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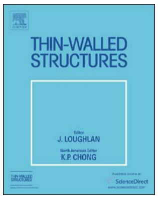

Full length article

Hysteretic behaviour of SHS brace-H-shaped chord T-joints with transverse stiffeners

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ABSTRACT

The hysteretic behaviour of square hollow section (SHS) brace-H-shaped chord T-joints with transverse stiffeners was investigated using experimental and finite element (FE) analyses. Three specimens with different brace widths were fabricated for the experimental test. The test results indicated that all of the specimens under brace cyclic axial loading failed during the inelastic stage. The failure modes of the specimens included the overall flexural failure of the chord and the local warping failure of the top flange around the brace corner, with slight cracks occurring along the weld toe at the brace/chord intersection. The test results also revealed that the joint demonstrated good hysteretic behaviour. The FE models of SHS brace-H-shaped chord T-joints with transverse stiffeners were subsequently built in the numerical analysis software ABAQUS. The FE and experimental results for the hysteretic curves, backbone curves, energy dissipation, stress distributions and failure modes showed good agreement, thus validating the accuracy and reliability of the FE models. Finally, based on the verified FE method, a parametric study was conducted to investigate the influence of the geometric parameters β, γ, τ, n, ξ and ε on the hysteretic behaviour of the stiffened SHS brace-H-shaped chord T-joints. The numerical results demonstrated that an overly small β or overly large γ reduced the hysteretic behaviour of the joint, whereas τ and ξ had little influence. The addition of a pair of transverse stiffener plates at the brace/chord intersection effectively changed the failure mode of the joint, and the constraint effect of the stiffener was adequately performed on the top flange when $\varepsilon \geq \beta$.

1. Introduction

On account of the advantages including high strength, light weight, good machinability and design flexibility, steel tubular structures are widely used in stadiums, terminals, harbour engineering, long span bridges and offshore platforms, etc. As the key components of steel tubular structures, tubular joints are one of the areas where stress concentration tends to appear. Moreover, compared with the axial stiffness of the brace, the radial stiffness of the chord is generally much lower at the brace/chord intersection, which mainly causes local failure of the chord. Thus, the mechanical properties of tubular joints have been extensively studied.

Since the 1980s, research on tubular joints has extended from uniplanar joints to multi-planar joints [1–4], and the hysteretic behaviour [5–10], fatigue behaviour [11–16], fire resistance behaviour [17–21] and impact behaviour [22–25] of tubular joints have been increasingly investigated in addition to the static behaviour. Furthermore, as the radial stiffness of the chord is generally much lower than the axial stiffness of the brace for unstiffened tubular joints, various strengthening methods have been proposed to improve the mechanical properties of tubular joints. Choo et al. [26,27], Shao et al. [9], Gao et al. [21] and Qu et al. [25] successively studied the static strength, hysteretic performance, fire resistance and impact behaviour of tubular T-joints reinforced with collar plates, and their experimental and numerical analyses revealed that the reinforced joints were more ductile and had better ultimate capacity, energy dissipation capacity, fire resistance and impact resistance. The internally ring-stiffened method was used in studies of the fire resistance behaviour of stiffened circular hollow section (CHS) T-joints [20], the stress concentration factors (SCF) of stiffened KT-joints subjected to axial loading [28] and the static behaviour of stiffened CHS tubular DT-joints under brace axial loading [29], and the corresponding finite element (FE) models, probability density functions (PDFs) and stiffener strength equations were established, respectively.

In general, previous studies mainly focused on CHS and square hollow section (SHS) tubular joints. In contrast, limited research has conducted on hybrid tubular joints such as CHS-to-SHS joints, CHS-to-H-shaped joints and CHS-to-channel-section joints, which are

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Nomenclature

l_0	chord length
l_1	brace length
h_0	chord height
b_0	chord flange width
b_1	brace width
b_s	stiffener width
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 ($= t_s/t_w$)
ε	stiffener to chord flange width ratio ($= b_s/b_0$)
F	anticipated yield load
Δ	anticipated yield displacement
P_y	yield load
δ_y	yield displacement
δ_{yt}	tensile yield displacement
δ_{yc}	compressive yield displacement
δ_u	maximum displacement
δ_{ut}	maximum tensile displacement
δ_{uc}	maximum compressive displacement
μ	ductility ratio ($= \delta_u/\delta_y$)
μ_t	tensile ductility ratio ($= \delta_{ut}/\delta_y$)
μ_c	compressive ductility ratio ($= \delta_{uc}/\delta_y$)
E_T	total energy dissipation
E_C	cumulative energy dissipation
E_y	energy dissipation during elastic stage
E_i^t	energy dissipation in tensile stage
E_i^c	energy dissipation in compressive stage
η	cumulative energy dissipation ratio ($= E_T/E_y$)

increasingly used in engineering projects. Wardenier [30] proposed a new form of connection fabricated by welding an SHS brace to an H-shaped chord, and conducted a series of tests on this type of joint to establish the corresponding static strength formulas. His contribution has been widely recognised and the proposed formulas were adopted by Eurocode 3 [31]. Bian et al. [12] experimentally studied the static and fatigue behaviour of CHS-to-RHS T-joints subjected to both axial and in-plane bending loads. The results indicated that the hybrid tubular joints inherited the advantages of CHS-to-CHS and RHS-to-RHS joints in terms of fatigue strength and economic efficiency. Chen et al. [32–35] carried out a series of studies on the static performance of SHS-to-H-shaped joints and CHS-to-H-shaped joints, and evaluated the design strength of the hybrid joints under axial compression and in-plane bending. Their thought-provoking studies revealed that the corresponding design equations given by Eurocode 3 were not conservative and should be modified. Actually, as shown in Table 1, H-shaped section has advantages of low self-weight, excellent bending behaviour, straight cutting and flexible design, and SHS steel tubes generally show good torsional behaviour. Therefore, compared with other types of joints, the SHS-H joint shows unique advantages.

Like other unstiffened tubular joints, the transverse stiffness of the H-shaped chord is much smaller than the axial stiffness of the SHS brace at the brace/chord intersection. Hence reinforcement measures should also be taken for SHS-to-H-shaped joints. However, current research on stiffened SHS-to-H-shaped joints is far from enough [32,34], and scholars have not reached a consensus on how to effectively strengthen the joint. As transverse stiffeners are widely used in modern engineering and are recommended in Eurocode 3 to increase the transverse stiffness of H-shaped steel, this strengthening method is worth studying and applying in SHS-to-H-shaped joints.

Furthermore, little research has focused on the hysteretic behaviour of SHS-to-H-shaped joints. In addition to the bearing capacity and stiffness, the ductility and energy dissipation capacity of the joints are also of great research significance for structural seismic design.

In conclusion, research on the hysteretic behaviour of SHS-to-H-shaped joints reinforced with transverse stiffeners, which has not yet been conducted, is vital for the seismic safety of relevant engineering applications.

In this paper, the hysteretic behaviour of SHS brace-H-shaped chord T-joints with transverse stiffeners was investigated using experimental and FE analyses. Three specimens with different brace widths were fabricated for the experimental test. The hysteretic curves, backbone curves, ductility ratios, energy dissipation and failure modes of the joints were analysed based on the experimental observations, thus the hysteretic behaviour of the stiffened SHS brace-H-shaped chord T-joints was evaluated. The FE models of the joints were subsequently built in the numerical analysis software ABAQUS and experimentally validated. Finally, a parametric study was conducted to investigate the influence of the geometric parameters β, γ, τ, n, ξ and ε on the hysteretic behaviour of the joints.

2. Experimental investigation

2.1. Test specimens

Three SHS-to-H-shaped T-joint specimens (SP1, SP2 and SP3) were designed for the experiment. The SHS braces and H-shaped chords were made of seamless steel tubes and hot rolled steel plates, respectively. Each joint was fabricated by welding an SHS brace to an H-shaped chord. The geometric properties of the specimens are summarised in Fig. 1 and Table 2. To connect specimens with the test rig, a 40-mm-thick square flat plate and two ear plates were welded to the end of the brace, and both ends of the chord were welded onto 20-mm-thick flat plates and ear plates. The configuration of the specimens is shown in Fig. 2.

2.2. Test rig

An HDTS-1000 hydraulic servo universal test system was used for the axial load application. The test rig consisted of a movable roof, a hydraulic cylinder, a clamping device and a test platform, as shown in Fig. 3(a). The maximum stroke and applied load of the hydraulic cylinder were ± 150 mm and ± 500 kN, respectively. As shown in Fig. 3(b), the end of the brace was bolted to the clamping device, resulting in the cyclic axial load being applied from the hydraulic cylinder to the joint specimen. Both ends of the chord were bolted to the steel supports to form an articulated system. Displacement transducers and the corresponding data acquisition system were fitted to the test rig to measure the vertical movement of the hydraulic cylinder, thus enabling the vertical displacement at the end of the brace to be determined. In addition, the cyclic axial load was measured by the dynamic data

Table 1
Comparison of joints with different cross-section types.

Cross-section types	Mechanical properties	Fabrication process
CHS	Good torsional behaviour	Curved cutting
SHS	Good torsional behaviour	Straight cutting
H-shaped section	Low self-weight Good bending behaviour	Straight cutting Flexible connection techniques