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Stress concentration factors test of reinforced concrete-filled tubular Y-joints under in-plane bending

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Abstract. To study the stress concentration factors (SCFs) of concrete-filled tubular Y-joints subject to in-plane bending, experiments were used to investigate the hot spot stress distribution along the intersection between chord and brace. Three concrete-filled tubular chords forming Y-joints were tested with different reinforcing components, including doubler-plate, sleeve, and haunch-plate reinforcement. In addition, an unreinforced joint was also tested for comparison. Test results indicate that the three different forms of reinforcement effectively reduce the peak SCFs compared with the unreinforced joint. The current research suggests that the linear extrapolation method can be used for chords, whereas the quadratic extrapolation method must be used for braces. The SCF is effectively reduced and more evenly distributed when the value of the axial compression ratio in the chord is increased. Furthermore, the SCFs obtained from the test results were compared to predictions from some well-established SCF equations. Generally, the predictions from those equations are very consistent for braces, but very conservative for concrete-filled chords.

Keywords: experimental investigation; Y-joints; concrete-filled; stress concentration factor; in-plane bending; extrapolation method

1. Introduction

Tubular joints are the most common form of joints in tubular structures and are widely used in A-shaped substation trusses for their characteristics of appealing aesthetics, simple structure, material savings, and easy maintenance. Compared with traditional trusses, 750 kV ultra high voltage substation trusses have relatively larger heights, longer spans, and higher load levels. In order to protect the strength and stiffness of the joints, they often need to be reinforced. In addition to pouring concrete into the chords of a tubular truss to strengthen the joints, other common strengthening measures include adding doubler-plates, sleeves, or haunch-plates to the chords (Hoon *et al.* 2001).

Because inherent defects and geometric discontinuities of intersecting welds cause serious stress concentration at the intersecting areas, fatigue cracks usually occur and expand at the maximum stress points and will lead to material fractures (Xu *et al.* 2015). The stress distribution at the joint region has a significant influence on the fatigue performance of structures. For substation trusses, which need to withstand dynamic loads, fatigue failure may play a controlling

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role in structural damage (Fricke 2002). Currently, the hot spot stress method is generally used to evaluate the fatigue life of tubular joints with the use of a mechanical parameter—the stress concentration factor (SCF)—to evaluate hot spot stress (Zhao *et al*. 2001).

The SCFs of various configurations of unreinforced empty tubular joints subjected to different types of basic loading, such as axial tension, axial compression, in-plane bending, and out-of-plane bending, have been empirically established by many researchers (UEG 1985, Chen and Wang 2015). For reinforced tubular joints, previous studies mainly focused on grouted tubular joints. For example, Lloyd's (1980), Marshall (1977), and DNV (2005) have performed fatigue analysis of grouted tubular joints, proposing that the thickness equivalence method can be used together with the formulae for steel tubular joints to calculate the SCFs of grouted tubular joints. Lalani's (1996) research showed that the SCFs of grouted T-joints subjected to axial loading were significantly lower than those of pure steel joints. HSE (1993) showed a discrepancy in the experimental results, and their study pointed out that, only under axial loading or out-of-plane bending, the SCFs of grouted joints were significantly lower than that of pure steel joints; whereas under in-plane bending, the SCFs showed little change.

However, investigation of concrete-filled steel tubular joints is few, some research on concrete-filled CHS joints is concluded as follows. Tong *et al*. (2010) and Mashiri and Zhao (2010) tested the SCFs of the CHS and SHS concrete-filled tubular chords forming T-joints respectively, the test result showed that the SCFs of concrete-filled steel tubular joints was significantly lower than that of pure (or called unfilled) steel joints. Chen *et al*. (2010) have experimentally investigated the SCFs of concrete-filled steel tubular joints under in-plane bending and out-of-plane bending and compared this with relevant international specifications (Lloyd's 1980, Zhao *et al*. 2001, API 2005). Wang *et al*. (2013) investigated the fatigue behavior of CHS and concrete filled CHS T-joints and compared the SCFs of two kinds of T-joints. Furthermore , the existing research is only focused on the empty tubular joints reinforced with internal ring stiffeners (Murthy *et al*. 1991, Ahmadi and Lotfollahi-Yaghin 2015) and doubler-plate reinforced tubular joints (Soh *et al*. 1994, Hoon *et al*. 2001), there are very few studies on the fatigue properties of reinforced concrete-filled steel tubular joints.

With the above research results, it is concluded that the SCFs were generally lower in reinforced joints than in unreinforced joints of similar geometry and size. In this paper, the basic theory and methods of hot spot stress test were followed for hollow welded tubular joints. This was applied to the actual situation of the Qiaowan 750 kV substation project at Gansu, China, and experimental investigations of SCF were carried out on four 1:2 scaled Y-shaped welded tubular joints that connected tubular braces and concrete-filled tubular chords, including an unreinforced joint and three different types of reinforced joints (doubler-plated, sleeved, and haunch-plated). The study focused on the SCF distributions in chords and braces when the joints were subjected to combined loads of axial pressure on the chords and in-plane bending on the braces, and the test results were compared with the relevant specifications of, LR (1980), Zhao *et al*. (2001), and API (2005).

2. Experimental study

2.1 Design of specimens

The specimens were based on the 750 kV A-shaped steel concrete substation truss at Gansu, China. Taking into account the requirements of specimen production and loading equipment, four

1:2 scaled specimens were designed. Meanwhile, in order to eliminate the influence of the end restraint of chords on the joint area, the lengths of the chords and braces were selected to be three times larger than their diameters.

Fig. 1 shows the shape and dimensions of the test specimens. Table 1 contains the primary geometric parameters of all joint specimens. The braces of all the specimens were tubular steel and the chords were steel concrete. One of these specimens was an unreinforced joint (SJ1) to be used as a reference specimen, and the other three were reinforced joints, including doubler-plate reinforcement (SJ2), sleeve reinforcement (SJ3), and haunch-plate reinforcement (SJ4). All

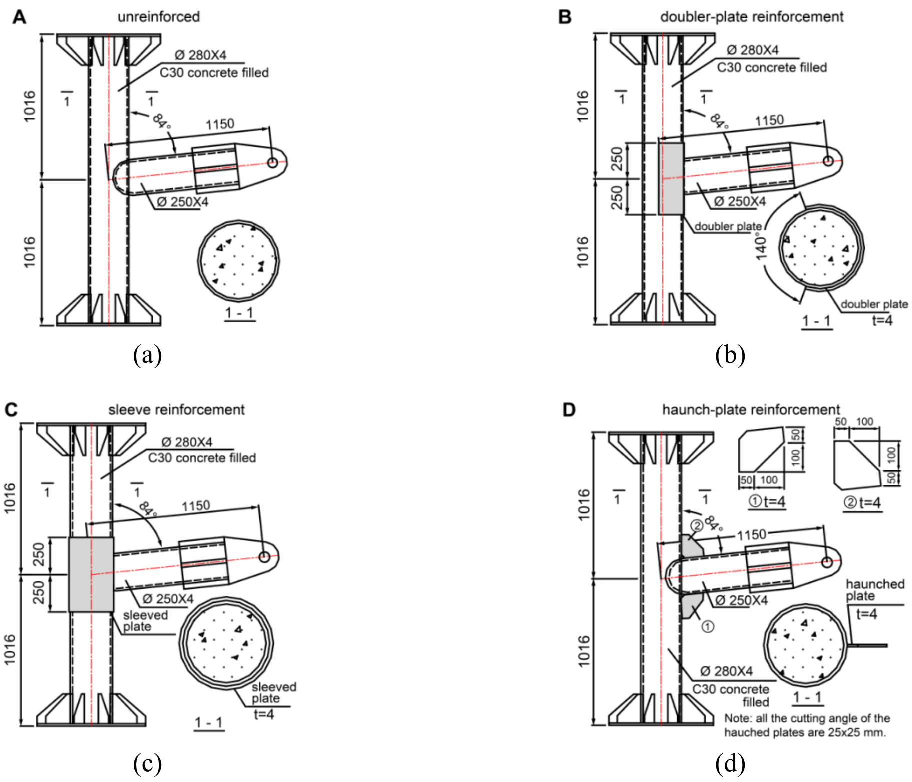


Fig. 1 Geometry of specimens (unit: mm): (a) unreinforced joint; (b) doubler-plated reinforcement; (c) sleeved reinforcement; (d) haunch-plated reinforcement

Table 1 Experimental parameters of specimens

Specimen	Reinforcement type	Chord (CFT)		Brace (Pure steel tube)		Reinforcing plate
		Diameter / mm	Thickness / mm	Diameter / mm	Thickness / mm	Thickness / mm
SJ1	Unreinforced	280	4	250	4	/
SJ2	Doubler-plated	280	4	250	4	4
SJ3	Sleeved	280	4	250	4	4
SJ4	Haunch-plated	280	4	250	4	4

Table 2 Material properties of steel

Steel	t / mm	f_y / MPa	f_u / MPa	δ / %	E / GPa	f_u/f_y
Q345B	3.8	405	490	31	195	1.21

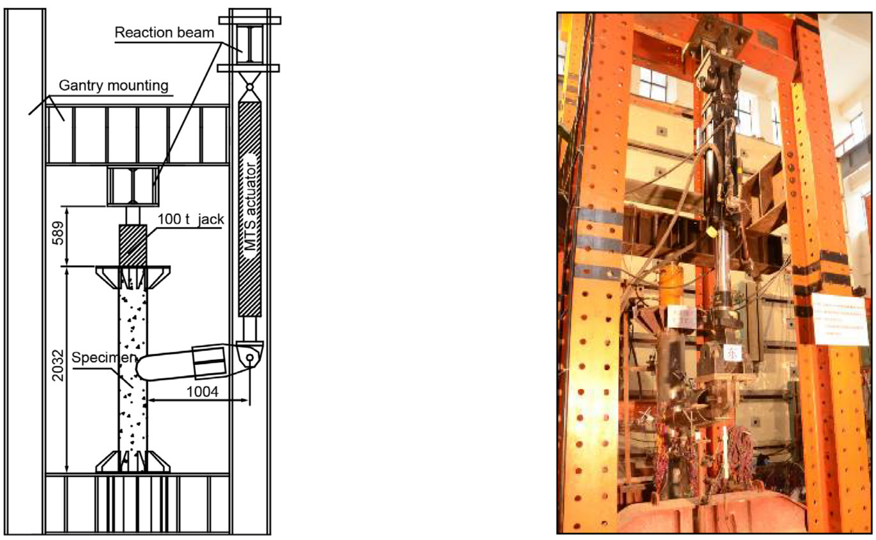
specimens were factory processed welded tubular steel. The chords and braces were connected using carbon dioxide gas shielded welding, with full penetration welds for intersecting weld seams. The quality rating of the welds was two, with testing required.

All specimens were made from Q345B (Chinese standard) steel. The test results of the material properties are shown in Table 2. The chords were filled with C30 concrete, which was poured in a conventional construction method, processed with plug-in vibrators, and cured naturally. After being cured for 28 days, the measured compressive strength of the concrete cubes was 36.2 MPa.

2.2 Experimental setup and loading method

The experimental setup is shown in Fig. 2. The pedestal of the chord was rigidly connected to the base, which was fixed to the top of the experiment by anchor bolts at the two ends of the pressure beam. A 100-ton hydraulic jack was placed on the top end of the chord, and a set of independently developed regulator devices was connected in parallel to ensure constant loading. The end of the brace was connected to a 50-ton MTS actuator through a pin connection to apply vertical loads in the direction perpendicular to the brace so that the joint was subjected to in-plane bending.

In the experiment, the impacts of the axial compression ratio on the SCFs of the joints were investigated by applying different axial compression ratios (0.2 and 0.4). For each specimen, 30%, 40%, and 50% of the minimum yield moment obtained by finite element simulation was loaded for three times each to calculate an average hot spot stress.



(a) Loading device (b) Photo of the setup

Fig. 2 Experimental setup: (a) loading device; (b) photo of setup

2.3 Experimental methods

2.3.1 Experimental principle

The SCF reflects the uneven distribution of hot spot stress and the stress concentration level of the joint area, which is useful for applications of engineering design. In this paper, the strain concentration factors (SNCF) of the joints were obtained from the experimental data of resistance strain gauges that were attached to weld toes at intersecting weld seams and were then converted to the SCFs of the joints. The SNCF is defined as

$$\mathrm{SNCF} = \frac{\varepsilon_{\perp}}{\varepsilon_{\mathrm{n}}} \tag{1}$$

where $\varepsilon_{\perp}$ is the vertical strain at the weld seam and is obtained by extrapolating the strain perpendicular to the weld seam; ε_n is the nominal strain of the tubular joint, which is the strain in the brace at the end away from the weld seam. The nominal strain ε_n can be obtained with basic principle of mechanics, independent of the boundary conditions of the chord.

The nominal strain under in-plane bending $\varepsilon_{n,\mathrm{I}}$ can be calculated as

$$\varepsilon_{\mathrm{n,I}} = \frac{32dM_{\mathrm{I}}}{\pi\left[d^4-(d-2t)^4\right]E} \tag{2}$$

where M_{I} is the in-plane bending moment, d is the diameter of the brace, t is the thickness of the brace, and E is the elastic modulus.

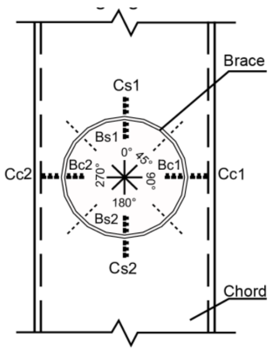
The SCF can be calculated from the SNCF as

$$\begin{aligned}\mathrm{SCF} &= \frac{\left(1+\upsilon\dfrac{\varepsilon_{//}}{\varepsilon_{\perp}}\right)}{(1-\upsilon^2)}\times\mathrm{SNCF} \\ &= c\times\mathrm{SNCF}\end{aligned} \tag{3}$$

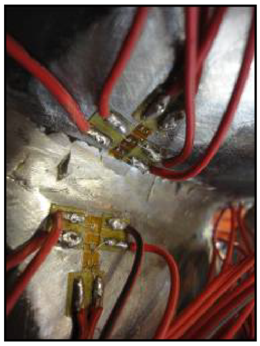
where υ is the Poisson ratio of steel (0.3 in this work), $\varepsilon_{//}$ is the parallel strain at the weld seam, which is obtained by extrapolating the strain reading of strain gauges in the direction parallel to the weld seam, and c is the ratio between the SCF and the SNCF. This ratio can be determined from the ratio between the parallel strain and vertical strain and is usually between 1.1 and 1.2. The value 1.2 was used in this study (Tong *et al*. 2010, Chen *et al*. 2010).

2.3.2 Arrangement of strain gauges

There are two extrapolation methods suggested by CIDECT (2001) for obtaining hot spot stress: linear extrapolation and quadratic extrapolation, this two different extrapolation methods can be used in getting the test results if their difference is less than 15%, otherwise, the quadratic extrapolation should be used. First, an interpolation area was defined based on the minimum and maximum distances to weld toes. Three reference points were selected in this area. In this work, positions with distances of 4 mm, 6 mm, and 8 mm to weld toes were taken based on the thickness of the brace wall. To facilitate the arrangement, BX120-0.5AA miniature strain gauges were used, with a grid size of only 0.5 × 0.5 mm. The strain values at these three reference points could be measured first, and then the strain at the weld seam could be obtained by quadratic interpolation or



(a) Arrangement of strain gauges



(b) Photo of the gauges

Fig. 3 Arrangement of strain gauges and test photo: (a) arrangement of strain gauges; (b) photo of gauges

linear interpolation.

The hot spot stresses of tubular joints were generally larger at crown points or saddle points of intersecting lines, and the crown positions of the tubular joint are significantly affected by the local loading on the chord and the bending moment in the chord (Lotsberg 2011). In order to investigate whether there are larger hot spot stresses between crown points and saddle points in a concrete-filled chord, three additional strain gauges were attached to the chord and brace around the weld seam at every 45° to measure the strain perpendicular to the intersecting weld seam. Additional strain gauges were also attached to the crown point and saddle point along a direction parallel to the weld seam to measure the strain parallel to the intersecting weld seam. The specific arrangement of the primary strain gauges is shown in Fig. 3.

3. Test results and discussion

3.1 Different extrapolation methods

There are two extrapolation methods suggested by Zhao *et al*. (2001) for obtaining hot spot stress: linear extrapolation and nonlinear extrapolation. HSE (1993) suggested that the linear extrapolation method could be used for 90° T-joints and the nonlinear extrapolation should be used in some cases of Y-joints. Lloyd's Register (1988) had conducted research on the hot spot stresses of 67 T/Y joints and showed that the two extrapolation methods gave similar results in the case of joints under axial force, but they gave significantly different SCF values when joints were subjected to in-plane bending. In the study by Tong *et al*. (2010), the extrapolation methods were also compared, leading to the conclusion that the hot spot stresses of chords can be obtained by linear extrapolation and the hot spot stresses of braces require the use of a quadratic extrapolation.

To avoid discrepancy in the test results caused by using different extrapolation methods, three layers of strain gauges were placed at intersecting regions, and both extrapolation methods were used to obtain the hot spot stress. The two measured results are shown in Fig. 4. For each specimen, the values as well as the trend of the SCF obtained by linear interpolation and quadratic interpolation were nearly consistent. The SCF values obtained for braces by the two interpolation methods showed significant differences at crown points. The differences in the SCFs of braces at crown points were 18% and 21% for SJ1 and SJ3, respectively. The differences in the SCFs of

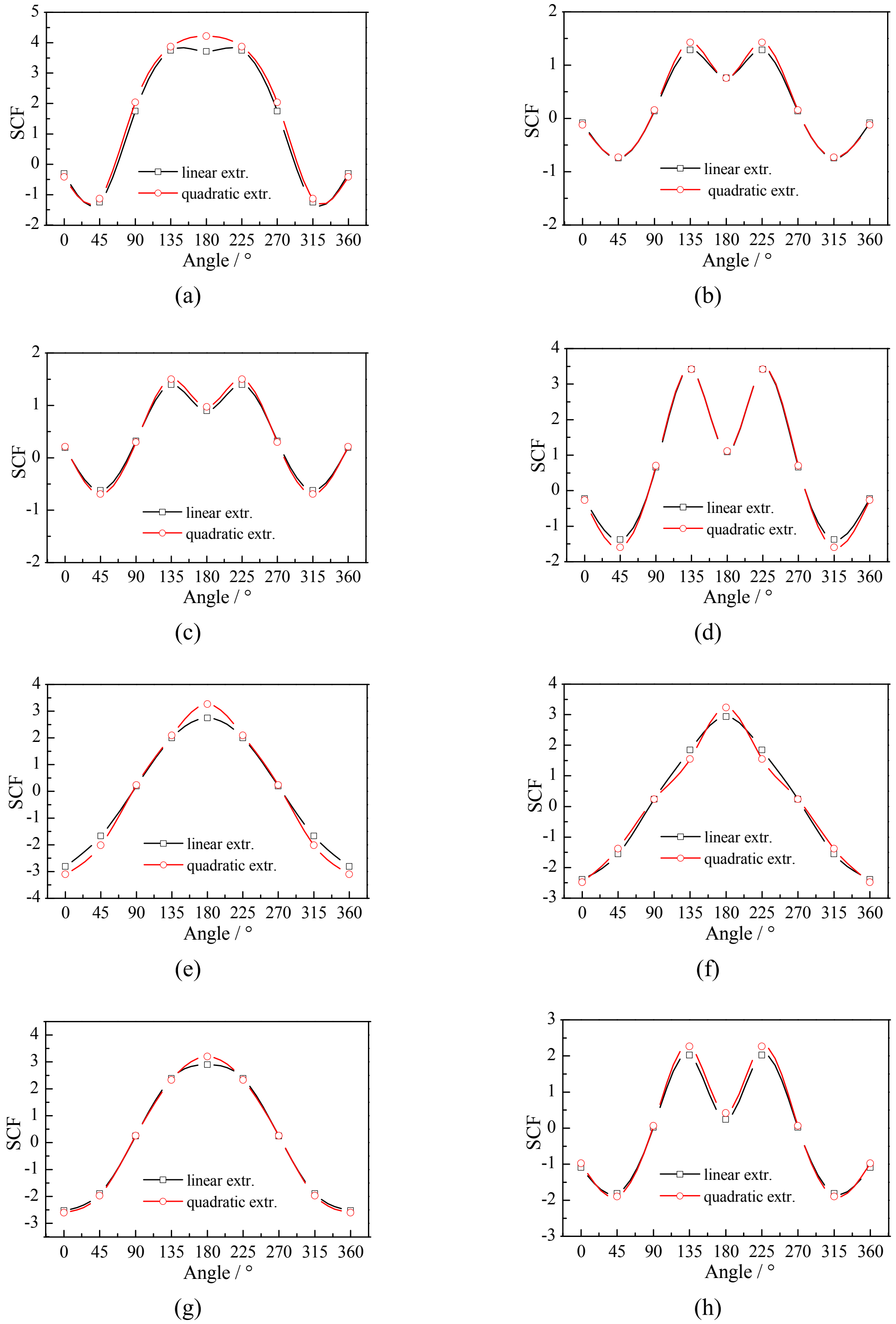


Fig. 4 Comparison of the SCFs obtained by linear and quadratic extrapolation: (a) SJ1 chord; (b) SJ2 chord; (c) SJ3 chord; (d) SJ4 chord; (e) SJ1 brace; (f) SJ2 brace; (g) SJ3 brace; (h) SJ4 brace

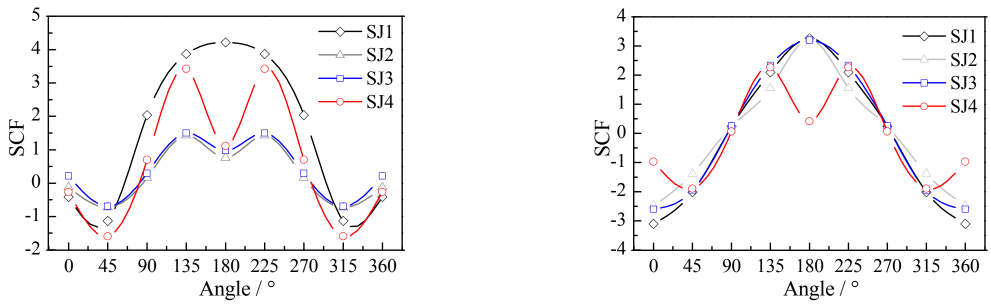
chords were 13% and 8% for SJ1 and SJ3, respectively, which were greater than those of the other specimens.

Overall, the chord SCF values obtained by linear interpolation and quadratic interpolation showed little difference—no more than 15%. Therefore, the hot spot stresses of chords can be obtained via linear extrapolation. However, the maximum difference in the SCF values for braces reached 21%, so nonlinear extrapolation is necessary. These finding agree with the previously stated conclusions of Tong, *et al*. (2010).

3.2 Different forms of reinforcement

Fig. 5 shows the distribution of SCF values for each chord and brace under in-plane bending. The specific calculated results are presented in Table 3.

Fig. 5 and Table 3 show that the SCFs of chords for reinforced joints SJ2, SJ3, and SJ4 clearly present a decreasing trend. At the lower crown points (corresponding to the 180° position) of the maximum SCF values, the SCF values for specimens SJ2, SJ3, and SJ4 were, respectively, only 18%, 23%, and 26% of that for the unreinforced joint, SJ1. This indicates that the forms of reinforcement used in this work significantly reduced the hot spot stresses of chords. However, the reduction was less significant for the braces. The SCF values for SJ2 and SJ3 only decreased by 1% and 3%, respectively, compared with that for SJ1. However, the SCF value for SJ4—with haunch-



(a) (b)

Fig. 5 Comparison of the SCF distributions in joints with different forms of reinforcement: (a) chord; (b) brace

Table 3 Comparison of the SCFs of joints with different forms of reinforcement

Angle / °	SJ1		SJ2				SJ3				SJ4			
	Chord	Brace	Chord		Brace		Chord		Brace		Chord		Brace	
	SCF_c	SCF_b	SCF_c	$\frac{SJ2}{SJ1}$	SCF_b	$\frac{SJ2}{SJ1}$	SCF_c	$\frac{SJ3}{SJ1}$	SCF_b	$\frac{SJ3}{SJ1}$	SCF_c	$\frac{SJ4}{SJ1}$	SCF_b	$\frac{SJ4}{SJ1}$
0	-0.41	-3.10	-0.12	0.30	-2.48	0.80	0.21	-0.51	-2.61	0.84	-0.27	0.64	-0.97	0.31
45	-1.14	-2.02	-0.73	0.64	-1.38	0.69	-0.69	0.61	-1.97	0.98	-1.59	1.40	-1.90	0.94
90	2.04	0.23	0.15	0.08	0.23	1.00	0.30	0.15	0.26	1.10	0.70	0.34	0.06	0.26
135	3.87	2.09	1.42	0.37	1.55	0.74	1.50	0.39	2.33	1.11	3.42	0.88	2.27	1.08
180	4.22	3.27	0.75	0.18	3.23	0.99	0.97	0.3	3.20	0.97	1.12	0.26	0.42	0.13

plate reinforcement—decreased by 87% compared with that for SJ1. The comparison of SJ2, SJ3, and SJ4 shows that the SCF distributions and values for chords and braces for doubler-plate reinforced SJ2 and sleeve reinforced SJ3 had no significant difference. This indicates that the effects of these two reinforcement methods are very similar. —Although the SCFs at crown points of the chord and the brace were significantly reduced for haunch-plate reinforced SJ4, the SCF of the chord at 135° was roughly equal to that for the unreinforced specimen. The methods of doubler-plate and sleeve reinforcement show obvious impacts on the SCF distributions and values in chords but no significant effect on the SCFs in braces, whereas the haunch-plate reinforcement shows exactly opposite influences.

The main reason for this phenomenon is that the distribution of hot spot stress is closely related to the stiffness distribution in the joints. Filling the chords with concrete or reinforcing them in other ways strengthens the stiffness of the joints, resulting in a change in the stiffness distribution around intersecting weld seams. Furthermore, the haunch-plate in SJ4 attenuated most of the bending moment at the joint, resulting in a significant reduction of stress at the crown point.

3.3 Different axial compression ratios

Fig. 6 shows the SCF distributions in the chord and brace for each specimen under different axial compression ratios of the chords. As shown in Fig. 6, the axial compression ratio of the chord has a consistent effect on concrete-filled steel joints with different forms of reinforcement: it does not change the distribution of the SCFs in the joints but only causes changes in the SCF values. As

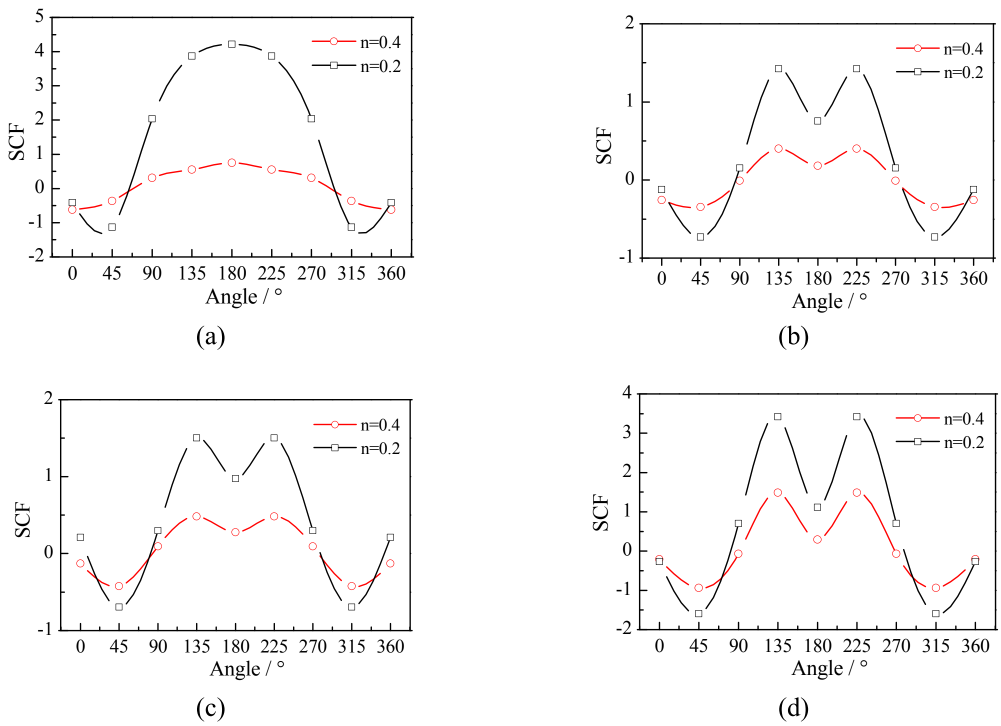


Fig. 6 Effect of the axial compression ratio on the SCF distributions in joints: (a) SJ1 chord; (b) SJ2 chord; (c) SJ3 chord; (d) SJ4 chord; (e) SJ1 brace: (f) SJ2 brace; (g) SJ3 brace; (h) SJ4 brace

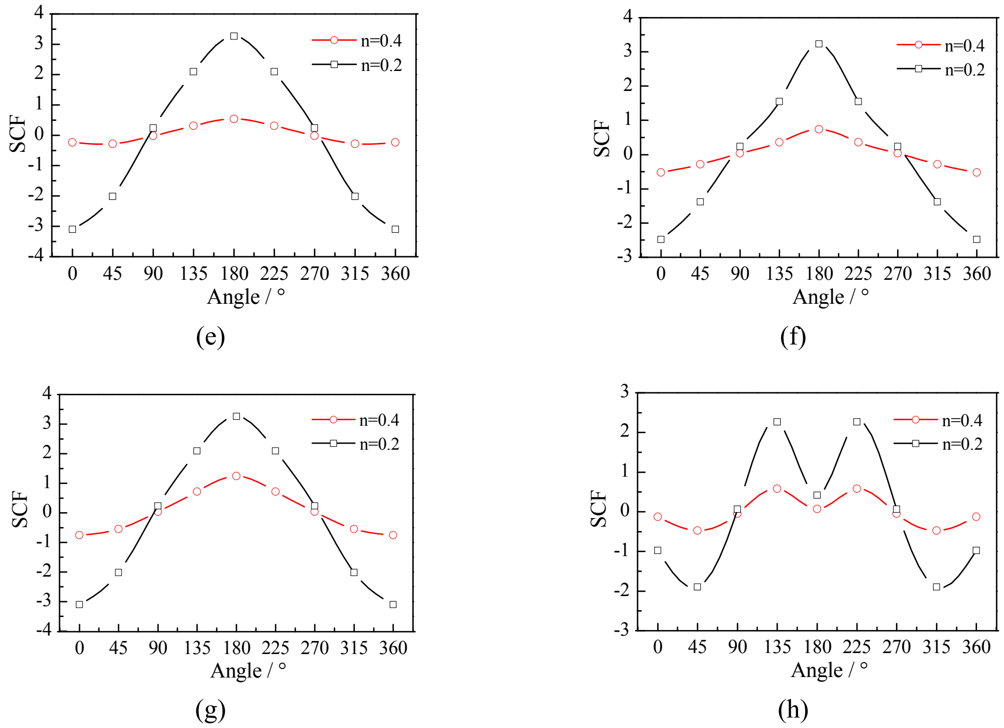


Fig. 6 Continued

the axial compression ratio of the chords increased from 0.2 to 0.4, the SCFs of the chords and braces decreased by almost half for each specimen. The distribution of the SCF along the intersecting weld seam became more uniform for higher axial compression ratios.

Therefore, for concrete-filled steel joints subjected to in-plane bending, an increase of the axial compression ratio is beneficial to the value and distribution of the SCFs in the joints. However, in an actual substation truss, for the truss column on the side that receives tension (chord under tension in this case), the axis tensile force might cause more adverse effects on the SCFs of the joints that still need to be explored further.

4. Design predictions

4.1 Formulae for the SCF from various specifications

Methods for calculating the SCFs of steel tubular joints under different loading are not available in any specification that is relevant to steel structures. However, there are many formulae provided by foreign institutes for calculating the SCFs of tubular joints. Among them, we consider those of the CIDECT Design Guide (Zhao *et al*. 2001) by the International Association of Leading Manufacturers of Hollow Sections and Pipes, the API Standard (2005) by the American Petroleum Institute, and the LR Guide (1980) by the Lloyd's Register Foundation. The formulae provided by the above institutes for calculating the SCFs of tubular joints under in-plane bending are as follows:

CIDECT Design Guide

$$SCF_{\mathrm{cc}} = 1.45\beta\tau^{0.85}\gamma^{(1-0.68\beta)}\sin^{0.7}\theta\,, \tag{4a}$$

$$SCF_{\mathrm{bc}} = 1 + 0.65\beta\tau^{0.4}\gamma^{(1.09-0.77\beta)}\sin^{(0.6\gamma-1.16)}\theta\,. \tag{4b}$$

API specification

$$SCF_{\mathrm{c}} = 1.2\sqrt{\gamma}\tau\sin\theta\,, \tag{5a}$$

$$SCF_{\mathrm{b}} = 1.0 + 0.375(1 + \sqrt{\tau/\beta}SCF_{\mathrm{c}}) \geq 1.8\,. \tag{5b}$$

LR specification

$$SCF_{\mathrm{c}} = 1.22\beta\tau^{0.8}\gamma^{(1-0.68\beta)}\sin^{(1-\beta^3)}\theta\,, \tag{6a}$$

$$SCF_{\mathrm{b}} = 1 + \beta\tau^{0.2}\gamma(0.26 - 0.21\beta)\sin^{1.5}\theta\,. \tag{6b}$$

In the above formulae, β is the ratio of between the diameters of the chord and brace, 2γ is the ratio between the chord diameter and the thickness of the chord wall, τ is the ratio between the thicknesses of the brace wall and the chord wall, and θ is the brace inclination angle. The SCF of the chord and brace at crown points are SCF_{cc} and SCF_{cb}, respectively, and the maximum SCF of the chord and brace are SCF_c and SCF_b, respectively.

4.2 Comparison between the SCF from the test results and the specification formulae

Comparisons were also made between the stress distributions obtained from the experimental results and those predicted by design methods. Tables 4-6 show the comparison between the SCFs from the test results and the specification formulae.

For the chords used in this work, the SCF values calculated by existing specifications are quite different from the test results and are all on the conservative side. Especially for reinforced joints, the use of existing specifications for the design may result in an excess use of materials. For braces, the differences between the test results and the specification calculations are relatively small, which suggests that filling the chords with concrete has a very small impact on the SCFs of the

Table 4 Comparison between the SCFs from the test results and the CIDECT design formulae

Specimen #	Test value		CIDECT		Test / CIDECT	
	SCF_{cc}	SCF_{cb}	SCF_{cc}	SCF_{cb}	SCF_{cc}	SCF_{cb}
SJ1	4.22	3.27	5.49	3.28	0.77	1.00
SJ2	0.75	3.23	5.49	3.28	0.14	0.99
SJ3	0.97	3.20	5.49	3.28	0.18	0.98
SJ4	1.12	0.42	5.49	3.28	0.20	0.13

Table 5 Comparison between the SCFs from the test results and the API design formulae

Specimen #	Test value		API specification		Test / API	
	SCF_{cc}	SCF_{cb}	SCF_{cc}	SCF_{cb}	SCF_{cc}	SCF_{cb}
SJ1	4.22	3.27	7.55	4.37	0.56	0.75
SJ2	1.42	3.23	7.55	4.37	0.19	0.74
SJ3	0.97	3.20	7.55	4.37	0.13	0.73
SJ4	3.42	2.27	7.55	4.37	0.45	0.52

Table 6 Comparison between the SCFs from the test results and the LR design formulae

Specimen #	Test value		LR specification		Test / LR	
	SCF_{cc}	SCF_{cb}	SCF_{cc}	SCF_{cb}	SCF_{cc}	SCF_{cb}
SJ1	4.22	3.27	4.63	3.57	0.91	0.91
SJ2	1.42	3.23	4.63	3.57	0.31	0.91
SJ3	0.97	3.20	4.63	3.57	0.21	0.90
SJ4	3.42	2.27	4.63	3.57	0.74	0.63

braces. Therefore, the use of existing specifications for calculating the SCFs of braces is reliable, but the case of haunch-plate reinforcement needs to be considered separately.

In addition, comparing the CIDECT, API, and LR specifications, the API specification is the most conservative, whereas the calculations from the CIDECT and LR specifications more closely match the test values. The main reason for this difference is that the SCF calculation formulas for CIDECT and LR specification considered the parameters of β, γ, τ, and θ, and the chord and branch are unrelated, see Eqs. 4(a)~(b) and Eqs. 6(a)~(b); while the API specification formula of chord SCF only considers the three parameters γ, τ, and θ, does not take into account the ratio of between the diameters of the chord and brace β, so the form of its formula is too simple to get the more accurate SCF value (see Eq. 5(a)), and the brace SCF formula of API specification is based on the charge of SCF value again, which maybe cause a higher error when calculating the brace SCF value, see Eq. 5(b).

5. Conclusions

Based on the engineering background of the first 750 kV concrete-filled tubular substation in China, the SCFs of four concrete-filled tubular Y-joints with different forms of reinforcement were tested under the in-plane bending, and the SCFs obtained from the test results were compared to predictions from some well-established SCF equations. The following conclusions can be made on the basis of this study:

- With the comparison between the SCF results obtained with linear interpolation and quadratic interpolation, the errors in the SCF values for chords and braces are different, and the hot spot stresses of chords can be obtained by linear extrapolation, whereas the hot spot stresses of braces require the use of quadratic extrapolation.
- In this paper, all forms of reinforcement have significantly reduced the SCF values

compared the unreinforced joint. Doubler-plate and sleeve reinforcement show obvious impacts on the SCF distributions and values in chords but no significant effect on the SCFs of braces; however, haunch-plate reinforcement shows the opposite influences.

- The axial compression ratio for chords has a consistent effect on the SCF values of the four different forms of joints in this paper, but it does not change the distribution of the SCFs in joints. For concrete-filled steel joints subjected to in-plane bending, an increase of the axial compression ratio is beneficial to the value and distribution of the SCFs in joints. However, in an actual substation truss, for the truss column on the side that receives tension (chord under tension in this case), the axial tensile force might cause more adverse effects on the SCFs of the joints. Additional testing and result analysis are needed to evaluate this issue.
- For chords used in this study, the SCF values calculated by existing specifications are quite different from the test results and are all on the conservative side. For braces, the differences between test results and specification calculations are relatively small, which suggests that filling chords with concrete has a very small impact on the SCFs of braces. Therefore, the use of existing specifications for calculating the SCFs of braces is reliable.
- Note that in the case of haunch-plate reinforcement, the presence of a haunch-plate caused an obvious change in the stress distribution around the intersecting weld seam. Thus, it needs to be considered separately.

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