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Capacity of steel CHS T-Joints strengthened with external stiffeners under axial compression

Lei Zhu[a,*], Qiming Song[a], Yu Bai[b], Yue Wei[a], Limeng Ma[a]

[a] School of Civil and Transportation Engineering, Beijing Higher Institution Engineering Research Center of Structural Engineering and New Materials, Beijing University of Civil Engineering and Architecture, Beijing, China
[b] Department of Civil Engineering, Monash University, Clayton VIC 3800, Australia

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ABSTRACT

The capacity of steel circular hollow section (CHS) T-joints reinforced with external stiffeners under axial compression is studied by finite element (FE) modeling and theoretical analysis in this paper. The FE modeling approach is first validated by results from axial compressive experiments on nine T-joints with and without stiffeners. Then 256 T-joint FE models are established and analyzed to investigate the influence of the size of external stiffeners and joint geometry on the improvement of ultimate capacity of the joints under axial compression. The results from parametric analysis show that the increment in ultimate capacity decreased when the diameter ratio between the brace and the chord β increased, whereas it remained almost proportional to the factor of stiffener length to the brace diameter η. In addition, for such T-joints, when the thickness of external stiffener was no less than that of the chord wall, the effect of the factor of stiffener thickness to the chord thickness λ and the diameter to thickness ratio of the chord 2γ on the improvement of ultimate capacity was not obvious. On the basis of the yield line model, a theoretical formula is further derived to predict the ultimate strength enhancement of reinforced T-joints with external stiffeners.

1. Introduction

Tubular systems are among the most common forms utilized in steel structures because of their excellent mechanical properties and aesthetic nature. Steel tubular members (chord and brace) are usually regarded as being in an axially loading condition and their buckling is crucial to structural safety when they are loaded in compression [1–4]. In contrast to tubular members, tubular joints are usually subjected to complex loadings and can become the weak points of the whole tubular structure. Early research was conducted from the 1950 s by experimental studies on steel tubular joints [5]. Along with many further systematic experimental studies and theoretical analyses, formulae for calculation of bearing capacity have been proposed for simple planar joints, such as T, K, Y, and X- joints, such as the formulae included in the Design Criteria of Offshore Platform Structure (API RP2A) [6] and CIDECT [7]. In China, the Chinese Code for Design of Steel Structures (GB50017-2003) [8] also specifies strength calculation formulae for simple planar joints, such as T, Y, K, and X-joints and multi-planar tubular joints. In that code, the formulae have been verified by large full-scale joint experiments and FE results, and have also been applied in many practical engineering projects [8].

Several joint reinforcement methods have been proposed to improve joint bearing capacity, with relevant experimental and numerical investigations. These methods include the use of FRP, doubler- or collar-plates, joint cans, internal stiffening rings, and filled concrete. Lesani et al. [9,10] used experimental and finite element analysis to study CHS T-joints reinforced with FRP under brace axial compression. Cai et al. [11], Choo et al. [12], Sui et al. [13], and Vegte et al. [14] adopted doubler and collar plates to strengthen CHS T-joints and their research indicated that this method efficiently reinforced and significantly increased the strength of T-joints. Nassiraei et al. [15,16] further conducted numerical parametric analysis of CHS T/Y-joints reinforced with collar plates under brace compressive or tensile loading, carried out nonlinear regressive analysis, and proposed formulae to calculate the enhancement effects. Shao et al. [17] investigated the use of a joint can to improve the performance of CHS T-joints, and both American Petroleum Institute (API) and American Welding Society (AWS) have recommended this alternative method. Li et al. [18] used ANSYS to analyze how internal longitudinal stiffeners strengthened the axial strength of CHS T-joints. Thandavamoorthy et al. [19] and Lee et al. [20] used experimental method and FE method respectively to analyze the axial loading capacity of internal-ring-stiffened joints. Alternatively,

* Corresponding author.
E-mail address: zhulei@bucea.edu.cn (L. Zhu).

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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
l_s	stiffener length
h_s	stiffener height
t_s	stiffener thickness
α	chord length parameter $2l_0/d_0$
β	diameter ratio between brace and the chord d_1/d_0
γ	half-diameter to thickness ratio of the chord $d_0/(2t_0)$
τ	brace wall-to-chord wall thickness ratio 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_{y0}	yield stress of chord
f_{y1}	yield stress of brace
f_{y2}	yield stress of stiffener
$F_{u,test}$	ultimate strength from test
$F_{u,num}$	ultimate strength from numerical analysis
$N_{u,s}$	ultimate strength of reinforced joint
N_u	ultimate strength of unreinforced joint
η	stiffener length factor l_s/d_1
λ	stiffener thickness factor t_s/t_0
Ψ	joint ultimate strength enhancement coefficient $\Psi = N_{u,s}/N_u$

the chord can be filled with concrete to increase the joint loading capacity. Wardenier et al. [7] presented some specifications for grouted joints, stating that the brace capacity may be dominant in the case of brace compression. Chen et al. [21] performed 16 tests of bare and concrete-filled CHS T-joints with curved chords and straight chords. Their results showed that joint strength was significantly enhanced by the filled concrete.

The above methods may effectively enhance the joint loading capacity. However, wrapping FRP is not time- or labor-efficient. Doubler plates, joint cans, internal stiffening rings, and filled concrete cannot be applied to completed joints, and using collar plates entails much welding labor. Therefore, Zhao et al. [22] and Zhu et al. [23,24] adopted external stiffeners and stiffening rings to reinforce CHS T-joints and completed an experimental program and numerical simulation. Unlike the above joint strengthening methods, reinforcement of CHS T-joints with external stiffeners has obvious advantages because it is convenient to apply to a tubular structure either during or after construction. This method may be more cost-effective due to the reduced requirement for material and labor.

Very limited ranges of parameters were investigated in Ref. [23], including only three β, three stiffener length (l_s) values and three stiffener height (h_s). Moreover, a mechanism based formula for the prediction of the joint strength enhancement could not be developed or validated due to inadequate results. To fully understand the influence of external stiffener size and joint geometry on the ultimate strength enhancement of joints under axial compression, this paper further investigates the static strength of CHS T-joints reinforced with external stiffeners, considering a wide range of design parameters by validated FE analysis. 256 unreinforced and reinforced FE models which include four β values, four γ values, three stiffener length (l_s) values and five stiffener width (t_s) values are established in this paper and examined accordingly. A theoretical formula is proposed based on the yield line model and nonlinear regressive analysis to calculate the reinforcement effect, and the results compare well with those from FE analysis and previous experiments.

2. Brief summary of previous experiments

Three groups of unreinforced and reinforced CHS T-joints with external stiffeners were experimentally examined by Zhao et al. [22] and Zhu et al. [23,24]. This resulted in nine specimens (Fig. 1), with the geometric parameters and material properties given in Tables 1 and 2, for the subsequent FE-based parametric analysis.

The specimens were supported at the two chord endplates by two steel bases and the brace compressive load was applied through a transducer by a jack (Fig. 2). During the entire loading stage, the displacements at the brace end and the chord center were recorded.

The residual stresses caused by the welding were not measured in the experiment. Generally, the residual stresses may affect the buckling strength of tubular members and the fatigue behavior of tubular joints [25–27]. But the influence of the residual stresses on the static strength of tubular joints may be minor because the joint failure is often due to the chord plasticization. The numerical simulation also indicates that the influence of the residual stresses is insignificant since the FE models did not include the residual stresses while agreed well with the experimental results.

3. FE analysis

3.1. Basic assumptions

The finite element analysis in the present study adopts the following assumptions:

(1) The material model is the ideally elastic plastic model with the Poisson's ratio of 0.3.
(2) All materials are isotropic hardening and follow the Von Mises yield criterion.
(3) The influence of the welds on the load-carrying capacity of a joint is ignored.
(4) The influence of the welding residual stress is ignored.

3.2. FE modeling

The finite element software ABAQUS/CAE (Version 6.10) was used for simulation. The 20-noded quadratic solid element with reduced integration (C3D20R) was used to establish the FE models. To reduce computational time, quarter models were adopted in the numerical parametric investigation because the model and the loading were symmetric; therefore, the numerical results could be extended to the full specimens. The mesh density was nearly uniform over the whole joint. A typical mesh model is shown in Fig. 3.

To simulate the contact relationship between the chord, brace, and

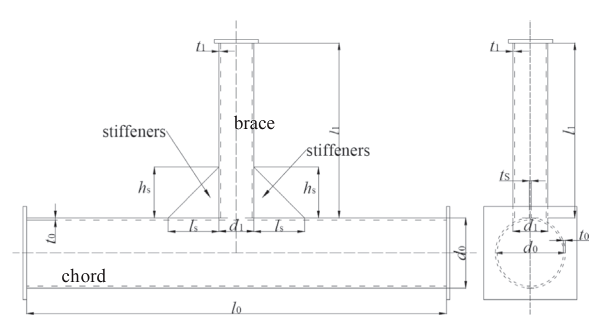

Fig. 1. Detail of T-joint reinforced with external stiffeners [22,23].