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Retrofitting tubular steel T-joints subjected to axial compression in chord and brace members using bonded FRP plates or through-wall steel bolts

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ABSTRACT

T-joints of Hollow Steel Sections (HSSs) are vulnerable to local instabilities of the web under the orthogonal compression in both members. Unlike W-sections stiffeners cannot be installed inside the closed sections. Therefore, alternative strengthening methods are needed. This experimental study explored the effectiveness of two retrofitting methods by controlling the web buckling of the longitudinally compressed 203 × 76 × 3.09 mm chord, which is also subjected to transverse axial compression loading through the brace member. The web height-to-wall thickness (h/t) ratio of the chord is 65. In the first method, 8 mm diameter through-wall steel bolts were used to brace the webs of the chord at the vicinity of the brace. In the second method, 76 × 185 × 9.5 mm glass fiber reinforced polymer (GFRP) plates were adhesively bonded to the two webs of the chord at the brace location. Two levels of sustained axial compression load were induced in the chord, representing 45% and 80% of its full axial capacity, in addition to control specimens without axial loads. The transverse brace load was then gradually increased to failure. The through-wall steel bolts increased the joint capacity by 13–25%, depending on the chord's axial load level, while the bonded GFRP plate increased the capacity by 38–46%.

1. Introduction

Tubular steel structures are commonly used in the form of trusses, vierendeel girders, and frames. The connection between the chord and vertical member (brace) in vierendeel girders and at mid-span of N-trusses, or between beam and column in frames, take the form of a T-joint. The capacity of the structure may be governed by the strength of its joints. Therefore, upgrading the joint capacity may be essential in certain structures, particularly if the members have been upgraded. This is crucial in thin-walled members, where the bearing of the brace member on the chord member produces web crippling of the thin walls of the chord. Unlike steel W- and S-sections, it is not possible to install steel web stiffeners inside tubular sections. In offshore structures with circular tubes, the commonly used concepts include the 'can' whereby the chord members are partially thickened at the joints, or the 'doubler plate', sometimes slightly modified to a system referred to as the 'collar', where the brace is welded directly to the doubler plate through a penetration weld, whereas the doubler plate is fillet-welded to the chord [1]. It should be noted that all these strengthening techniques are primarily used in circular hollow sections, commonly used in offshore structures.

For Rectangular Hollow Sections (RHSs), different strengthening techniques may be employed. Failure of the chord side walls by yielding or crippling is the most common for T-, Y- and X-joints, especially when their β ratios (breadth of brace/breadth of chord) are close or equal to unity. Welded rectangular HSS T-joints have been studied experimentally by a number of researchers in the past (e.g. [2,3]). When β is within 0.8 and 1.0, web buckling normally governs. When β is less than 0.8, the failure modes depend on the chord flange width-to-chord thickness ratio. A deformation limit, in the form of the level of local indentation of flange chord face, is adopted in the design of welded tubular joints as described in the latest IIW static design procedures for welded tubular joints [4–6]. Filling hollow sections with concrete to improve the web crippling behavior was found to be efficient [7]. Another technique was adopted [8,9], where a single bolt was used to brace the chord sidewalls against the outward buckling, and resulted in an increase of 18% in capacity. Another study [10] recommended that a wooden brace be inserted into the RHS in addition to the through-wall bolt to avoid the inward buckling of the chord sidewalls. The use of externally bonded fiber reinforced polymers (FRPs) laminates has also been successfully used to strengthen HSS columns against

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global buckling [11]. Limited work addressed local instabilities of HSS members. For example, a study [12] demonstrated the benefits of using carbon-FRP wraps to control web crippling of HSS sections under end bearing. Another study [13] investigated axially loaded carbon-FRP-wrapped short HSS columns to control local buckling.

Two previous studies by the authors on the subject [14,15] investigated the strengthening of T-joints comprising RHS chord and HSS brace members, where the brace was gradually loaded axially to failure. The chord members did not include any axial compression loads; hence simulating a beam-column joint in a frame system. This paper also investigates the strengthening of T-joints but with sustained axial compression loads in the chord members, while the brace member is gradually loaded to failure. This simulates joints in trusses or vierandeel girders, where the combined longitudinal and transverse compression loads is more critical to web stability at the T-joint. Both through-wall steel bolts and adhesively bonded GFRP plates techniques are investigated. The two techniques were selected for two reasons, namely, the ease and simplicity of installation, and suitability to the geometric nature of the section. Both techniques have minimal impact on the esthetic appearance of RHS sections. Unlike W-sections, welded steel stiffeners to the web at the joint are not convenient for RHS sections. The study also addresses the effect of the level of sustained axial compression in the chord on the strengthening effectiveness.

2. Experimental program

The following sections describe test specimens and parameters, material properties, fabrication of specimens, test setup and instrumentation.

2.1. Test specimens and parameters

Table 1 provides a summary of the test matrix. T-joints were fabricated and tested under combined brace and chord axial compression loads. The T-joint consisted of a horizontal, 1220 mm long chord member welded to a 400 mm long brace member (Fig. 1a). Two key parameters were explored, namely, the type of retrofitting reinforcement (through-wall steel bolts and adhesively bonded GFRP plates (Fig. 1b), and the level of axial load in the chord member. The chord member was a 203 × 76 × 3.09 mm RHS, with an (h/t) ratio of 65. This section is classified as class 4 in accordance with CAN/CSA-S16-01 [16] based on the web (h/t) ratio. The brace member was a 76 × 76 × 8.9 mm HSS with a thick wall to avoid failure of the brace. The study included three control specimens, one with no axial load in the chord (T1), one with 200 kN (T2), and one with 350 kN (T3). The axial compression loads in specimens T2 and T3 represent 45% and 80%, respectively, of the pure axial strength of the chord, calculated according to CAN/CSA-S16-01 [16]. The chord loads were kept constant during gradual application of the load on the brace member to failure.

Specimens T4–T6 are counterparts of specimens T1–T3 and were retrofitted with the through-wall steel bolts system (configuration A in Fig. 1b), where the two bolts were located directly below the brace member, 40 mm below the compression flange of the chord, where the maximum local buckling was expected in the chord. Specimens T7–T9 are also counterparts of T1–T3 and were retrofitted by two 76 × 185 × 9.5 mm adhesively bonded GFRP plates, one on each web, directly below the brace member (configuration B in Fig. 1b). A previous study [15] has compared GFRP and CFRP plates. It was shown that thick GFRP plates, which are more economical than CFRP, are more effective in mitigating local buckling in these T-joints.

2.2. Material properties

2.2.1. Cold-formed tubular sections

Two types of HSS sections were used, a rectangular one (RHS), 203 × 76 × 3.09 mm, for the chord, and a square (SHS) 76 × 76 × 8.9 mm section for the brace. Both the RHS and SHS were manufactured in accordance with ASTM A500 C [17]. Uniaxial tension tests were performed according to ASTM E8/E8M-09 [18] on dog-bone coupons cut from the flange and the web of the RHS chord. A 50 mm extensometer was used to measure and record strains. The stress–strain plots for the steel coupons are shown in Fig. 2. The yield strength (offset secant at 0.2%) and modulus of the chord were 426 MPa and 209 GPa. The reported characteristic yield strength by manufacturer was 410 MPa.

2.2.2. Through-wall bolts

The bolts used in the strengthened specimens are standard 8 mm diameter (Grade 8) high-strength bolts with a reported yield and ultimate strengths of 896 and 1034 MPa, respectively.

2.2.3. GFRP plates

A 9.5 mm thick commercially available GFRP plate was used. It consists of alternating layers of unidirectional E-glass roving and random mats impregnated with polyester resin. The manufacturer reported longitudinal and transverse tensile strengths of 138 and 69 MPa, and moduli of 12.4 and 6.9 GPa, respectively. The reported longitudinal and transverse compressive strengths and modului by the manufacturer are 165 and 110 MPa and 12.4 and 6.9 GPa, respectively. To confirm these results, three coupons were cut from the plates and tested in tension in the longitudinal direction according to ASTM D3039/D3039M [19]. The stress–strain curves are shown in Fig. 2. The average longitudinal tensile strength and elastic modulus were 268 MPa and 20.6 GPa, respectively.

Table 1
Test matrix.

Specimen ID	Chord wall thickness (mm)	Retrifitting system and configuration	Axial compression Load of Chord (kN)	Maximum transverse Load (kN)	% Age gain in strength
T1[a]			0	131.1	–
T2		N/A (control)	200	103.8	–
T3			350	58.3	–
T4[a]	3.09		0	164.3	25.3
T5		2 Bolts (Config. A in Fig. 1)	200	116.9	12.6
T6			350	66.0	13.2
T7[b]		76 × 185 × 9.3 mm GFRP Plate (Config. B in Fig. 1)	0	180.9	38.0
T8			200	151.6	46.1
T9			350	80.6	38.3

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