strength assessment. Also, damage evolution was considered in the analyses to consider the post-damage behavior in which the FRP elements were removed once damage variables for all failure modes reached their criteria limit. This would ensure analysis continuation even after first ply failure (FPF) occurence since the joint would still have capacity for load carrying beyond (FPF) and termination of the analysis at this point would underestimate the ultimate strength of the joint.

4. FRP layup and orientation

The FRP reinforcement layup and the extent of reinforcement including the number of layers, length of reinforcement and orientation are of great importance when dealing with composites. This is due to their flexible attitude which makes them adjustable for any structure. The only limitation in FRP application is the