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Experimental Study of Failures in Steel Tubular Bridge Structures due to Cyclic Loading

Feleb N Matti[1], Fidelis R Mashiri[2] and Idris Musa[3]

[1]PhD Candidate, School of Computing & Mathematics, Western Sydney University, NSW, Australia
[2]Associate Professor, School of Computing & Mathematics, Western Sydney University, NSW, Australia
[3]PhD Candidate, School of Computing & Mathematics, Western Sydney University, NSW, Australia
Corresponding author's E-mail: 17738907@student.westernsydney.edu.au

Abstract

Circular hollow sections (CHS) are widely used in most types of structures such as bridges, communication towers and offshore platforms that are subjected to different types of loading. The main girder for truss arch bridges and cabled stayed bridges can be made of CHS and concrete-filled circular hollow sections (CFCHSs) in large span bridges. Extensive experimental determinations of stress concentration factors (SCFs) on empty tube to tube T-joints have been previously investigated. These investigations resulted in the development of design guidelines for fatigue of CHS uniplanar T-joints such as CIDECT Design Guide No. 8. On the other hand, little research has been carried out on the determination of the SCFs of T-joints with concrete-filled chords. As a result, there is no design guide for T-joints with concrete-filled chords. An experimental investigation was performed at Western Sydney University (WSU), Kingswood Campus. The strain gauging process was used to install strip and single strain gauges onto two T-joint specimens with concrete-filled chords for the measurement of strains. The strain gauging enabled the measurement of strains in concrete-filled T-joints and determined the SCFs of two concrete-filled T-joints specimens under axial tension, axial compression and in-plane bending. The stress distributions around the weld joints for empty T-joints have been previously researched. Calculations of the SCFs for these empty T-joints under axial load and in-plane bending can be determined based on the CIDECT Design Guide No.8. The calculated SCFs values for empty joints are compared to the SCFs of the concrete-filled chord T-joints obtained from the results of the experiment. The purpose of this comparison is to find out if it is beneficial to use concrete- filled T-joints for fatigue design.

Keywords: SCFs, Concrete-filled T-joints, Experimental investigation

1. INTRODUCTION

Wang et al (2013) designed a CHS to CHS joint plus ten CHS to CFCHS joints to consider the effect of concrete strength grades on SCFs at joints as well as considering the effects of different non-dimensional geometric parameters. The CHS brace members were subjected to axial tensile and compressive force. Chen et al (2016) carried out the SCF testing of 4 large eccentricity N-joints under axial compression load in the vertical CHS brace, axial tension loading in the inclined CHS brace and without additional axial loading in the horizontal CHS chord. Jiao et al (2013) investigated fatigue behaviour of very high strength (VHS) circular steel tube to plate T-joints subjected to cyclic in-plane loading. Chen et al (2010) tested five tubular T-joint specimens with concrete-filled chords and three specimens of hollow steel tubular T-joints under in-plane bending and axial loading to determine and study SCFs. The stress distributions around the weld joints for empty T-joints have been previously researched. However, research on concrete-filled T-joints has not been much investigated previously. Therefore, more information on the behaviour of concrete-filled T-joints needs to be provided to practicing engineers.

The purpose of this research carried out is to investigate the stress distribution around the brace and chord intersection (welded connection) of the concrete-filled T-joints subjected to axial tension, axial compression and in-plane bending. Furthermore, the objective of this project is to determine SCFs and the hot spots' location in two concrete-filled T-joint specimens. In addition, the aim of this research is to compare the values of the SCFs of the concrete-filled T-joints and the values of the SCFs of empty joints based on the CIDECT Design Guide (Zhao 2001) to study the benefits of concrete-filled T-joints for fatigue design. Finally, this research carried out is also aimed to assist in identifying the parameters that may influence the fatigue strength of weld connection in joints with concrete-filled chord and to study the effects of cyclic loading on steel bridges and how cyclic loading can cause steel bridges to fail. The paper outlines the strain gauging process to enable the measurement of strains in T-joints. The test set-ups for axial load and in-plane bending are also described. The procedure of determining strain concentration factors (SNCFs) and SCFs of concrete-filled T-joints is also outlined.

2. EXPERIMENTAL INVESTIGATION

2.1. Specimens and Material Properties

Two concrete-filled T-joint specimens (T2 and T3) shown in Figure 2 and with sizes and non-dimensional parameters shown in Table 1 were tested in this investigation. The non-dimensional parameters are defined as follows: β, brace to chord diameter ratio (d_{br}/D_{ch}) ranging from 0.37 to 0.69, γ, chord radius to chord wall thickness ratio ($D_{ch}/2T_{ch}$) equal to 15.29, τ, brace to chord wall thickness ratio (t_{br}/T_{ch}) equal to 1 and α, chord length to chord radius ratio ($2L/ D_{ch}$) equal to 16.84, see Table 1.
Strip and single strain gauges were installed onto two concrete-filled T-joint specimens for the measurement of strains. The average compressive strength of the concrete used to fill the chords was 36MPa.
The strain gauging enabled the measurement of strains in T-joints that were carried out at Western Sydney University, Kingswood campus. Strain gauges were attached on the two concrete-filled T-joints specimens through the use of cyanoacrylate strain gauge glue. Single strain gauges were attached in the middle of the brace (around 285mm from the top) and at quarter points of the brace (around 142.5mm from the top plate) of both specimen T2 and T3 at 0°, 90°, 180°and 270°. However, the strip strain gauges were attached along the chord and the brace intersection at 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315° and 360°. The first strain gauges of each strip strain gauge were located on the centerline of the marked location, 4mm from the toe of the weld as recommended by (Zhao et al 2001).

Figure 1. (a) T-joint specimens; (b) dimensions of T3 specimen

b

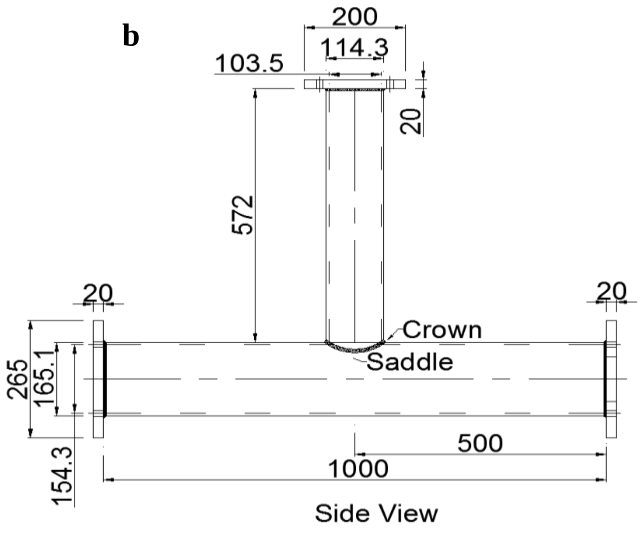

Figure 2. (a) T-joint specimens; (b) dimensions of T3 specimen

Table 1. Non-dimensional parameters

Concrete-filled T-joints specimens	Chord		Brace		Geometric Parameters			
	Diameter (mm)	Thickness (mm)	Diameter (mm)	Thickness (mm)	β	γ	τ	α
T2	165.1	5.4	60.3	5.4	0.37	15.29	1	16.84
T3	165.1	5.4	114.3	5.4	0.69	15.29	1	16.84

2.2. Test Set-Up for Axial Load and In-Plane Bending

The test of specimen T2 were set-up under axial tension and compression on the brace. The test set-up shown in Figure 3 was used in the measurements of strains under axial loads. Axial tension and then axial compression forces were applied to the specimen T2. About 10 cycles of loading were applied to the specimen to ensure the test set-up was stabilized. Each cycle included 4 quasi-static load levels. These loads fall within the elastic response region of the connection. The test of specimen T2 was then set-up under in-plane bending on the brace. The test-set up shown in Figure 4 was used in the measurements of strains for specimen T2 under in-plane bending. For in-plane bending, horizontal forces were applied to the brace. The procedure of the test set up for specimen T2 under axial load (tension and compression) and in-plane bending were repeated for specimen T3.

Figure 3. Test set-up for axial loading

Figure 4. Test set-up for in-plane bending

2.3. Determination of Strain Concentration Factors (SNCFs) and Stress Concentration Factors (SCFs) of Concrete-Filled T-Joints

The values of the nominal strain for specimen T2 and T3 under axial tension and compression were calculated by averaging the values of the four single strain gauges located in the middle of the brace at 0°, 90°, 180° and 270°. The nominal strain values for in-plane bending were calculated by averaging the values of the strains extrapolated to the weld toes based on the single strain gauges located at the crown points. The value of the SNCF for each graph was then calculated using the following equation:

$$\mathrm{SNCF} = \frac{\text{Hot Spot Strain (HSSN)}}{\text{Nominal Strain}} \tag{1}$$

Since strains were measured at four (4) load levels, four (4) SNCFs values were calculated for each strip strain gauge and for each location from 0^o to 360^o. The average value of the SNCFs is the strain concentration factor for the connection ($SNCF_{CHS}$)for each strip strain gauge or location from 0^o to 360^o.The value of the SCF_{CHS} was calculated using the following formula as recommended by Frater and van Delft et al, cited in Zhao et al (2001):

$$\mathrm{SCF_{CHS}} = 1.2 \times \mathrm{SNCF_{CHS}} \tag{2}$$

3. RESULTS AND DISCUSSION

3.1. SCFs under Axial Loading

As shown in Figure 5 and Figure 6, the hot spot location of both of the empty T-joint specimens at the chord and brace under axial loading occurred at the saddle points (90° and 270°). However, the hot spot locations of the concrete-filled T-joint specimens under axial tension or compression are not prominent but have SCFs of similar magnitude around the brace-chord intersections. The hot spot location at the chord and brace of concrete-filled T2 specimen under axial tension occurred at the saddle points. Furthermore, the hot spot location at the chord and brace of concrete-filled T3 specimen under axial compression occurred at the crown points (0°, 180° and 360°). The parameter that influences the fatigue strength was identified. As shown in Table 1, the change in dimensions of the brace diameters of both specimens T2 and T3 influence the non-dimension parameter (β). Since the non-dimensional parameter (β) of both of the specimens are not the same, different SCFs were obtained under different loading cases, showing that SCFs are influenced by the non-dimensional parameter, β**.**

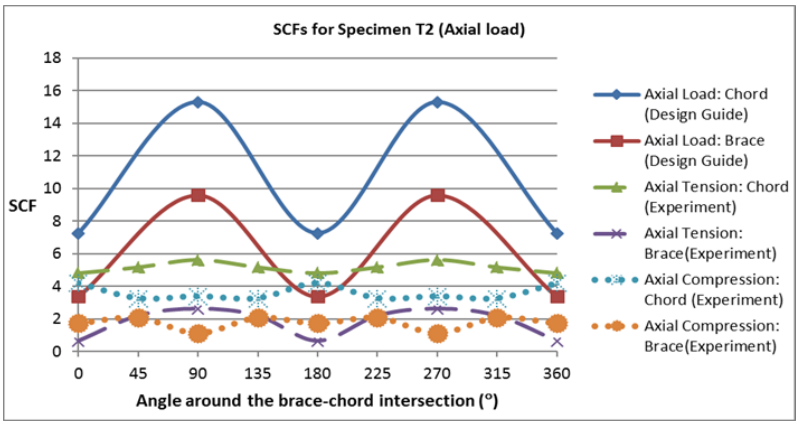

Figure 5. SCF distribution of specimen T2 under axial load along chord/brace intersection

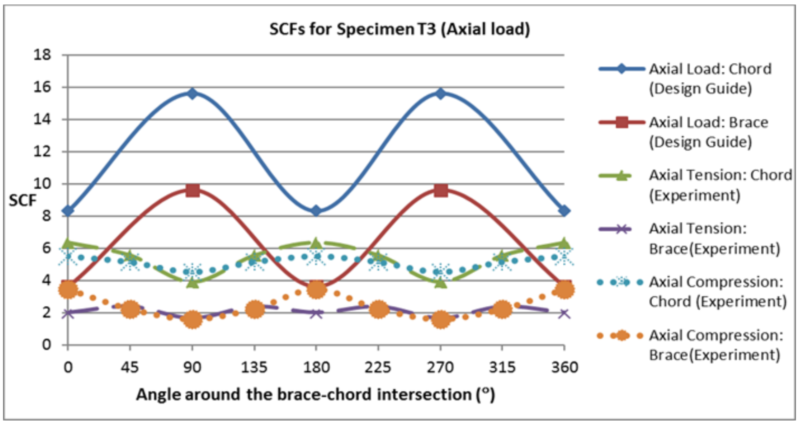

Figure 6. SCF distribution of specimen T3 under axial load along chord/brace intersection

3.2. SCFs under In-Plane Bending

As shown in Figure 7 and Figure 8, the SCF of both of the empty T-joint specimens at the chord and brace subjected to in-plane bending occurs at the crown points. However, the SCF of both of the concrete-filled T-joint specimens subjected to in-plane bending generally occurred at the crown point and in the middle of the crown and saddle points (45° and 315°). For example, the hot spots locations of the concrete-filled T2 specimen subjected to in-plane bending occurred at the chord crown points whereas T3 specimen occurred at 45° and 315°.

The SCF of the concrete-filled T2 specimen under in-plane bending is lower than the empty T-joint at the chord. Similarly, at the brace, the SCF of the concrete-filled T2 specimen under in-plane bending is also lower than the empty T-joint. However, the SCFs of the concrete-filled T3 specimen under in-plane bending are more than the empty T-joint. The maximum SCF of the concrete-filled T3 joint at the brace under in-plane bending occurred at 45°, however, the SCF of the concrete-filled T3 joint at 0° (Crown) is less than the maximum SCF of the empty T3 joint at 0°.

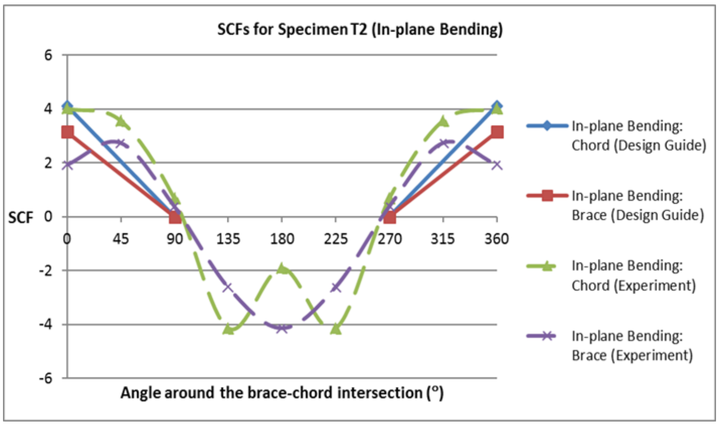

Figure 7. SCF distribution of specimen T2 under in-plane bending along chord/brace intersection

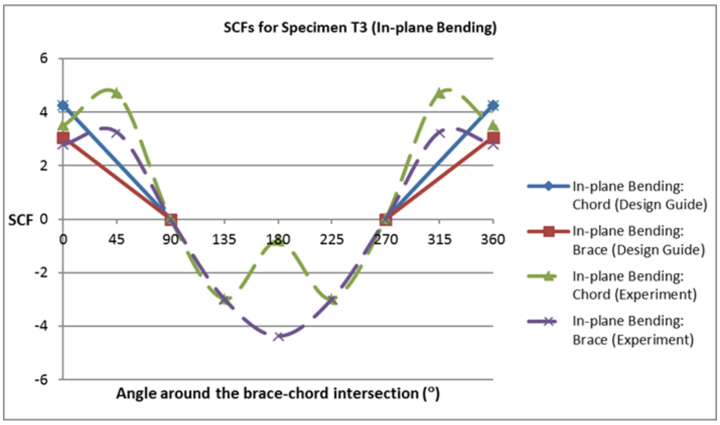

Figure 8. SCF distribution of specimen T3 under in-plane bending along chord/brace intersection

It is evident from all the graphs shown in Figure 4 to 7 that the Design Guide does not allow engineers to obtain the SCFs at 45°, 135°, 225° and 315°. These are the angles located in the middle of crown and saddle point. However, the Design Guide only allows engineers to obtain SCFs at the crown points (0°, 180° and 360°) and at the saddle points (90° and 270°). In this investigation, the SCFs have been determined at additional points: 45°, 90°, 135°, 180°, 225°, 270°, 315° and 360°. This project has therefore extended the understanding of SCFs distribution in the tubular connections in this respect. The change in dimensions of the brace diameters of specimens T2 and T3 influence the non-dimension parameter (β). Different SCFs were obtained as the non-dimensional parameter (β) of both of the specimens are not the same.

In this investigation, the SCFs between 90° and 270° are negative. This is because when the horizontal loads are applied to the brace of the specimens in the direction of the longitudinal axis of the chords, the region between 90° and 270° is under compression. This is shown in Figure 9. Hence, these SCFs are negative. The experiment shows both positive and negative SCFs whereas the CIDECT Design

Guide No. 8 shows only positive SCFs. This project has extended the understanding of the SCFs to that on the compression side of brace-chord intersections in tubular joints when compared to current standards which only give SCFs for the side under tension.

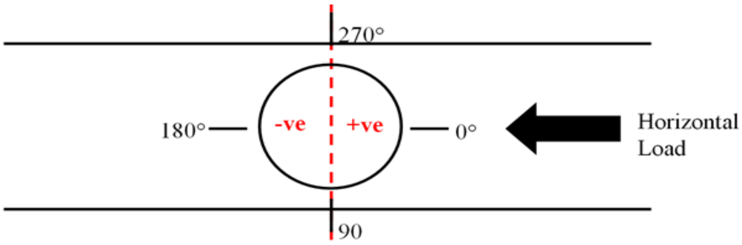

Figure 9. T-joint under in-plane bending

4. CONCLUSION

The experimental investigation provided more information on the behavior of T-joints specimens with concrete-filled chords which assisted in understanding the effect of concrete-filling on the reduction of stress around the welded joints. The stress distributions of concrete-filled T-joints were investigated. The hot spot location is different for each loading type. The locations of the hot spots generally occur at the crown and saddle points. Specimens with concrete-filled chords T-joints have lower SCFs compared to empty T-joints when subjected to axial tension or compression. Similarly, concrete-filled T2 specimen subjected to in-plane bending at the chord and brace has lower SCFs than the empty T-joint. However, the SCFs of the concrete-filled T3 specimen under in-plane bending are more than the empty T-joint. The maximum SCF of the concrete-filled T3 joint at the brace under in-plane bending occurred at 45°, however, the SCF of the concrete-filled T3 joint at 0° is less than the maximum SCF of the empty T3 joint at 0°. Therefore, it is beneficial to have concrete- filled T-joints for fatigue design as concrete filling efficiently decreases the peak SCFs. As a result, the life of the concrete-filled bridge will be longer and resulting in reduced maintenance cost. In the future, the effect of tube size (thickness) and the effect of different section shapes (square) will be studied.

5. REFERENCES

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