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Behaviour of SHS brace-H-shaped chord T-joints under cyclic in-plane bending

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ABSTRACT

The behaviour of square hollow section (SHS) brace-H-shaped chord T-joints under cyclic in-plane bending was investigated using experimental and finite element (FE) analyses. Six specimens were tested. The test parameters were the section dimension of the brace and the setting of transverse stiffeners at the brace/chord connection. Failure modes, moment resistances, rotational stiffness, rotation capacity and energy dissipation of the T-joints were evaluated. It was also found that failure modes of the specimens are consistent with the prediction in Eurocode 3. The FE software ABAQUS was then used to simulate the joint specimens, and the extended finite element method (XFEM) was adopted to study the effect of crack development on the hysteretic behaviour of the joints. The FE method accurately predicted the stress distribution, hysteretic curves, backbone curves and locations of the cracks, thus validating its accuracy. A parametric study was subsequently conducted to investigate the influence of the geometric parameters β, γ, τ, n and ξ on the hysteretic performance of the T-joints in detail.

1. Introduction

In regions with possible high intensity earthquakes, steel structures are more often chosen for the construction of stadiums, offshore platforms, industrial factories and large-scale grids. It is mainly because steel material has light weight, high strength, and good ductility [1–8], which possibly makes steel structures more easily dissipate the energy under seismic action. However, the joints inevitably formed in welded steel structures are inefficient at resisting seismic action because the high stress concentration and residual stress generally exist at these locations and may make the whole steel structure behave in a brittle manner. In the Northridge earthquake and the Kobe earthquake, brittle fracture failure occurred at the beam-to-column joints of steel frame structures. The principle of the strong joint is therefore emphasised in seismic design codes. Among the many forms of joints, tubular joints are most commonly used because the hollow interior gives structures a lighter weight, better mechanical properties, a more aesthetic appearance, and useful functions for transporting gas or liquid. The hysteretic behaviour of steel tubular joints is thus attracting increasing interest.

Gao et al. [9] and Shao et al. [10] experimentally and numerically investigated the hysteretic behaviour of tubular T-joints reinforced with/without doubler plates after fire exposure. It was found that the hysteretic behaviour, ductility ratio, and energy dissipation of the reinforced/unreinforced joints tended to be poorer after fire exposure than at ambient temperature. Wang and Chen [11] experimentally investigated the performance of unstiffened circular hollow section (CHS) T-joints under cyclic in-plane bending, and found that the in-plane bending loaded joints dissipated energy mainly by plastic deflection of the brace with brace member efficiency larger than one. Shao et al. [2] performed experimental and FE analyses on the hysteretic behaviour of unstiffened and chord reinforced square tubular T-joints. The experimental hysteretic curves of the tubular T-joints are generally plump, revealing that these joints have good capacity to dissipate energy and are therefore especially useful in resisting seismic loading. Xia et al. [12] experimentally and numerically studied the hysteretic behaviour of square hollow section (SHS) tubular T-joints reinforced with doubler-plate under axial cyclic loading. The results showed that the doubler-plate increased the strength of the joints effectively, but the energy dissipation capacities of T-joints reinforced with doubler-plates were lower than the corresponding unreinforced ones. Yin et al. [13] conducted an experimental investigation on the tubular N-joints with concrete-filled chord, which was found to be more effective to improve the static strength and hysteretic behaviour of the joint than setting doubler plates. Qin et al. [14] and Soh et al. [15] experimentally

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Nomenclature

l_0	chord length
l_1	brace length
l_n	nominal brace length
h_0	chord height
b_w	effective width of chord web
b_0	chord flange width
b_1	brace width
b_{eff}	effective width for brace to chord connection
t_w	chord web thickness
t_f	chord flange thickness
t_1	brace wall thickness
t_s	stiffener thickness
β	brace to chord flange width ratio ($= b_1/b_0$)
γ	chord flange width to thickness ratio ($= b_0/t_f$)
τ	brace to chord flange thickness ratio ($= t_1/t_f$)
n	stiffener number
ξ	stiffener to chord web thickness ratio ($= t_s/t_w$)
f_{y0}	yield strength of chord
f_{y1}	yield strength of brace
F	anticipated yield load
Δ	anticipated yield displacement
K_r	initial rotational stiffness
M_u	maximum moment
M_y	yield moment
φ_u	maximum rotation
φ_y	yield rotation
μ	ductility ratio ($= \varphi_u/\varphi_y$)
E_T	total energy dissipation of last loop
E_L	linear energy dissipation of last loop
η	energy dissipation ratio ($= E_T/E_L$)
$M^c_{u,EC3}$	moment resistance on chord web yielding
$M^b_{u,EC3}$	moment resistance on brace failure

investigated the hysteretic behaviour of completely overlapped tubular K-joints under axial cyclic quasi-static loading. Their results indicated that the local buckling of the brace was the main energy dissipation mechanism, and the completely overlapped joints possessed a better hysteretic performance than gapped N-joints. All these studies revealed the advantages of steel tubular joints in hysteretic performance.

However, the fabrication of the circular tubular joints is considered to be comparatively inefficient and time consuming due to the demand for special cutting and welding techniques. For this reason, a hollow section brace-to-H-shaped chord joint has been developed, which can be easily fabricated by welding the end of the hollow section to the flange of the H section [16]. Moreover, since the H-shaped chord has the advantage of excellent bending behaviour, straight cutting and flexible connection techniques, this type of joint has been widely used in long-span structures and single-layer reticulated roof structures with high span-to-height ratios. Wardenier [16] and Chen et al. [17–20] carried out a series of tests to determine the static strength of the joints with CHS brace and SHS brace, and established the corresponding static strength formulas. This contribution has been widely recognised and the proposed formulas were adopted by Eurocode 3 [21]. Nevertheless, little research has been carried out on the hysteretic behaviour of hollow section brace-to-H-shaped chord joints. Therefore, the experimental and numerical investigations were conducted in this study on the behaviour of SHS brace-H-shaped chord T-joints under cyclic in-plane bending. The failure modes, hysteretic curves, backbone curves, ductility ratios and energy dissipation of the joints were obtained. Corresponding FE models were established and calibrated against the test results. An extensive parametric study was carried out to analyse the influence of geometric parameters on the hysteretic behaviour of the SHS-to-H-shaped joints.

2. Experimental investigation

2.1. Test specimens

A total of six SHS-to-H-shaped T-joint specimens were designed for the experiment, including three specimens with no stiffener (SP1, SP2 and SP3) and three specimens with two pairs of stiffeners (SP1S, SP2S and SP3S). According to the previous study [8], it seems to be reasonable to put the stiffener plates under the brace wall so that the reinforcing and constraint effects can be performed adequately. For each connection, the SHS brace was welded to the H-shaped chord by fillet welds. In the manual arc welding process, the welding rod E43 was used and the fillet weld size was measured to be 6 mm. The H-shaped chords and SHS braces were made of hot rolled steel plates and seamless steel tubes, respectively. The geometric properties of the specimens are summarised in Table 1 and Fig. 1. A 40-mm-thick square flat plate and an ear plate were welded to the end of the brace, and two 20-mm-thick flat plates and ear plates were welded to both ends of the chord. The specimens were connected to test rigs by the ear plates and nuts. The configuration of the specimens is shown in Fig. 2.

2.2. Material properties

Tensile coupon tests were conducted to determine the mechanical properties of the steel material. The coupons were taken from the longitudinal direction of the chords and braces following the specification in ISO [22]. A microcomputer-controlled electro-hydraulic servo universal testing machine was used to perform the tensile coupon test. The loading rate was controlled as accurately as possible at 500 N/s to ensure the accuracy of the test results. The material properties obtained from the tensile coupon test are summarised in Table 2. It should be noted that the transverse stiffeners were manufactured from the same batch of steel plates as the webs. Therefore, the mechanical properties of the stiffener can be considered to be identical to those of the web.

2.3. Test set-up

A WinQuick hydraulic servo universal test system was used for the in-plane bending application. The test rig consisted of the reaction force wall, the hydraulic horizontal loading device and the support device, as shown in Fig. 3. One end of the hydraulic loading device was fixed on the reaction force wall and the other end was connected to the brace of the test specimens with anchor bolts. Both ends of the chord were bolted to the steel supports to form an articulated system. Considering the possible movement of the supports along the chord axial direction, the linear variable differential transformer (LVDT) with 50 mm measurement range was arranged at both ends of the chord. The cyclic in-

Table 1
Geometric parameters of SHS brace-H-shaped chord T-joint specimens.

Specimen	Chord (mm)						Brace (mm)		
	l_0	h_0	b_0	t_w	t_f	t_s	l_1	t_1	b_1
SP1	1500	200	200	8	12	0	400	5	160
SP1S						8			
SP2						0			120
SP2S						8			
SP3						0			80
SP3S						8			