Recent Research on Fatigue of Tubular Joints

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Abstract

Some of the structural systems used in the agricultural, road and mining industries are subjected to cyclic loading and are therefore prone to fatigue failure under service loads. These structural systems range from trailers, road sign portals, towers, bridges and dragline structures. Recent development has resulted in the production of steel materials that are relatively higher in strength and thin-walled. There has also been an increased use of concrete-filled tubular members in structural systems especially in long span bridge structures and towers. The understanding of tubular joints with concrete-filled chords has therefore become important. This paper therefore outlines recent research that has been carried out to better understand the behaviour of various welded thin-walled tube-plate and tube-tube joints under cyclic loading. The research has also included tests on tubular joints with concrete-filled chords under cyclic loading. The research has focussed on high cycle fatigue loading which is typical of loads in the agricultural, road and mining industries. The cyclic loading reveal the typical failure modes in the empty tubular joints and tubular joints with concrete-filled chords under cyclic loading. Measurement of stress distribution is also important in understanding the behaviour of structures under cyclic loading. The measurement of stress distribution can be carried out using both experimental and numerical methods. The welded connection interface shows that the areas of high stress concentration are the hot spots where fatigue cracks initiate and propagate leading to failure.

Keywords: Fatigue, cyclic loading, failure mode, stress concentration, design curve

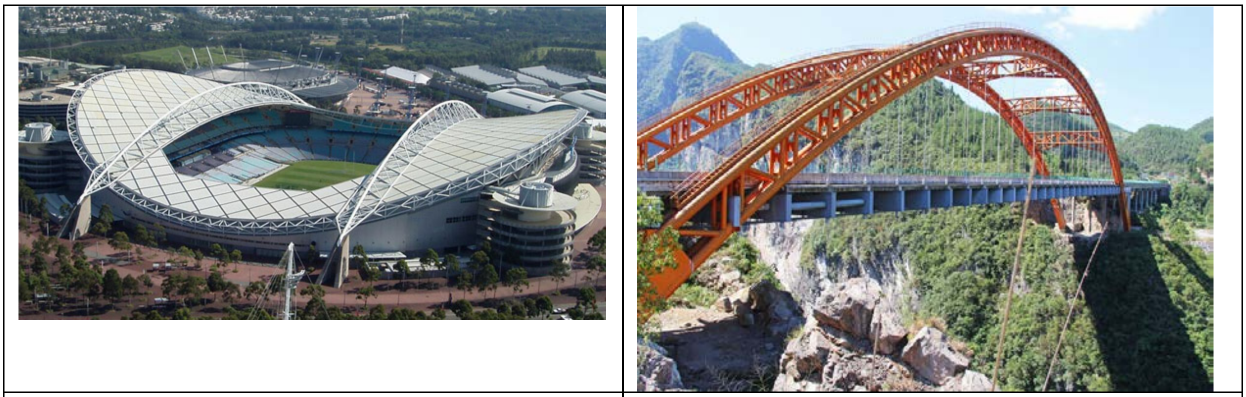
1. INTRODUCTION

Various structural systems are subjected to cyclic loading in service. These structures include equipment used in the agricultural industries, road sign portals, lighting poles, bridges, towers and mining equipment. The cyclic loading in these structural systems typically produces high cycle fatigue behavior resulting in failures after tens of thousands to millions of cycles. Some of the structures subjected to cyclic loading are increasingly being built using tubular members as shown in Figure 1. Some examples include Australia Stadium, which consists of a 295.6m span main arch, Figure 1(a); Xisha Bridge, a 190m span through-arch bridge with concrete filled tubular ribs, Figure 1(b); a mining dragline with a boom length of about 100m, Figure 1(c) and the 610m tall Canton Tower with concrete filled tubes, Figure 1(d).

Significant research has been carried out on tubular joints to determine behavior and strength under static loading. This research has been captured in CIDECT Design Guides No. 1 and 3 for circular hollow section connections and square hollow section connections respectively (Wardenier et al 2010, Packer et al 2010). Similarly, a considerable amount of research on tubular joints under high cycle fatigue loading has also been carried on empty tubular joints and design rules have been formulated in CIDECT Design Guide No. 8 (Zhao et al 2001). The fatigue design guidelines for welded tubular joints show that the tubes covered by CIDECT Design Guide No. 8 are mainly of wall thicknesses equal to and greater than 4mm. Therefore, there is a lack of design guidance for tubes of thicknesses less than 4mm. Tubes with wall thicknesses less than 4mm are now common on the steel industry markets around the world. A large number of research studies have also been carried out and continue to be carried out on empty and concrete-filled tubular columns (Mashiri et al 2014, Zhao et al 2010).

As new materials and new construction techniques evolve, practicing engineers need to have confidence in the use of these new materials and construction techniques in designing equipment, accessories and infrastructure for the future. In Australia, steel tubes with thicknesses less than 4mm are now commonly available (Standards Australia 2009). The steel tubes are cold-formed and of grades C250, C350 and C450 with corresponding yield stresses of 250MPa, 350MPa and 450MPa. Very High Strength (VHS) steel tubes are also available on the Australian market with a yield stress of 1350MPa and thicknesses below 4mm (Mashiri et al 2014). As these tube wall thicknesses are not covered by current fatigue design standards, research is required to enable engineers to safely design structural systems subject to cyclic loading with these relatively new tubes. A review of bridge construction techniques also show that a significant number of long span arch bridges are being built around the world (Chen and Wang 2009) using tubular joints with concrete-filled chords. Despite these developments there are no dedicated design standards for tubular joints with concrete filled chords. Therefore, research on tubular joints with concrete-filled chords is required to develop standards for use by practicing engineers.

Recent research has been carried out to contribute towards the updating of existing standards and the development of new standards to facilitate reliable design. This paper reports on some of the recent research on empty welded thin-walled tubular joints as well as on tubular joints with concrete-filled chords. The research focusses on failure modes, an understanding of stress concentrations on the welded tube-plate or tube-tube interface using experimental or numerical methods. Fatigue test data has also been obtained which has enabled further insight into the design of these connections using the stress range (S_r) versus number of cycles to failure (N) curves or S_r-N curves.



(a) Stadium Australia (Austadiums 2016)

(b) Xisha Bridge, Chongqing (Highest Bridges.com 2017)

(c) Mining Dragline (Altra Industrial Motion 2017)

(d) Canton Tower, Guangzhou (Detail Inspiration 2017)

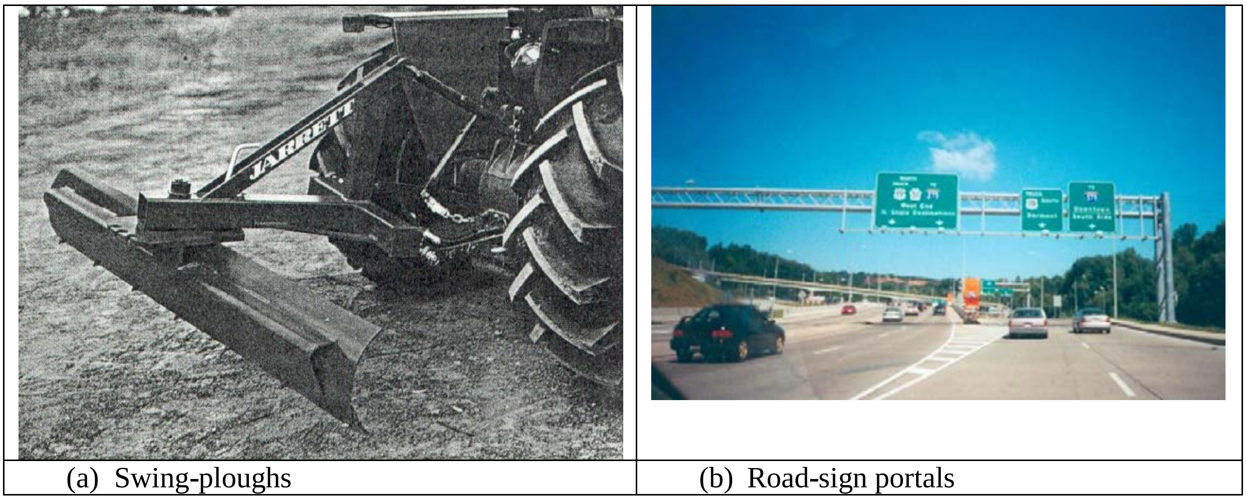
Figure 1: Structural systems using welded tubular joints

2. FATIGUE BEHAVIOUR OF WELDED THIN-WALLED JOINTS

2.1. Background

Welded thin-walled hollow section joints of thicknesses, *t*, less than 4mm can be used in structural systems in the road and agricultural industry. Some of the equipment used in the agricultural industry that is subjected to cyclic loading in service include swing-ploughs, trailers, linkage graders and bale handlers. This equipment is subjected to cyclic loading in service. Road sign portals and lighting poles are used in the roads and highways for signalling. These accessories are also subjected to cyclic loading due to wind and traffic induced oscillations. Some of the equipment and accessories used in the road transport and agricultural industries are shown in Figure 2.

A review of current standards and design codes for welded joints shows that fatigue design rules are given in standards such as CIDECT Design Guide No.8 (Zhao et al 2001), IIW (2000), API (1991) and Department of Energy (1990). These fatigue design rules cover welded hollow section connections with thicknesses typically greater than 4mm. Therefore, fatigue design rules need to be developed for welded hollow section connections for thicknesses less than 4mm.



(a) Swing-ploughs (b) Road-sign portals

Figure 2: Equipment and accessories used in the road transport and agricultural industry

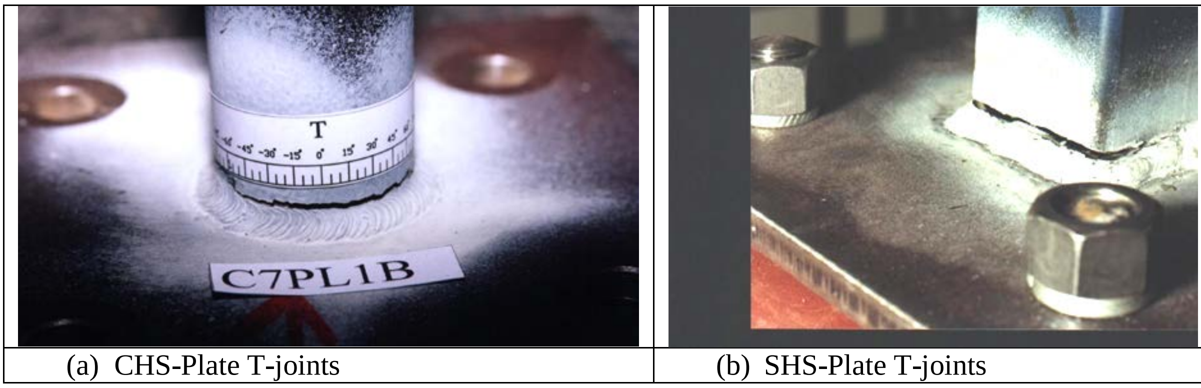
2.2. Current Research

Some of the current research on fatigue of welded thin-walled joints under cyclic loading has focused on understanding how material properties and stress concentrations can influence fatigue failure and how different design methods can be used for design. Some of the research objectives for welded thin-walled joints under cyclic loading are as follows:

(a) To investigate the effect of thickness, welding defects and material properties on fatigue life of thin-walled connections, with thickness less than 4 mm,
(b) To determine stress concentrations at hot spots and their relationship to crack growth patterns and,
(c) To recommend fatigue design rules based on the classification and hot spot stress methods.

Recent research has investigated the fatigue behavior of connections made up of circular hollow section (CHS) and square hollow section (SHS). As part of recent research circular hollow sections and square hollow sections were used to manufacture CHS-Plate and SHS-Plate T-joints as shown in Figure 3.

The thin-walled hollow section to plate T-joints were subjected to cyclic in-plane bending in the brace. Figure 3 shows that failure of these types of joints occurs at the weld toes in the brace for both the CHS-Plate and SHS-Plate T-joints under cyclic in-plane bending. Compared to the weld toes in the plate, the weld toes in the brace are the locations of highest stress concentration or the *hot spots*.(Mashiri et al 2002(a); Mashiri and Zhao 2006).



(a) CHS-Plate T-joints (b) SHS-Plate T-joints

Figure 3: Hollow section to plate T-joints

As part of recent research circular hollow sections (CHS) and square hollow sections (SHS) were also used manufacture tube-tube T-joints. The following T-joints were manufactured and tested under cyclic in-plane bending; SHS-SHS T-joints, CHS-SH T-joints and CHS-CHS T-joints as shown in Figure 4 (Mashiri et al 2002(b); Mashiri et al 2004(a),(b)).

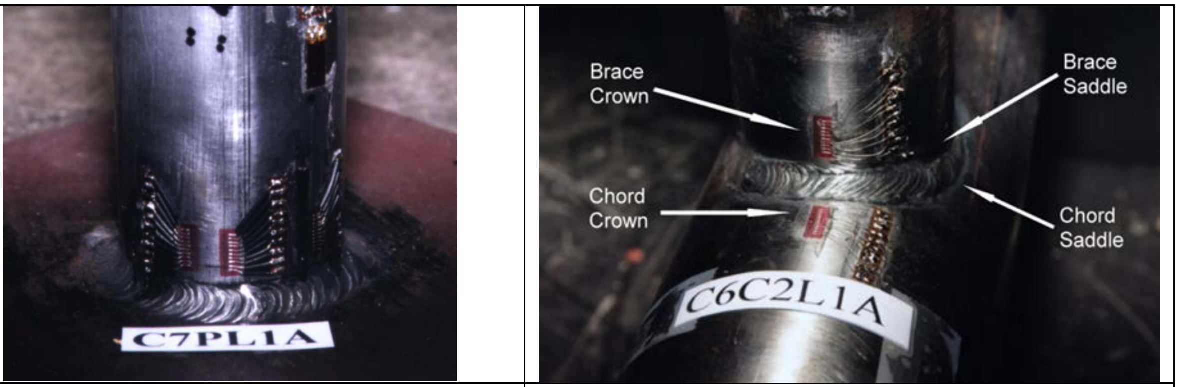
Figure 4(a) shows that for SHS-SHS T-joints subjected to cyclic in-plane bending load, three modes of failure were observed; failure in the chord, failure in the brace and failure in both the brace and the chord. The type of failure was found to be depended on the ration of the width of the brace (b_1) to the width of the chord (b_0), also referred to as the non-dimensional parameter, β. Figures 4(b) and (c) show that for CHS-SHS T-joints and CHS-CHS T-joints, only cracking in the chord was observed. This is due to the comparatively lower SCFs in the CHS brace.

(a) SHS-SHS T-joints

(b) CHS-Plate T-joints (c) SHS-Plate T-joints

Figure 4: Hollow section tube-to-tube T-joints

Understanding the failure modes in the different types of connections can be achieved through the determination of stress distribution at the weld toes of the tube-plate and tube-tube T-joints using experimental investigation as shown in Figure 5. In experimental determination of stress distribution, single gauges are used for the determination of nominal stresses and strip strain gauges with 3 to 5 individual strain sensitive elements are used to determine the stress distribution at the weld toes. The weld toes are the common locations for hot spots. The location of the strip strain gauges for measuring stress distribution at the weld toes are governed by standard recommendations such as CIDECT Design Guide No. 8 (Zhao et al 2001). The measurement of stress distribution at the weld toes is designed to measure geometric stress due to the configuration and size of the welded tubes and to avoid taking into account the influence of the weld. The stress distribution at the weld toes enables also enables the hot spot stresses to be determined for the hot spot stress method.

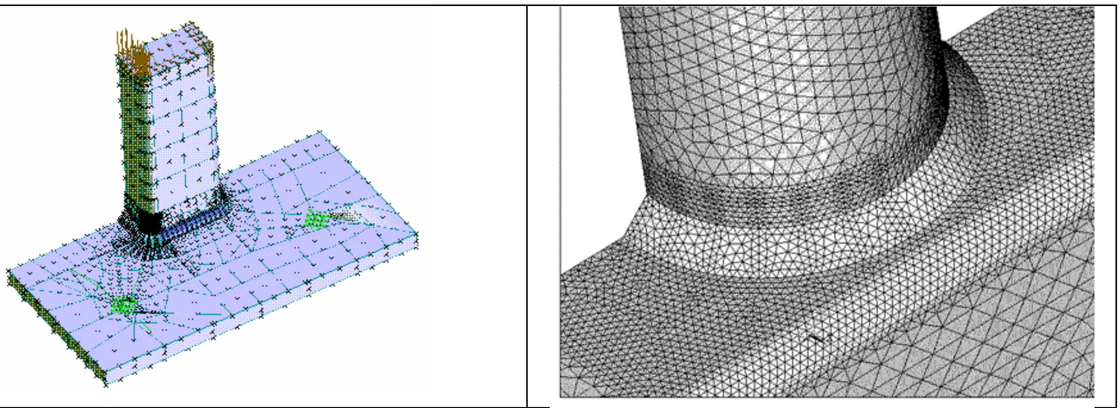


(d) Strain gauged CHS-Plate T-joint

(e) Strain gauged CHS-CHS T-joints

Figure 5: Experimental determination of stress distribution

The stress distribution around the weld toes in the welded connections can also be determined using the boundary element method and the finite element method as shown in the SHS-plate T-joint and CHS-SHS T-joints in Figure 6. The use of the numerical methods such as the boundary element method (BEM) and the finite element methods (FEM) enables parametric studies to be carried out thereby enabling researchers to go beyond parameters that are measured in experiments. Successful numerical modelling however depends on the models being able to capture experimental results. This is done through mesh sensitivity analysis to enable the model to be calibrated to reflect experimental behavior.



(a) BEM of SHS-Plate T-joint

(b) FEM of CHS-SHS T-joint

Figure 6: Stress distribution using numerical methods

2.3. Design Recommendations

Data for joints tested under cyclic loading can be given in terms of the number of cycles to failure (N) against the applied stress range (S_r), as shown in Figure 7. The tests can be performed under constant amplitude stress range by applying a nominal minimum stress (S_{min}) and a nominal maximum stress (S_{max}) in repeated cycles of loading. The difference between the nominal maximum stress (S_{max}) and the nominal minimum stress (S_{min}) is the stress range (S_r).

A plot of the nominal stress range (S_r) versus the number of cycles to failure (N), on a log-log graph can be used to determine the design curves for a given construction detail or joint. The least squares method of statistical analysis can be used to determine a design Sr-N curve for a given joint. The design Sr-N curve can be defined as the mean minus two-standards deviation curve.

The deterministic method can also be used to determine the design S_r-N curve by plotting the fatigue test data on a set of design S_r-N curves recommended by a fatigue design guideline or standard as shown in Figure 7.

When design is based on nominal stress range (S_r) versus number of cycles to failure, the design methodology is referred to as the classification method. Alternatively, the nominal stress range can be converted into a hot spot stress range by multiplying the nominal stress range by the maximum stress concentration factor (SCF) in a welded joint. A plot of the hot spot stress range (S_{rhs}) versus number of cycles to failure (N) can then be used for design in what is referred to as the hot spot stress method. One of the advantages of the hot spot stress method is that welded tubular joints can then be designed for fatigue based on their thickness instead of the type of constructional detail.

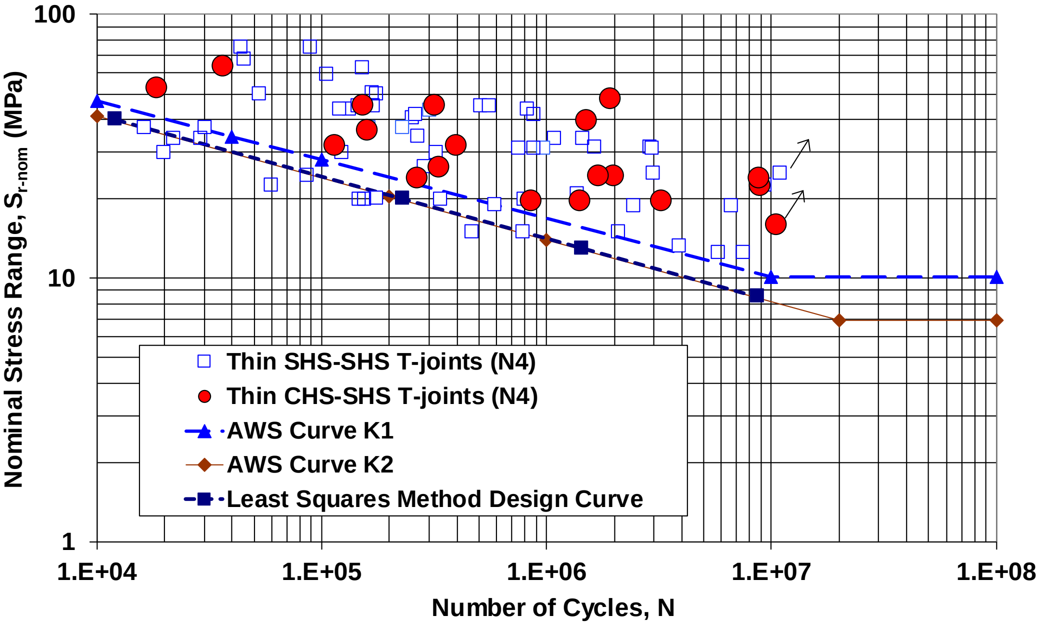


Figure 7: Fatigue design S-N curves and fatigue test data

3. CONCRETE-FILLED TUBULAR JOINTS: STATIC AND FATIGUE STRENGTH

3.1. Background

A review of research around the early 2000s showed that numerous researchers have studied the fatigue behaviour of empty welded tubular nodal joints (Wardenier 1982, van Wingerde et al 1997). At present, many existing standards also contain fatigue design rules for empty welded tubular nodal joints (IIW 2000, CIDECT (Zhao et al 2001), Department of Energy 1990, API 1991).

Fatigue failure in empty welded tubular nodal joints occur mainly due to high stress concentrations at weld toes in the chord as discussed earlier. The fatigue failure in empty welded tubular joints is caused by local bending resulting from chord face deformation.

One method to reduce stress concentrations in the chord is through concrete filling of the chord member to reduce chord face deformation. A review of bridge construction trends around the world shows that truss bridges with concrete filled chords already exist and are increasingly being used in construction (Zhou and Chen 2003). At present although an increasing number of studies have been carried out, relatively few studies of welded composite tubular joints have been carried out. Therefore, there is a lack of fatigue design rules for these types of joints.

3.2. Current Research

In an effort to develop a better understanding and obtain comprehensive data for the design of welded tubular joints with concrete-filled chords, research is currently being carried out to study welded thin-walled tube-tube joints with concrete-filled chords. As part of the research in this direction, research was carried out on SHS-SHS tubular T-joints with concrete filled chords under cyclic in-plane bending in the brace as shown in Figure 8 (Mashiri and Zhao 2010).

The failure modes that were observed in SHS-SHS T-joints with concrete filled chords are shown in Figure 9. The failure modes are similar to those that were observed for empty SHS-SHS T-joints. For low to medium values of β ranging 0.35 to 0.50, chord-tension-side failure was observed, see Figure 9(a) and (b). For relatively larger values of β equal to 0.67, the largest value of β tested in this investigation, chord-and-brace-tension-side failure as well as brace-tension-side failure were observed, see Figure 9(c) and (d). The trend in failure modes shows a change in the location of high stress concentration from the weld toes in the chord when β is low, to the weld toes in the brace as the value of β becomes high and approaches 1.0.

A comparison of the experimental SCFs determined at weld toes in the chord for SHS-SHS T-joints with concrete-filled chords and those for empty SHS-SHS T-joints under in-plane bending are shown in Table 1. At most hot spot locations, SCFs of the concrete filled chord T-joints are lower than SCFs in empty joints. This is attributed to increased rigidity and reduced chord face flexibility due to concrete filling. There is an anomaly to these results for specimen S6S1Con1-1, where the SCF for the composite joint is slightly higher than that in the corresponding empty tubular joint. This may be attributed to the errors in strain gauge placement and sensitivity of quadratic extrapolation for small distances of extrapolation in thin-walled joints.

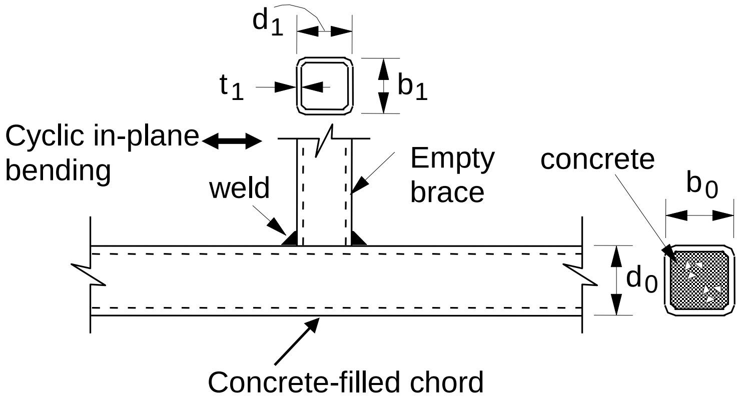
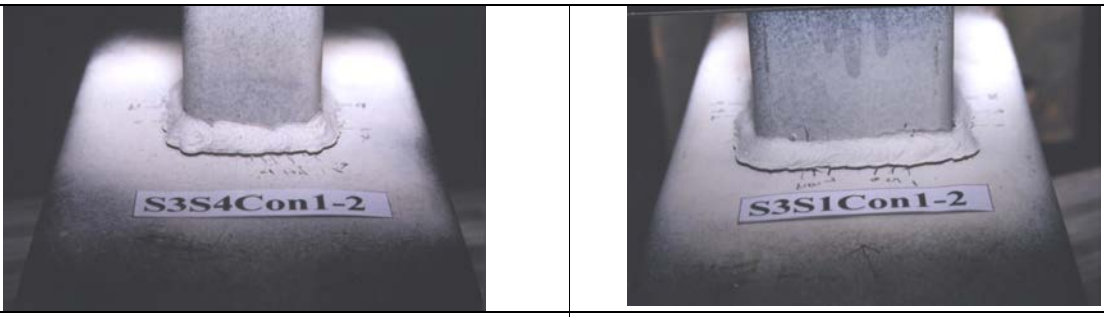


Figure 8: SHS-SHS T-joint with concrete filled chord under cyclic in-plane bending load



(a) Chord-tension-side failure, β=0.35

(b) Chord-tension-side failure, β=0.50

(c) Chord-and-brace-tension-side failure, β=0.67

(d) Brace-tension-side failure, β=0.67

Figure 9: Failure modes in SHS-SHS T-joints with concrete-filled chords

Table 1. Experimental SCFs for composite and empty SHS-SHS T-joints

Series Name	Experimental SCF (Average Quadratic)						Ratio of Maximum SCFs
	Composite Joints			Empty Joints			$\frac{\text{Composite Joints}}{\text{Empty Joints}}$
	Line B	**Line C**	**Line D**	**Line B**	**Line C**	**Line D**	
S3S1Con1-1	**8.0**	6.6	4.7	9.3	**12.0**	7.8	0.67
S3S2Con1-1	**6.4**	4.6	2.3	5.6	**7.1**	5.1	0.90
S3S4Con1-1	4.9	**6.3**	4.2	4.6	**12.7**	7.7	0.50
S3S5Con1-1	2.8	**4.8**	4.1	3.7	**5.9**	5.8	0.81
S6S1Con1-1	2.9	**10.8**	2.5	3.2	**8.4**	4.2	1.29
S6S2Con1-1	-0.2	**2.5**	1.3	2.5	**8.3**	1.6	0.30

A comparison of the fatigue test data for composite and empty SHS-SHS T-joints subjected to cyclic in-plane bending is shown in Figure 10 for the classification method. Figure 10 shows that welded composite tubular T-joints have a better fatigue life compared to empty tubular joints. The composite joints have a class that is 1.25 times that of empty SHS-SHS T-joints. The fatigue life at a given stress range is 2 times that of empty SHS-SHS T-joints.

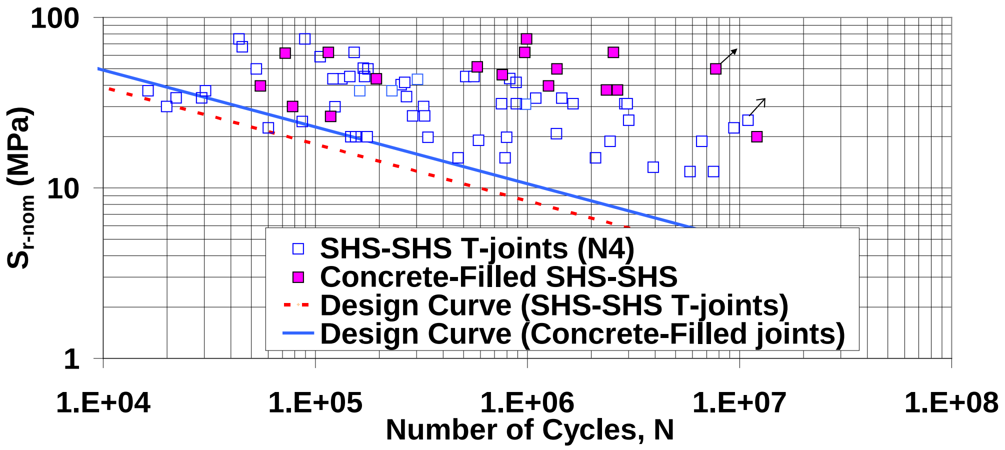


Figure 10: Failure modes in SHS-SHS T-joints with concrete-filled chords

4. CONCLUSIONS

Different structural systems in the agricultural, road and mining industries are subjected to cyclic loading in service. With the continuous development of new materials, research is required to determine the reliability of the use of these materials in these structural systems. Research is also required to ensure that new methods of construction are also safe for developing critical infrastructure and for manufacturing equipment subjected to cyclic loading.

For fatigue of welded thin-walled joints made up of high strength materials, recent research shows that failure under high cycle fatigue loading occurs at the weld toes in the tube or brace for tube-plate T-joints under cyclic in-plane bending.

For fatigue of welded thin-walled tube-tube T-joints, different failure modes were observed which depend on the non-dimensional parameters of the joints, especially the ratio of the width (b_1) or diameter (d_1) of the brace to the width (b_0) or diameter (d_0) of the chord member.

Fatigue failure in new construction methods utilizing concrete-filled chords in tubular joints, shows that the type of failure modes that are obtained in these composite joints are similar to those that are observed in empty tubular joints. However, the concrete-filling of the chords reduced chord face deformation in the composite tubular joints resulting in a significant reduction in stress concentrations and improving fatigue life. The investigation of the distribution of stress around the welded interface can be reliably determined using experimental methods as well as numerical methods.

Future research is required to increase fatigue test data that will enable greater confidence in the determination of design rules for practicing engineers in their design of both empty and composite tubular joints.

ACKNOWLEDGMENTS

The author would like to that Professor Xiao-Ling Zhao and the late Prof Paul Grundy for their contribution to this research, Engineering Laboratory staff, OneSteel, International Committee for the Development and Construction of Tubular Structures (CIDECT) and the Australian Research Council (ARC).

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