Title	Stress Concentration Factors of Reinforced Square Hollow Section T-Joints(Mechanics, Strength & Structure Design)
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Citation	Transactions of JWRI. 2001, 30(2), p. 103-108
Version Type	VoR
URL	https://doi.org/10.18910/7557
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Stress Concentration Factors of Reinforced Square Hollow Section T-Joints †

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Abstract

This paper reports on an investigation into the stress concentration factors of a reinforced Square Hollow Section T–joint under brace axial compression. The project consists of both experimental and numerical studies. A full-scale reinforced T-joint specimen was tested with the brace loaded under axial compression. The results were compared to those obtained from a finite element model and the model was observed to be able to predict the stress concentration factors satisfactorily. A parametric study was then conducted to understand the influence of the geometric parameters on the stress concentration factor at various hot-spots on the reinforced joint. The results of the parametric study show that the stress concentrations generally increase with increasing β (brace to chord diameter ratio), and increasing 2γ (chord diameter to thickness ratio). The results have shown that the plate reinforcement reduces the stress concentration factors at the joint as compared to the stresses of a similar unreinforced joint. It can be concluded that the doubler plate reinforcement may enhance the fatigue strength of the joint. Empirical equations to predict the stress concentration factors at various points of the doubler plate reinforced T–joint are proposed.

KEY WORDS : (Reinforced T-Joint) (Stress Concentration Factor) (Doubler Plate) (Square Hollow Section)

1. Introduction

Hollow section structural elements are favoured for use in steel structures due to the high torsional rigidity of these closed-section members. Various methods of strengthening the joints of hollow sections include the use of reinforcements and internal and external stiffeners. Local strengthening is generally more economical compared to the provision of a stronger member. Recent research has determined that the addition of a doubler plate reinforcement could greatly improved the axial load bearing capacity of a tubular T-joint [1)-3)]. This project aims to investigate the influence of a doubler plate reinforcement on the stress concentration factors (SCF) of square hollow section (SHS) T-joints.

A full-scale specimen was tested under brace axial compression and this was used to validate a finite element model of the joint. A parametric study was conducted to determine the influence of the various geometric parameters on the stresses at the joint and to develop parametric formulae to predict the stress concentrations. The effect of the doubler plate was examined by a comparison with data on unreinforced joints.

2. Hot Spot Stresses and Stress Concentration Factors

A hot spot is the term used to refer to the critical points in a structure, where fatigue crack initiation is expected and joint failure starts. Hot spot stress (HSS) is the stress in the most highly stressed region within the structure and is thought to best characterize fatigue in tubular joints. In the HSS method of fatigue analysis, the fatigue strength is expressed as an S_r-N_f curve which gives the relationship between the stress range, S_r (difference between the maximum and minimum stresses) and the number of cycles, N_f,

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† Received on February 1, 2002

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Transactions of JWRI is published by Joining and Welding Research Institute of Osaka University, Ibaraki, Osaka 567-0047, Japan.

to failure for a specified probability of failure. The magnitude of load to cause fatigue failure decreases with increasing number of load applications.

The SCF is defined as the geometric HSS divided by the nominal stress in an attached brace. When the SCF for various types of load cases are known the HSS for any arbitrary combination of loads can be determined. Parametric formulae derived for various joint configurations are used to determine the SCF at pre-specified hot spot locations. One advantage of the HSS approach is the possibility of predicting the fatigue lives of various joint configurations using a single S_r-N_f curve with parametric formulae for determining the SCFs for different types of joints.

However, much of the fatigue data for tubular joints are referred to strain gauge measurements on steel models and converted to stress. On the other hand, analysis is usually based on direct stress analysis. The conversion from hot spot strains ε_{HSS} to SCF can be described as follows:

$$SCF = \frac{1}{1-\nu}\left(1+\nu\,\frac{\varepsilon_{HSS'}}{\varepsilon_{HSS}}\right)\left(\frac{\varepsilon_{HSS}}{\varepsilon_{nom}}\right) \qquad (1)$$

where $\varepsilon_{HSS'}$ is the strain at the weld toe perpendicular to the ε_{HSS} direction, υ is the Poisson's ratio and the ratio of the hot spot strain to the nominal brace strain, $\varepsilon_{HSS}/\varepsilon_{nom}$ is the strain concentration factor. Dutta [4] proposed that the SCF for a SHS joint be simplified to

$$SCF = 1.1\left(\frac{\varepsilon_{HSS}}{\varepsilon_{nom}}\right) \qquad (2)$$

A recent preliminary study by Soh et. al. [5] of the stress analysis on doubler plate reinforced CHS joints subjected to axial tension and in-plane bending load showed that doubler plate would not cause a more severe fatigue problem as compared with the corresponding unreinforced joints if the doubler plate thickness was close to the thickness of the chord. The study also concluded that the length and width of the doubler plate do not have significant effects on the reinforced joints.

3. Experimental Investigation

A full-scale doubler plate reinforced square T-joint as shown in **Fig. 1** was fabricated with a doubler plate of 200x200x10mm. The geometric parameters used to define a SHS joint are also illustrated in Fig. 1. These corresponded to non-dimensional parameters α (2L/B) = 10.3, β (b/B) = 0.3, 2γ (B/T) = 21.9, τ (t/T) = 0.63.

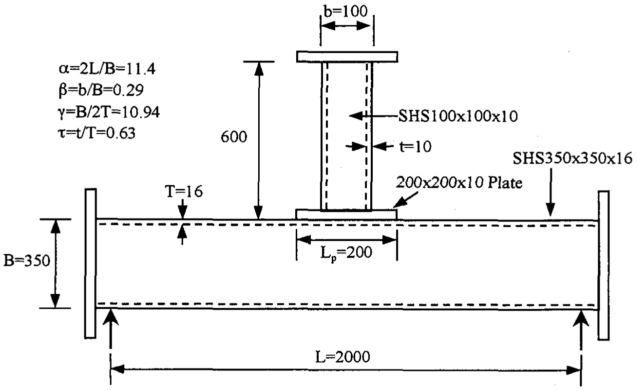

Fig. 1 Geometric parameters and dimensions of test specimen

A total of 12 five-in-line strain gauges (FLA2-5-11) were placed at lines A to F and at the opposite corner of the brace, A' to F'. This was to ensure that the brace was loaded symmetrically and the results are the mean of the two sets of readings. Another 12 single gauges were placed at the mid-brace and mid-chord of the specimen to monitor the application of load. The location of the strain gauges on the test specimen is illustrated in **Fig. 2**. The chord ends were simply supported and a nominal axial compressive load was applied onto the brace.

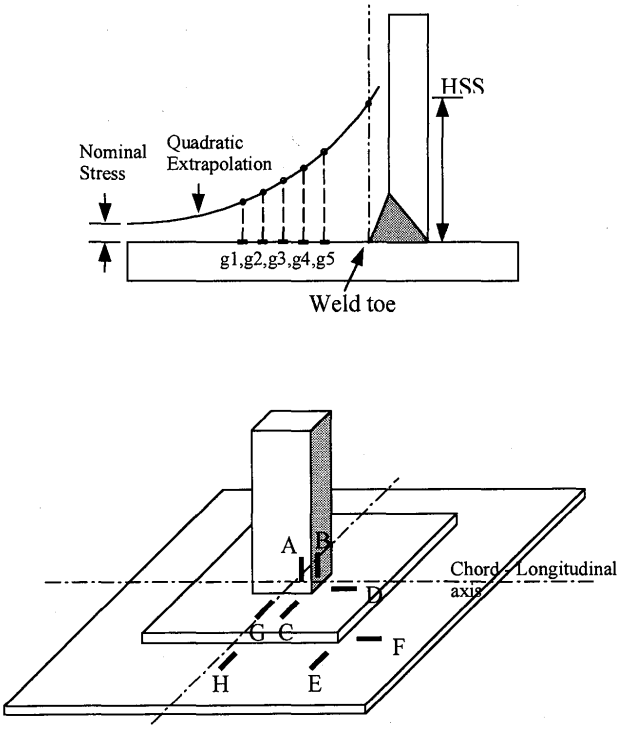

Fig. 2 Method of extrapolation of stresses to weld toe and position of the HSS on the reinforced joints

The strain readings obtained from the five-in-line gauges at different load applications were extrapolated to the weld toe by adopting a quadratic equation. The result was the hot spot strain at the pre-assigned locations. Figure2 shows the quadratic extrapolation of the strains to the weld toe. **Table 1** shows the results of the strain concentration factors (SNCF) from the test specimen.

Table 1 Strain concentration factors for the test specimen

Location	Test	FE Model	Error, %
Line A	3.0	3.3	9.1
Line B	7.5	8.3	9.1
Line C	11.2	12.2	7.9
Line D	4.6	5.3	12.4
Line E	3.3	6.8	51.7
Line F	4.1	4.4	5.8

The maximum SNCF occurred at line C on the doubler plate followed by the line B on the brace. The SNCFs at all the other locations were not particularly high with values ranging from 3.0 to 4.6.

4. Finite Element Analysis

The stress analysis of a doubler plate reinforced SHS T-joint in this project was carried out using a commercial finite element program. Due to symmetry, only a quarter of the doubler plate reinforced square T-joint was modeled when subjected to brace axial compression. The end plates were included in the FE model and the lower edge of the plates was vertically restrained to simulate simple supports. The corner radii of the hollow section members, especially the brace member, is important in the finite element model as it can affect the SCF values to a large extent. Preliminary studies concluded that a sharp-cornered brace member achieved SCF values at the hot spot brace location three times larger than that obtained with corner radius modeled on the brace.

The 20-noded 3-dimensional isoparametric brick element was employed to model the entire reinforced joint. Gap/friction elements were adopted to model the contact interaction between the doubler plate and the chord surface. A convergence test confirmed that the 571 element model as shown in **Fig. 3** was sufficiently accurate and an increase in the number of elements up to 921 did not provide any significant improvement.

The FE model was used for comparison of SNCF values with those obtained from the test at the pre-assigned locations. The model showed predictions that were close but marginally higher compared to those obtained in the test. The location of the highest SNCF was also observed to be at the weld toe on the doubler plate. The difference between the test results and the FE predictions was approximately 10%, except at line E where a discrepancy of more than 50% was obtained. Wingerde [6] showed that stress distributions were sensitive to small changes to the geometry of the joint and that slight variation in the dimension of corner radii, or weld thickness may give rise to differences in results obtained. Two additional HSS locations (G and H) were identified in the FE study and are included for the parametric study.

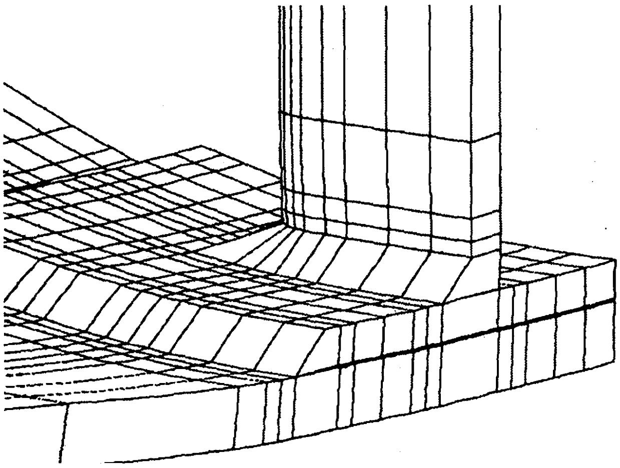

Fig. 3 Finite element model of the reinforced SHS T-joint : a quarter model

5. Parametric Study

The geometric range adopted for this parametric study was limited to the range proposed by Wingerde et.al. [5] to allow for a comparison of the differences between unreinforced and reinforced SHS T-joints. Five values of non-dimensional parameter β were investigated: 0.30, 0.35, 0.40, 0.45 and 0.50; together with the non-dimensional parameter γ, which was varied from 10.0, 11.25 to 12.5. The doubler plate thickness was made similar to the chord thickness and of width 0.8 times the chord width to allow for a corner radius and welding, and the brace thickness was kept at 0.7 times the chord thickness ($\tau = 0.7$). A previous study Gibstein [7] indicated that the parameter α had insignificant effects on the SCFs and was excluded from this study.

Figure 4 shows the SCFs for the three γ values against the β parameter for all 8 HSS locations. The SCF was observed to increase as β increased from 0.3 to 0.5 at all locations except lines D and G where the SCFs were generally constant over the range investigated. The maximum SCF occurred at lines A and C at the brace to doubler plate intersection and at line H at the chord. The SCF at line E was small especially for small γ values. A comparison of the SCF for various γ values indicates that the SCF increased as the γ value was increased, except for lines F and H where the maximum stresses occurred at $\gamma = 11.25$.

A curve fitting program was used to obtain a best-fit curve, using an equation format similar to that proposed by Wingerde et.al. [6] for unreinforced SHS T-joints. The proposed formulae are listed in **Table 2**. **Figure 5** illustrates a scatter plot to show the accuracy of the predictions from the FE model compared with those obtained from the proposed formulae.

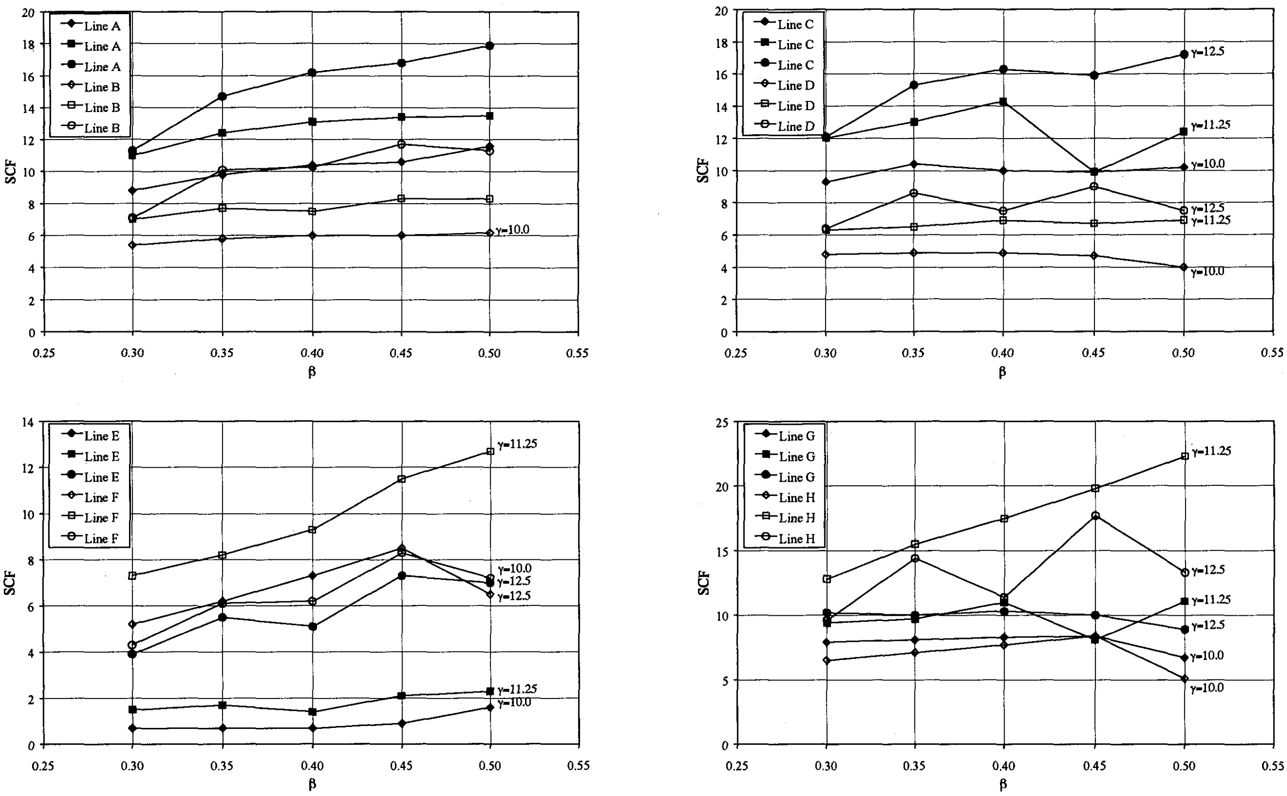

Fig. 4 SCF versus parameter β and γ for lines A to H

Table 2 Parametric equations for SCF on a doubler plate reinforced SHS T-joint

$$SCF_A = \left(0.425 - 1.52\beta + 1.42\beta^2\right)\left(2\gamma\right)^{\left(0.162+5.29\beta-2.79\beta^2\right)}$$

$$SCF_B = \left(-0.0356 + 0.199\beta - 0.247\beta^2\right)\left(2\gamma\right)^{\left(5.83-17.4\beta+22.1\beta^2\right)}$$

$$SCF_C = \left(0.682 - 2.71\beta + 2.71\beta^2\right)\left(2\gamma\right)^{\left(0.713+0.911\beta+5.39\beta^2\right)}$$

$$SCF_D = \left(-0.081 + 0.449\beta - 0.562\beta^2\right)\left(2\gamma\right)^{\left(6.32-21.2\beta+26.7\beta^2\right)}$$

$$SCF_E = \left(0.674 - 2.39\beta + 4.90\beta^2\right)\left[169 - 16.3(2\gamma) + 0.399(2\gamma)^2\right]$$

$$SCF_F = \left(-0.00912 + 0.0782\beta - 0.0611\beta^2\right)\left[-22600 + 2090(2\gamma) - 46.7(2\gamma)^2\right]$$

$$SCF_G = \left(-0.527 + 4.14\beta - 4.00\beta^2\right)\left(2\gamma\right)^{\left(1.54-2.20\beta+1.83\beta^2\right)}$$

$$SCF_H = \left(-0.570 + 7.98\beta - 5.45\beta^2\right)\left[-405 + 36.4(2\gamma) - 0.796(2\gamma)^2\right]$$

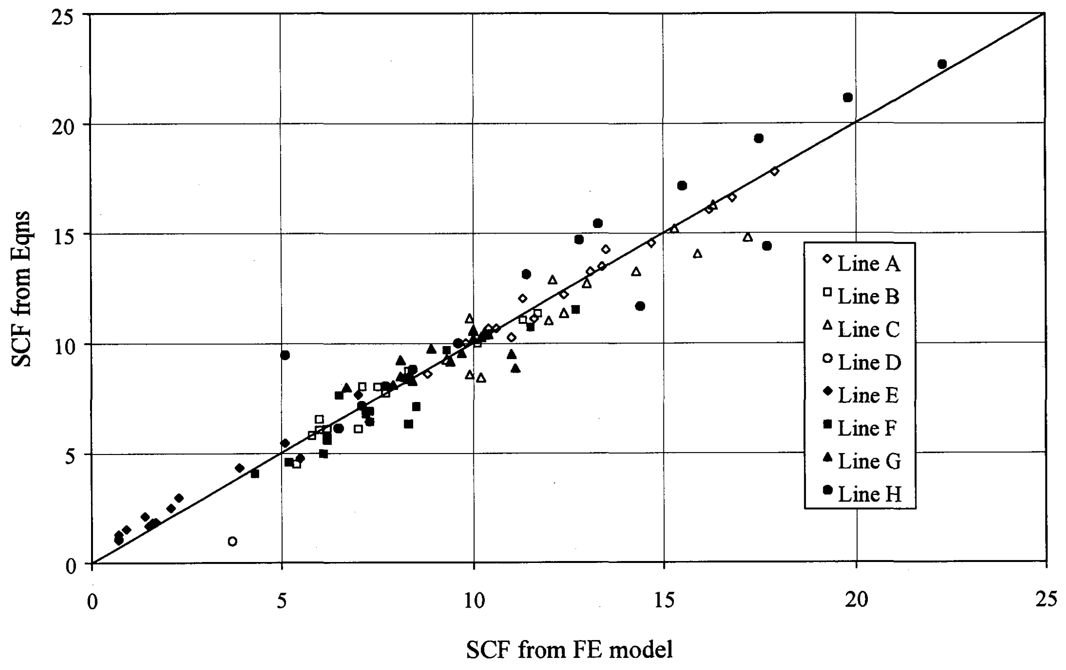

Fig. 5 Comparison of the SCF predictions from the Equations in Table 2 and FEM

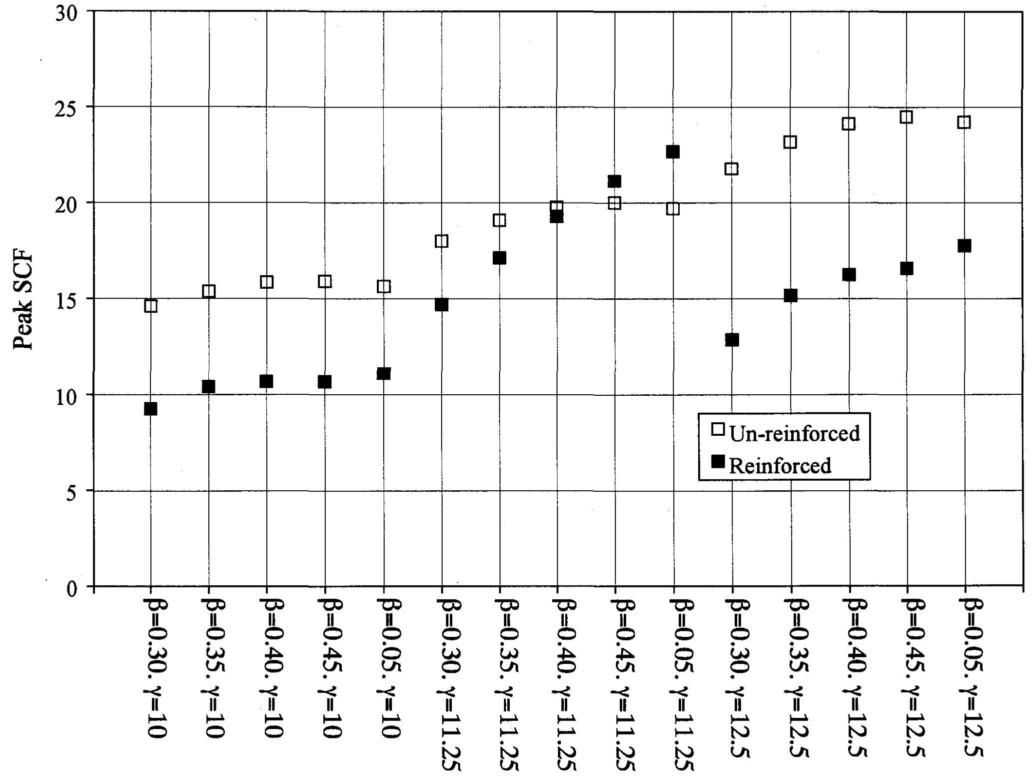

Fig. 6 Comparison of the peak SCFs for reinforced and unreinforced joints

6. Comparison with Unreinforced Joint

A comparison between the maximum SCFs of reinforced and unreinforced T-joints was made and the predicted SCFs were obtained from both the original Wingerde equations and the equations in Table 2. **Figure 6** compares the peak stresses for both the unreinforced and the reinforced T-joints for the same set of joint geometrical parameters. The peak SCF for the unreinforced case was observed to be at line C whereas the peak stresses were observed to occur at lines A, C and H for the doubler plate reinforced joint. The reinforced T-joint exhibited lower SCF values compared to a similar unreinforced joint except for joints with β=0.45 and 0.5 and γ = 11.25.

7. Conclusions

A parametric study of the influence of geometric parameters β and γ on the SCF of a double plate reinforced SHS T-joint was conducted through finite element analysis. Eight hot spot locations were established at the intersecting region and equations to predict the SCF were generated from the numerical results.

A comparison of the SCFs obtained from the doubler plate reinforced SHS T-joint with the unreinforced T-joint within the same geometric parameters indicate that the doubler plate reinforced joint generally exhibited lower SCFs. Hence it can be concluded that the doubler plate reinforcement may improve the fatigue performance of the joint.

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