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Capacity of steel CHS X-joints strengthened with external stiffening rings in compression

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ABSTRACT

This paper studies steel circular hollow section (CHS) X-joints by conducting experiments on the axial compressive strength of unreinforced and reinforced X-joints with external stiffening rings. Three pairs of unreinforced and reinforced X-joints were tested to compare their compressive load capacity. The diameter ratios (β) between the brace and the chord β were 0.25, 0.51 and 0.73 respectively. The experimental setup, parameters and results are presented. The failure modes and load-displacement curves of the unreinforced and reinforced X-joints were compared. It was shown that external stiffening rings greatly increased the axial compressive load capacity of the X-joints, by 86%, 75%, and 58% respectively. Finite element modelling accurately predicted the structural responses of the X-joints with and without external stiffening rings.

1. Introduction

Steel circular hollow sections (CHS) are widely used in civil structures. Usually, whole structures are regarded as truss systems and therefore steel tubular members (chord and brace) are mainly in an axial loading condition. Their buckling is crucial to structural safety and has been intensively investigated [1–4]. Unlike tubular members, however, tubular joints are usually subjected to more complex loadings and can become critical locations within a tubular structure. A common type of CHS joint is the X-joint fabricated by two collinear welding brace members to one chord member. When the CHS X-joint is subjected to brace axial loading, the joint may fail due to the chord yielding at the intersection between the chord and the brace members. Such CHS joints may be reinforced when a high capacity is required while the primary hollow section members remain unchanged.

Several methods have been used to enhance CHS joints, such as external stiffeners, external stiffening rings, internal stiffening rings, fibre reinforced polymer (FRP) composite strengthening, concrete-filled, doubler and collar-plate reinforcement, and chord-can. Experimental and finite element (FE) investigations were conducted by Zhu et al. [5–7] on the comparative axial compressive strength of unreinforced and external stiffener reinforced CHS T-joints. Both experimental and FE results showed that the external stiffeners were effective in strengthening the CHS T-joints. Experimental studies were performed by Zhu et al. [8] on the axial strength of CHS T-joints reinforced by external stiffening rings. The results indicated that the external stiffening rings significantly increased the axial compressive strength of the T-joints.

The mechanism of enhancement of axial strength of CHS X-joints through internal stiffeners was explored through numerical studies by Vegte et al. [9] and Choo et al. [10]. It was understood that the internal stiffeners could significantly enhance the static strength of the CHS X-joints. Furthermore, the effects of vertical inner plate and internal plain annular ring stiffeners on the static strength of CHS T-joints were investigated by Li et al. [11] and Lee et al. [12] using FE approaches. Crown- and saddle-stiffened X-joints subjected to brace axial loading were examined by Lan et al. [13], who further proposed a strength equation through numerical and theoretical studies. Joint axial stiffness was formulated by Qiu et al. [14,15] for the design of single-layer steel tubular structures. The analysis was implemented through FE analysis and factors such as joint geometry, chord axial force and brace bending moments that influence the axial stiffness of CHS X-joints were taken into account.

Lesani et al. [16,17] experimentally and numerically studied the static strength of CHS T-joints reinforced with FRP in axial compression. It was concluded that FRP could significantly improve the static

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Nomenclature

a	weld width
b	weld height
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
w_r	ring width
t_r	ring thickness
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 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 ring
f_{y0}	yield stress of chord
f_{y1}	yield stress of brace
f_{y2}	yield stress of ring
f_{u0}	ultimate stress of chord
f_{u1}	ultimate stress of brace
f_{u2}	ultimate stress of ring
$F_{u,test}$	ultimate strength obtained from test
$Y_{u,test}$	displacement according to ultimate strength obtained from test
F_A	ultimate strength obtained from finite element analysis
N_c	joint strength according to Chinese design code
N_w	joint strength according to Wardenier
N_v	joint strength according to Vegte
Fu,disp	load according to deformation limit
$Y_{u,disp}$	displacement according to deformation limit

strength of CHS T-joints. Concrete-filled reinforcement was studied by Chen et al. [18], who reported that concrete filled in the chord obviously improved the capacity of CHS X-joints. A comparative investigation was further conducted by Chen et al. [19] on hollow and concrete-filled CHS X-joints with curved chords under axial compression. It was found that the ultimate strength of the CHS X-joints with curved chords were generally greater than those of traditional CHS X- joints with straight chords; also the ultimate strength of the concrete-filled CHS X-joints was greater than that of the original CHS X-joints. Experimental and numerical investigations of double-skin CHS tubular X-joints were examined by Chen et al. [20] under axial compression. They found that the ultimate strength of double-skin CHS tubular X-joints was improved with the increase of brace to chord diameter ratio (β), and design equations were proposed accordingly. The behaviour of concrete-filled stainless steel tubular X-joints subjected to compression was tested by Feng et al. [21], who recommended that the use of stainless steel tubes should be included in the design rules since it had significant effects on the ultimate bearing capacity of concrete-filled stainless steel tubular joints.

Doubler-plate reinforced CHS X-joints were numerically examined by Choo et al. [22] for in-plane bending, where strength enhancement up to 240% was observed in comparison to that of the unreinforced joint. Choo et al. [23] also experimentally studied the static strength of collar-plate reinforced CHS X-joints subjected to in-plane bending. They concluded that the collar-plate strengthening was more effective than its doubler-plate counterpart in improving the joints' static strength. Remarkable efficiency of collar-plates in enhancing of the strength of CHS T-joints was also observed by Cai et al. [24]. A number of FE models were generated and analysed by Nassiraei et al. [25–27] for T/Y-joints reinforced with collar-plate subjected to compressive loading, in-plane bending and tensile brace loading. It was found that the ultimate strength of a collar plate reinforced tubular T/Y-joint under axial compression can be improved up to 270% compared to that of the corresponding unreinforced joint. This value is higher than the strength enhancement of 186% for the reinforced CHS X-joints examined in this study. Different ultimate strength formulae were developed through nonlinear regression analysis. The geometrical effects on the static strength of doubler-plate reinforced tubular T/Y-joints subjected to brace compressive and tension loading were studied by Nassiraei et al. [28,29] through a parametric investigation. According to [28], the strength enhancement of doubler-plate reinforced tubular T/Y-joints were found to be up to 295%, which was greater than that of collar plate reinforced tubular T/Y-joints (270%) and CHS X-joints strengthened with external stiffening rings (186%). This suggests the doubler-plate reinforcement may be more effective than the collar-plate and external stiffening rings when subjected to brace compression. A new formula was derived through nonlinear regression analysis to determine the strength ratio.

A chord-can has also been proposed to improve joint loading capacity. The effects of the chord thickness and the length of the reinforced chord on the static strength of tubular T-joints were clarified by Shao et al. [30] and an empirical equation was presented to predict the static strength of tubular T-joints subjected to axial compression. The static strength of uniplanar and multiplanar tubular T- and X-joints was examined by Vegte et al. [31] through experimental and numerical investigations. They proposed a general analysis method for use in CHS T- and X-joints and a series of strength formulae were also derived. An analytical method was further developed by Soh et al. [32], to provide a rational basis for the design of the ultimate strength of tubular joints.

The methods described can effectively increase the ultimate strength of CHS T- and X-joints. However, internal stiffeners are not easy to implement and those involving concrete-filled chord, require extra effort in construction. Some methods, such as doubler-plate, are difficult to apply to a completed CHS X-joint. This paper therefore focuses on the mechanical performance of X-joints with external stiffening rings. An external stiffening ring can be easily applied either before or after the construction of an X-joint. Moreover, the external stiffening ring may improve the ultimate strength of X-joints for different kinds of loading, such as brace compression or tension, in-plane or out-plane bending of brace, because the potential failure mode of chord plastification, as a major failure mode of such joints, may be postponed in this way. The efficiency of the external stiffening ring under different loadings may differ and this requires further studies. Both experimental and numerical studies are performed in this paper and the ultimate strength, failure mode and load-displacement responses of the examined joints are presented and discussed.

2. Experimental program

2.1. Specimens

Compression experiments were conducted for three unreinforced CHS X-joints (X1, X3, X5) and three corresponding reinforced joints (X2, X4, X6) as shown in Fig. 1 and Table 1. To maintain a constant ratio α of chord length to radius, the nominal chord diameter and length were 300 mm and 1800 mm respectively for each joint. This resulted in an α value close to 12, as shown in Table 1. The diameter and length of