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Stress concentration factors of bird-beak SHS X-joints under brace axial forces

Chen Li [b], Fenghua Huang [b], Yu Lou [b], Bin Cheng [a,b,*]

[a] State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai 200240, China.
[b] Department of Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China.

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ABSTRACT

Bird-beak joints are a new type of welded square hollow section (SHS) joints and their fatigue behaviors are of the most attentions recently. The stress concentration factors (SCFs) of both square and diamond bird-beak X-joints under brace axial forces were systematically investigated in this research by using experimental and numerical methods. Four specimens including two square bird-beak X-joints and two diamond bird-beak X-joints were tested. Elastic strain distributions within crown and saddle areas were measured, and the strain concentration factors (SNCFs) at specified hot spots were obtained by using the quadratic extrapolation approach. Refined finite element models, whose accuracies have been validated by experimental data, were developed to parametrically simulate the stress concentrations at weld toes of such innovative joints. The influences of three non-dimension parameters (i.e., brace/chord width ratio β, chord wall slenderness ratio 2γ, and brace/chord wall thickness ratio τ) on SCFs of bird-beak X-joints were revealed. Comparison also shows that the saddle areas commonly contain the highest SCFs within whole joint, and that square bird-beak X-joints provide lower stress concentrations than diamond ones in case of identical non-dimensional parameters. Based on numerous results from parametric analysis, design formulas were finally proposed to calculate the SCFs at typical hot spots of both square and diamond bird-beak X-joints subjected brace axial forces.

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1. Introduction

Bird-beak SHS joints, including square and diamond types, were generated by rotating the members of conventional SHS joints at 45° about their longitudinal axes, as shown in Fig. 1. Besides good aesthetics and lateral wind relieving, the structural rigidities and load bearing capacities of such new-type SHS connections have been proved by researchers including Ono et al. [1–3], Ishida et al. [4], Davies et al. [5], Owen et al. [6–8], Christitas [9], and Chen et al. [10–12] to be higher than the conventional joints with identical dimensions.

While for the structures (e.g., bridges) subjected to repeated loads, the fatigue behaviors of the connections could be much more important than their static behaviors. In this topic, Ishida [13] carried out the earliest fatigue tests of diamond bird-beak T-joints with the load case of brace axial force. Keizer et al. [14,15] investigated the stress concentration factors of diamond bird-beak joints under brace axial force. In recent years, more attentions have been focused on the fatigue related behaviors of bird-beak SHS joints. Tong et al. [16–18] investigated the stress concentrations and fatigue resistances of diamond bird-beak T-joints by using experimental and numerical approaches, especially in the load cases of axial force and in-plane bending. Cheng et al. [19–22] focused mainly on the hot spot stresses and fatigue behaviors of square bird-beak T-joints under chord axial forces, brace axial forces, and brace out-of-plane bending, where fatigue cracking characteristics were also revealed. However, these fatigue achievements are far from comprehensiveness.

It is suggested in current fatigue design guides that the hot spot stress based fatigue estimation method should be used. The process composes of three steps: (1) calculate the nominal stresses of members based on the analysis of entire structure and the beam theory; (2) calculate the hot spot stresses at different spots by multiplying the nominal stresses with stress concentration factors (SCFs); (3) calculate the fatigue lives by using the hot spot stress versus number of cycles (*S*—*N*) curves. During this process, the calculations of SCFs at potential hot spots are the most fundamental. In CIDECT fatigue design guide [23], the SCF formulae for conventional SHS X-joints under six basic load cases have been provided, while the provisions for innovative bird-beak joints are absent. Therefore, this paper carried out experimental measurement and numerical simulation of SCFs for both square and diamond bird-beak X-joints under the basic load case of brace axial forces. The aim of this research is to achieve SCF predictions of such connections and to provide references to specification revisions.

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[*] Corresponding author at: Department of Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China.
E-mail address: cheng_bin@sjtu.edu.cn (B. Cheng).

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Nomenclature

SHS	square hollow section
SNCF	strain concentration factor
SCF	stress concentration factor
β	brace/chord width ratio
2γ	chord wall slenderness ratio
τ	brace/chord wall thickness ratio
L_0	length of chord
L_1	length of brace
b_0	sectional width of chord
b_1	sectional width of brace
t_0	wall thickness of chord
t_1	wall thickness of brace
$NSNR_x$	nominal strain ratio about x-axis
$NSNR_y$	nominal strain ratio about y-axis

2. Test setup

2.1. Specimens

Four bird-beak X-joints, including two square type (SBBJ-X) and two diamond type (DBBJ-X), were fabricated and tested under brace axial tensile force. The specimens were design by considering the three major non-dimension parameters, that is, brace/chord width ratio $\beta = b_1/b_0$, chord wall slenderness ratio $2\gamma = b_0/t_0$, and brace/chord wall thickness ratio $\tau = t_1/t_0$. Fig. 2 shows the configurations of joint, where L_0 and L_1 are the length of the chord and the brace, b_0 and t_0 represent the sectional width and wall thickness of the chord, and b_1 and t_1 are the sectional width and wall thickness of the brace. In order to eliminate the influence of boundary conditions, the member ends were away from the junction area by at least triple the members' sectional width. In this test, the lengths of chord and brace are respectively selected as $L_0 = 1200$ mm and $L_1 = 500$ mm. Table 1 provides both dimension and non-dimension parameters of the specimens. Since current fatigue design guides contain rules for wall thicknesses on <4 mm only, and since the welding procedure and the fatigue behaviors of very thin-walled RHS joints (e.g., $t < 4$ mm) could be different from those of relatively thick wall joints [24], the minimum wall thicknesses of specimens are selected to be 4.5 mm. For comparison, the dimensions of square bird-beak joints SBBJ-X1 and SBBJ-X2 were identical to those of diamond bird-beak joints DBBJ-X1and DBBJ-X2 respectively.

The braces were welded to the chord by using 80% partial joint penetration groove welds plus fillet welds, as shown in Fig. 3. The material of steels is Q345D, which strictly conforms to national standards GB/T 6728-2002 [25]. To obtain the actual mechanical properties of this material, standard test-pieces were taken from the steel tube and then tested under uniaxial tension. The measured yield strengths, ultimate strengths, and Young's Modulus of the steel are listed in Table 2.

2.2. Test rig

A pair of axial tensile forces were applied at the brace ends, as shown in Fig. 4. The upper brace end was connected to the fatigue actuator via pin connection, so that a tensile (upward) concentrated force can be imposed to the specimen along the brace's longitudinal axis. The lower brace end was pin connected to the I-steel base support which has been previously fixed onto the ground with foundation bolts, so that a balanced reaction force (downward) is expected to be accordingly generated at the lower brace end. A force sensor was also placed between the upper brace end and the actuator for accurately measuring the loading.

2.3. Measurement of strain

Researches indicate that even a small eccentricity of the axial force could cause remarkable deviations of stress/strain results, especially for the junction areas where complicated stress/strain distributions are expected. In this test, pin connections were welded to the brace ends with the center of the pin hole being exactly aligned to the center of the brace section, so that the eccentricity of the concentrated force could be avoided. However, due to the unavoidable initial geometric imperfections, which were produced either during the tube manufacture or during the joint welding, the stresses/strains on the brace section could not be symmetric. Therefore, the measured nominal strains in the brace section were also used to verify the eccentricity of axial force. As shown in Fig. 5(a) and (b), twelve equally spaced nominal strain gauges were symmetrically arranged around the outer surface of brace section I—I which was located 250 mm away from the brace end (Fig. 2).

Besides the regular gauges for nominal strain measurement, the strip gauges, which are composed of several regular base elements, were placed along the potential hot line to record the continuous distributions of strains near weld toe, so that the hot spot strains at weld toes can be extrapolated. Referring to the findings of Tong et al. [16] and Cheng et al. [19], four crown hot lines (i.e., Cr-B and Cr-C in the chord, and Cr-A and Cr-F in the brace) and six saddle hot lines (i.e., Sa-B, Sa-C and Sa-D in the chord, and Sa-A, Sa-E and Sa-F in the brace) where the stress levels are expected to be the highest, as shown in Fig. 5(c) and (d), were selected for strain measurement. Strip gauges were symmetrically arranged on both upper and lower side of the chord, that is, totally 20 hot lines were recorded for each specimen.

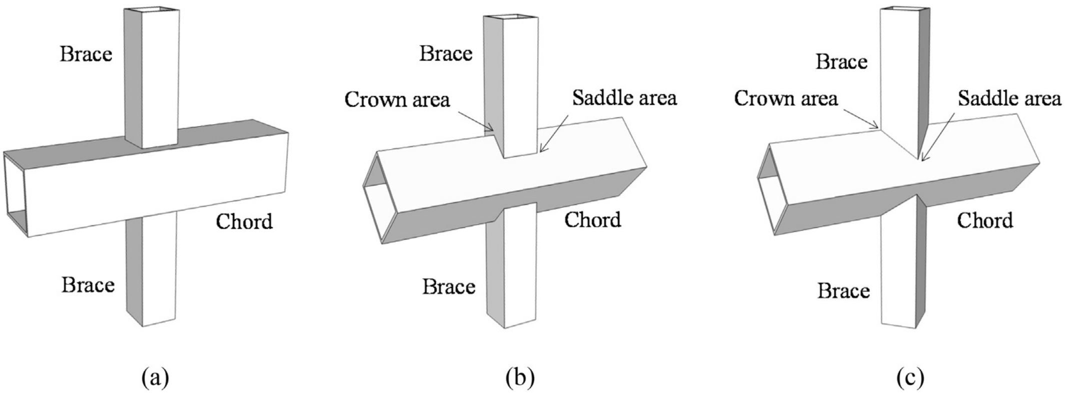

Fig. 1. Welded SHS X-joints: (a) conventional; (b) square bird-beak; (c) diamond bird-beak.

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