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CHS X-joints strengthened by external stiffeners under brace axial tension

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ABSTRACT

This paper presents an experimental and numerical investigation of the use of external stiffeners to reinforce circular hollow section (CHS) X-joints under brace axial tension. Six full-scale specimens with different brace to chord diameter ratios (β) of 0.25, 0.50, and 0.73 are tested, including three unreinforced X-joints and three reinforced X-joints. The experimental setup and detailed parameters are presented and results including failure modes, load–displacement curves, and ultimate capacity are compared. The experiment results show that the reinforced external stiffeners clearly increase the mechanical performance of joints in tension, supported by the improved ultimate strength and initial stiffness in comparison to the unreinforced specimens. Furthermore, the enhancement of ultimate strength increases along with the increase of brace to chord diameter ratio (β). Finite element (FE) modeling using SHELL181 element is also established and precisely describes the static behavior of the X-joints under brace tension with and without external stiffeners.

1. Introduction

The use of circular hollow sections (CHS) is becoming increasingly popular because of their technological advantages over open sections, such as resistance in compression, torsion, and lateral bending as well as their aesthetically pleasing shape. Nowadays, CHS are applied in structures such as stadiums, towers, bridges, long-span roofs, and platform jackets [1–3]. In many cases, the ultimate capacity of such CHS structures is governed by their joint capacity, due to the premature failure of the joints. A joint stiffened with external stiffeners welded to the chord member and brace member at the brace-chord intersection is called an external stiffener stiffened joint.

The bearing capacity and deformation of T-joints using external stiffeners was explored by Zhu et al. [4,5]. The results illustrated that the static strength and stiffness of stiffened joints was increased due to the enhancement of the connection length of the brace-chord intersection zone. Extensive studies of stiffened tubular X-joints have been performed, covering aspects such as the use of external stiffener [6], external stiffening ring [7], internal stiffening ring [8,9], fully grouted [10], double-skin grouting [11], longitudinal diaphragm [12], joint can [13], and collar plate [14].

Limited research has focused on the behavior and strength of brace axial tensile tubular X-joints. The ultimate strength of CHS X-joints subjected to brace tension has been investigated through a series of experiments [15]. Different approaches in the definition of joint strength were discussed and the results of these approaches were compared with the design recommendations in ISO and CIDECT design codes. Further study of the effect of chord stresses on static strength was also carried out by Choo et al. [16]. New design equations for CHS X-joint ultimate strength have been included in the CIDECT design code [17]. The existing codified guidance for the first crack loads and ultimate loads of X-joints in tension was reviewed by Dier et al. [18]. The ductile fracture of welded CHS-RHS X-joints was investigated by Ma et al. [19] under brace tension, where the stress and strain distribution of fillet welds were presented and the FE model was built to simulate the weld actual mechanical behavior. Furthermore, the calculation of load-deformation relationship for CHS joints were studied in [20,21] with the consideration of weld properties. These authors proposed revised mean and characteristic capacity formulations for predicting the first crack. A parametric study of axial stiffness of CHS X-joints subjected to brace tension was presented by Qiu et al. [22], who also investigated the factors influencing the axial stiffness and the formulae used to calculate the joint axial stiffness. Experimental tests and subsequent finite element (FE) calibration studies were conducted to study the static strength of axially loaded (tension and compression) elliptical hollow section X-joints [23,24].

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Nomenclature

d_1	brace diameter
d_0	chord diameter
l_0	chord length
l_1	brace length
t_0	chord wall thickness
t_1	brace wall thickness
t_s	stiffener wall thickness
l_s	stiffener length
h_s	stiffener height
α	ratio of chord length to radius $2l_0/d_0$
β	ratio of brace to chord diameter d_1/d_0
γ	ratio of chord diameter to twice the chord wall thickness $d_0/(2t_0)$
τ	ratio of brace wall thickness to chord wall thickness t_1/t_0
E_0	Young's modulus of chord
E_1	Young's modulus of brace
E_2	Young's modulus of stiffener
F_{FE}	joint load from numerical result
$F_{u,exp}$	ultimate strength obtained from test
N_C	joint strength according to the Chinese design code
N_I	joint strength according to ISO and CIDECT criteria
N_A	joint strength according to AISC criterion

Further, the ultimate static strength of 13 double-skin grouted X-joints in brace tension was tested by Feng [25], who discussed the failure modes of joints and compared the ultimate strength obtained from testing with the current design codes and then presented new formulations. A study of the static capacity of fully grouted X-joints under brace axial tension and in-plane bending was conducted by Chen [26], and significant improvements over punching shear formulations were gained according to the experimental results. Study of the static behavior of internally ring-stiffened CHS DT-joints subjected to brace axial compression or tension was reported by Wang et al. [27]. A large number (about 800) of FE models were built to obtain a strength design equation for stiffened joints. Furthermore, an extensive study of 1264 unstiffened and internally ring-stiffened DT-joints subjected to axial tensile and compressive loading was conducted by Lan et al. [28]. The failure mechanism and equations for predicting the stiffener strength were presented.

External stiffener strengthening is an effective and convenient reinforcement method for CHS joints, with broad applicability. Still, techniques for assessing the capacity of external stiffener stiffened joints under brace tension are lacking. Further research is needed to provide guidance for the application of external stiffeners, with the aim of enriching understanding of reinforced X-joints subjected to brace tension.

This paper investigates the static strength of external stiffener stiffened CHS X-joints under brace axial tensile load. Three different brace to chord diameter ratios (β = 0.25, 0.50, and 0.73) were used in the experimental study. The ultimate strength, failure mode, and load–-displacement curves of the specimens were recorded in the experiment. Furthermore, FE modeling was developed with experimental validation, to further understand the static behavior of the joints.

2. Experimental program

2.1. Experimental setup and instrumentation

Fig. 1 shows the typical setup of the X-joint experiments. Each brace end was provided with an endplate. One plate was bolted to a high-stiffness short beam and the other to the strong base of the test rig, which was fixed on the ground by a ground anchor. Loading was achieved through two 100-ton actuators acting on both ends of the short beam. The displacement-controlled actuator had a rated compression capacity of 1000 kN and a stroke of ± 300 mm. For each test, the load was applied at an initial stroke rate of 1.0 mm/min for the linear load range, which was then decreased to 0.3 mm/min at higher load ranges.

As shown in Fig. 1, two linear variable displacement transducers (LVDT1 and LVDT2) were located at the bottom plate. Four LVDTs (LVDT3 to LVDT6) were located at the top endplate to monitor the vertical displacement difference between two brace end plates with reference to the values measured by LVDT1 and LVDT2.

2.2. Specimen geometry and scenarios

The specimens' dimensions are shown in Table 1, with corresponding geometric variables illustrated in Fig. 2. The test series was divided into three pair groups: three specimens were reinforced with the stiffener (X-0.25-R, X-050-R, X-073-R) and the others were unreinforced (X-0.25, X-050, X-073), to serve as reference. Each specimen had the nominal chord diameter (d_0) of 300 mm and the nominal chord length (l_0) of 1800 mm, resulting in a ratio of chord length to radius (α) of 12, which avoided any short chord influence. The height (h_s) and length (l_s) of each external stiffener were designed to be twice those of the brace diameter and the nominal thickness of the stiffener (t_s) was 8 mm. Two 45 mm thick endplates were welded at two brace ends of the specimen to facilitate specimen installation and load application.

The brace to chord diameter ratio (β) varied from 0.25 to 0.73 and the wall thickness of brace was thick enough to avoid any premature failure in the member. The diameter and wall thickness of each tubular member were measured at three locations in a selected cross-section and then the average was used. The chosen geometric parameters (α, β, γ, and τ) correspond to typical values for X-joints in practical applications.

All braces and chords were hot-rolled seamless and low carbon steel tubes. All six chords were cut from a single 12 m long tube in order to

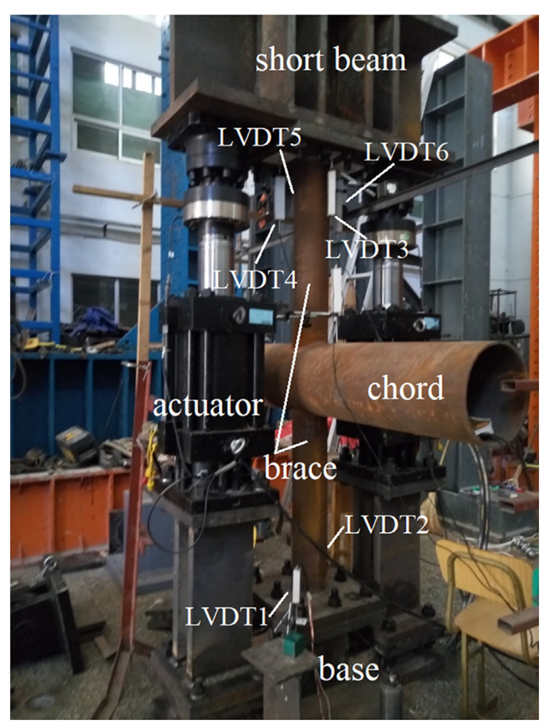

Fig. 1. Experiment setup.