Failures of Steel Bridge Structures due to Cyclic Loading – A Review

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Abstract

Previous research on failures of steel bridges due to cyclic loading have been examined and studied. The most common reasons for bridge failures are due to force majeure, accidental overload and impact, structural and design deficiencies, construction and supervision mistakes, as well as lack of inspection, maintenance and repairing. Furthermore, fatigue failure is another main cause of bridge collapse. Previous experimental determinations of Stress Concentration Factors (SCFs) on empty tube-to-tube T-joints have been investigated. This investigation resulted in the development of design guidelines for fatigue of empty CHS uniplanar and multiplanar joints. However, little research has been carried out on the determination of the SCFs of T-joints with concrete-filled chords. The aim of this paper is to highlight the research gaps for future research in order to reduce failures of steel bridges under cyclic loading.

Keywords: fatigue design, steel structures, Stress Concentration Factors (SCFs), concrete-filled joints

1. INTRODUCTION

Chen et al (2015) stated that the use of tubular structures has increased considerably because of their light weight, easy fabrication, rapid erection and pleasing appearance. Currently, in steel tubular structures, concrete-filled steel tubes (CFST) are widely used as main members. CFST have high stiffness, high strength and high ductility (Han, cited in Chen et al 2015). Zhou and Zhu (1997) stated that numerous research achievements of CFST structures were transferred to construction practices. As a result, CFST have been widely used in numerous structures for arch bridges, electricity transmission masts, industrial buildings and platform columns in underground railways. Zhao et al (2010) stated that there is an increasing trend in using CFST in structural frames and support, industrial buildings, spatial construction and transmitting poles. In bridge and high-rise buildings structures, such composite columns have become very popular.

Due to the increased application of CFST structures, CFST arch bridges have become one of the competitive styles in moderate span or long span bridges. Two types of long-span concrete-filled tubular arch bridges are listed in Table 1 and Table 2.

Table 1. Recent long-span concrete-filled tubular arch bridges (Zhou & Zhu 1997)

Bridge	**Main span (m)**	**Service date**	**Type**
Sanshanxi bridge	200	September 1995	Lohse arch
Huangbei River Bridge	160	November 1996	Upper loading fixed arch
Xialao River Bridge	160	November 1996	Upper loading fixed arch
Xiamenkou Wujiang Bridge	140	September 1996	Fixed arch

Table 2. Recent Reinforced Concrete (RC) arch bridges with concrete-filled tubular stiffened skeletons (Zhou & Zhu 1997)

Bridge	Main span (m)	Service date	Type
Wanxian Yangtze River Bridge	420	July 1997	Upper loading fixed arch
Shuanglong Bridge	168	October 1994	Fixed arch
Luonguo Zinshajiang Bridge	160	1995	Fixed arch
Taibai Bridge	130	1993	Rigid RC frame

The Huangbei River Bridge and Xialao River Bridge are two typical examples of concrete-filled tubular arch bridges. The Huangbei River Bridge shown in Figure 1 and Xialao River Bridge shown in Figure 2 were built in China and completed in 1996 to carry traffic (Zhou & Zhu 1997). The concrete-filled tubular arch bridges were confirmed to be economical and efficient. The concrete-filled tubular arches generate a composite structure of high load capacity that is light weight. The hollow tubular structure serves as formwork, reinforcement and false work during erection (Zhou & Zhu 1997).

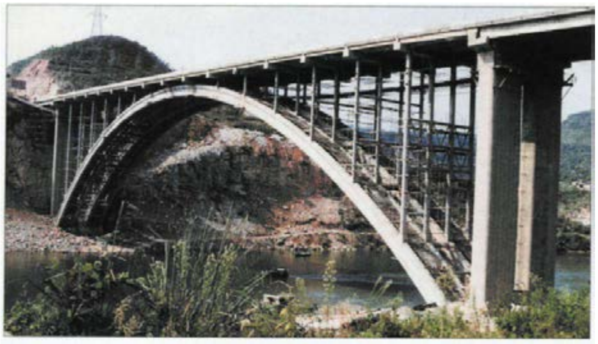

Figure 1. Huangbei River Bridge (Zhou & Zhu 1997)

Figure 2. Xialao River Bridge (Zhou & Zhu 1997)

A 370 m electric transmission line tower was constructed as shown in Figure 3. The lattice structures' joints connect the steel tube brace and concrete-filled steel tube chord (Chen et al 2015).

Figure 3. Electric transmission line tower in Zhejiang Province (Chen et al 2015)

2. LITERATURE REVIEW

Previous research on failures of steel bridges due to cyclic loading have been examined and studied. The main causes of bridge collapse are identified and examples of bridges that have failed are given. Previous experimental determinations of SCFs on concrete-filled tubular T-joints, tube-to-tube T-joints, CHS N-joints and tube-to-plate T-joints are provided. Existing design guidelines for fatigue are also reviewed.

2.1. Main Causes of Bridge Collapse

The most common reasons of bridge failures are due to force majeure, accidental overload and impact, structural and design deficiencies, construction and supervision errors, as well as lack of inspection, maintenance and repairing (Biezma & Schanack 2007). Bridges are susceptible to damage by aggressive environmental conditions, human actions and natural disasters. Furthermore, fatigue failure is another main cause of bridge collapse. Table 3 provides some examples of bridges that have failed due to the causes mentioned above.

Table 3. Summary of bridge failures (Biezma & Schanack 2007)

Date	Bridge Name	Location	Fatalities	Main Causes
06/12/1825	Bridge above the River Saale	Germany	55	Overload
28/12/1879	Tay Bridge	United Kingdom	75	Construction and supervision mistakes Design deficiencies
14/06/1891	Railway bridge above the River Birz	Switzerland	>70	Structural and design deficiencies
15/12/1967	Silver Bridge Pt.	Pleasant, New Jersey	46	Construction mistakes and lack of maintenance or inspection
15/10/1970	West gate Bridge	Melbourne, Australia	35	Construction, design deficiencies and supervision mistakes
10/11/1971	Rhine Bridge	Koblenz, Germany	13	Design deficiencies
14/04/2003	Sgt. Aubrey Cosens VC Memorial Bridge	Latchford, Canada	None	Design deficiencies, lack of maintenance and inspection
01/08/2007	I35W Bridge	Minneapolis, United States	13	Fatigue cracks in structural members (Hao 2010)

2.2. Experimental Determination of SCFs

2.2.1. Tube-to-tube T-Joints

The main girder for truss arch bridges and cable stayed bridges can be made of circular hollow sections (CHSs) and Concrete-filled Circular Hollow Sections (CFCHSs) in large span bridges (Wang et al 2013). The use of welded connections in bridges under cyclic loading determines the fatigue strength which controls the life of steel bridges. A CHS to CHS joint plus ten CHS to CFCHS joints were designed 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 subjected to axial tensile or compressive force were known to be fully welded. The quality of welds influences the fatigue strength of welded joint. High quality welding is necessary to avoid physical defects such as porosity and cracks. Wang et al (2013) noted that a crack is the worst type of defect. Figure 4 displays the set-up of the fatigue test for each T-joint specimen. The T-joint's brace is under a cyclic axial load.

2.2.2. Experimental Investigation of CHS N-Joints

Chen et al (2016) carried out the SCF testing of 4 large eccentricity N-joints. These N-joints were subjected to 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 (Chen et al 2016). Figure 5 shows a typical joint specimen. The welding that is located at the intersections was complete penetration groove weld. The ends of the inclined brace and chord, in the test specimen's set-up, were welded onto the end of the flat plates (10mm thickness) and bolted to create a pin support of inclined chord as well as brace.

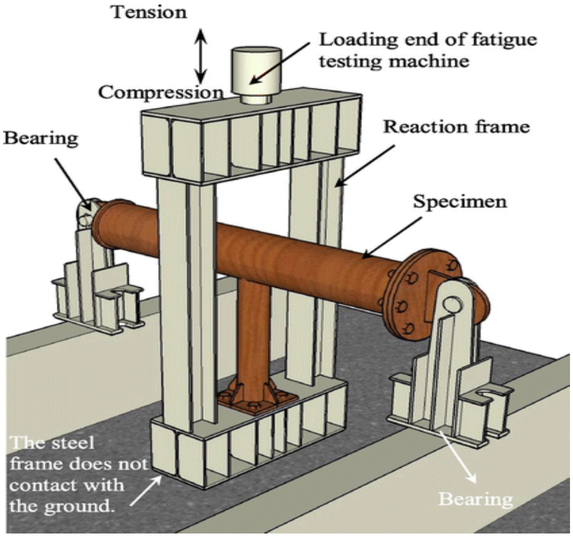

Figure 4. Fatigue test set-up (Wang et al 2013)

Figure 5. N-joints specimen subjected to axial loading (Chen et al 2016)

2.2.3. Fatigue Tests of Tube-to-plate T-Joints

Jiao et al (2013) investigated fatigue behaviour of very high strength (VHS) circular steel tube (t<2mm) to plate T-joints under cyclic in-plane loading. They carried out fatigue tests through the use of a MTS-810 testing machine. This machine had a loading capacity of 100KN. Figure 6 shows the set-up of the fatigue test. SHOWA strip strain gauges were used on the specimens' tension side in the bending plane to measure SCFs based on the hot spot stress method and to determine S-N fatigue design equations.

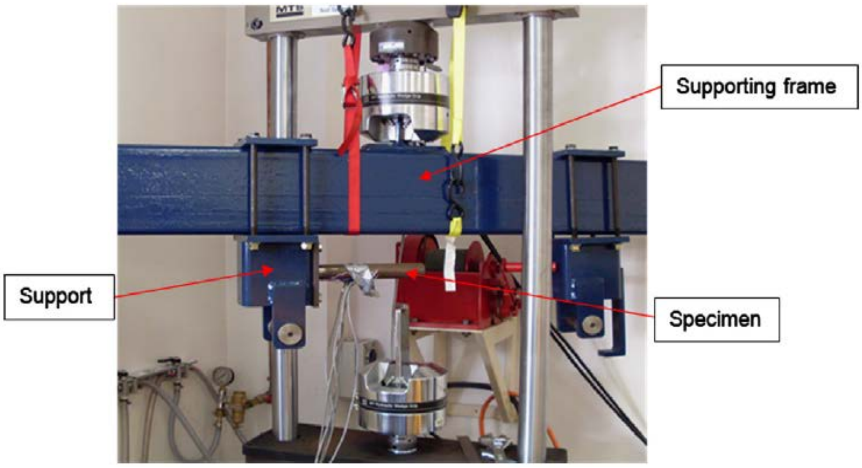

Figure 6. Fatigue test set-up (Jiao et al 2013)

2.2.4. Concrete-filled Tubular T-Joints

The SCFs of concrete-filled tubular T joints subjected to in-plane bending and axial loading were studied. The hot spot distribution was investigated through performing experimental investigation. In the research, five tubular T-joint specimens with concrete-filled chords and three specimens of hollow steel tubular T-joints were used. Chen et al (2010) stated that concrete filling decreases the peak SCFs. The test set-up for in-plane bending as well as axial loading is displayed in
Figure **7** and Figure 8. The test rig was used to test the tubular joints.

Figure 7. Test set-up for in-plane bending Chen et al (2010)

Figure 8. Test set-up for axial loading Chen et al (2010)

2.3. Fatigue design of CHS Uniplanar T or Y-joints using Design Guidelines

The CIDECT Design Guide No. 8 recommends that the SCF for uniplanar CHS T or Y-joints should be at least 2.0 (Zhao 2001). Figure 9 shows a CHS uniplanar T or Y-joint where the locations of the crown and saddle points as well as the geometric parameters are defined.

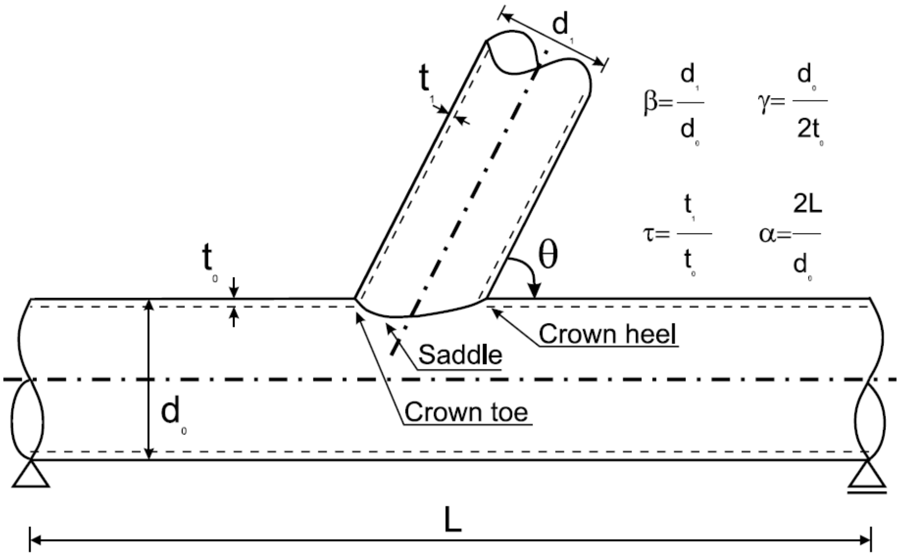

Figure 9. A uniplanar CHS T-joint or Y-joint (Zhao 2001)

The calculations for SCFs in CHS uniplanar T or Y-joint are based on the work of (Durkin, Ethymiou & Efthymiou, cited in Zhao 2001). An equation of SCF for CHS uniplanar Y-joint for the location of chord crown under axial loading is:

$$SCF = \gamma^{0.2}\tau[2.65 + 5(\beta - 0.65)^2] + \tau\beta(0.5C\alpha - 3)\sin\theta \qquad (1)$$

- Where C = Chord-end fixity
  - C = 0.5 (for fully fixed chord ends)
  - C = 1 (for pinned chord ends)

Efthymiou cited in Zhao (2001) found a typical value for C to be equal to 0.7. The formulas of the SCFs provided by Zhao (2001) including Equation 1 are only for empty T or Y-joints.

3. CONCLUSION

In summary, extensive experimental determination of SCFs on concrete-filled tubular T-joints, tube-to-tube T-joints, CHS N-joints and tube-to-plate T-joints were carried out. The literature review showed that there is limited research on the fatigue behaviour of concrete-filled T-joints. As a result, there are no standards for the design of tubular joints with concrete-filled chords. Therefore, T-joint specimens with concrete-filled chord should be tested under axial tension, axial compression and in-plane bending in order to determine the distribution of the SCFs around the brace-chord intersection and to find out if it is beneficial to have concrete-filled T-joints for fatigue design.

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