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# Review of fatigue assessment approaches for tubular joints in CFST trusses

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ABSTRACT

Specimen testing of concrete-filled steel-tube (CFST) joints and the fatigue assessment approaches for such joints were investigated and summarized to understand comprehensively the fatigue behavior of CFST trusses. The main factors that influence the fatigue resistance of CFST joints were discussed. Nominal stress- and hot-spot stress (HSS)-based methods were compared based on available experimental results, and the current state and development direction of fatigue assessment of CFST joints were explored. Results showed that the fatigue failure mode, fatigue damage mechanism, anti-fatigue optimization design, and fatigue strengthening technology of CFST joints are more complex than those listed in fatigue design guidelines or specifications. Sufficient fatigue specimen testing and finite element analyses are necessary to predict the fatigue behavior of CFST joints via the HSS approach. Fracture mechanics approaches for the fatigue damage mechanism of welded tubular joints is a future research direction.

## 1. Introduction

Steel-tube trusses have been widely used in various applications, such as offshore structures, industrial buildings, power transmission tower structures, and bridge structures, because of their good mechanical behavior, high strength-to-weight ratios, and attractive architectural shapes. Concrete-filled steel-tube (CFST) trusses, which are applied in bridge structures as a girder, arch rib, pier, and pylon, have been becoming increasingly popular in China. At the beginning of the current century, researchers effectively used CFST to reduce stress concentration in structural joints [1]. In CFST joints, the ends of brace members are connected to the surface of chord members by intersecting line welds. Fatigue cracks, which are induced by complicated joint structures, high stress concentrations, and inherent weld defects, generally initiate from the surface of CFST joints under cycle loading. The safety and durability of CFST trusses are affected by material performance degradation and local damage accumulation combined with environmental influence during long-term service.

Fatigue cracks have recently been detected in the tubular joints of several CFST truss bridges. Therefore, the fatigue behavior of CFST joints needs to be examined. Compared with systematic research on the fatigue behavior of circular hollow-section (CHS) joints, research on the fatigue of CFST joints is insufficient. Fatigue assessment methods for CHS joints are generally applied to fatigue-resistant design of CFST joints, and the special structural features of CFST joints (including different loading modes and time-dependent characteristics of concrete) are disregarded. Relevant methods must be established and verified, and advanced technologies need to be developed to address the fatigue phenomenon and conduct a reliable fatigue assessment of CFST truss bridges.

Specimen testing of CFST joints and fatigue assessment approaches were investigated and summarized in this study to understand the fatigue behavior of CFST joints comprehensively. Nominal stress- and hot-spot stress (HSS)-based methods were compared based on available experimental results. The current state and development direction of fatigue assessment of CFST joints were also explored.

## 2. Fatigue assessment methods for tubular joints

Three types of assessment approaches, namely, stress-, fracture mechanics-, and damage mechanics-based methods, are available for the fatigue damage evaluation and life prediction of welded joints. Compared with the damage mechanics-based method, stress- and fracture mechanics-based methods are more commonly applied in major industries and recommended by numerous national and international codes and standards. S–N curves are an essential feature of the stress-based method, in which nominal stress, HSS, notch stress, and structural stress are usually employed to describe the mechanical behavior of welded joints [2,3]. According to fatigue testing results of different welded details, the relationship between stress range $\Delta\sigma$ and cycle number (fatigue life) $N$ can be derived as $N\cdot\Delta\sigma^m = C$ in the stress-based method. Paris' law is a popular fatigue crack growth model used in the fracture mechanics-based method. This model relates stress intensity factor (SIF) range $\Delta K$ to crack growth rate $da/dN$ under a fatigue

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stress regime, that is, $da/dN = C(\Delta K)^m$.

Unlike the fatigue behavior of metal materials, that of welded joints is mainly affected by stress range, stress concentration, and welding defects. The fatigue life of welded structures is dominated by the propagation of small cracks, and fatigue cracks initiate on the weld roots or weld toe. Structural discontinuities at the intersections and the effect of weld geometry lead to stress concentration at the welded joint. The stress-based fatigue assessment approach depends on fatigue testing results, in which the effects of welding defects have been considered.

In the nominal stress method, nominal stress range $S_n$ is adopted to develop the $S_n$–N curve, which is calculated using nominal dimensions at the desired location away from the weld toe and structural discontinuities. Typical weld details are classified to quantify the local stress concentration effect, and the classified $S_n$–N curves are defined for particular weld details. In the HSS method, HSS range $S_{hs}$ is adopted to develop $S_{hs}$–N curves, which are extrapolated from stresses located in several extrapolation points away from the weld toe. HSS includes all the stress concentration features of weld details, except those due to the local weld toe geometry. Thus, a few $S_{hs}$–N curves are defined for typical weld details. However, the HSS method is only applicable to the fatigue failure mode in which cracks grow from the weld toe. In the notch stress method, notch stress range $S_N$ is utilized to develop the $S_N$–N curve via a finite element analysis (FEA). The actual sharp toe or root is rounded with a reference radius to avoid arbitrary or infinite stress results. Only one $S_N$–N curve must be used in the failure location and weld details to include all sources of stress concentration in notch stress. In the structural stress method, structural stress range $S_s$ is adopted, and a master $S_s$–N curve is established. By using an equilibrium-equivalent simple stress state represented by membrane and bending components instead of a complex stress state at the welded joint, through-thickness structural stress becomes consistent with elementary structural mechanics theory and can be easily calculated in a mesh-insensitive manner with conventional finite element (FE) models. The stress concentration behavior and different stress items are illustrated in Fig. 1.

In fracture mechanics, SIF is used to describe the stress field (stress intensity) near the tip of a crack and is the local crack driving force related to the rate of crack growth. Given a complicated structure and stress field, the SIF of tubular joints can be determined numerically with the finite element method (FEM) or extended FEM. The first crack always occurs at the weld toe near the crown point of chord members, and this crack is likely to propagate in two directions, namely, along the weld toe line and through the chord wall. The crack that emanates from the weld toe in tubular joints is simplified as a standard half-elliptical surface crack [4]. As shown in Fig. 2, the crack length is $2c$, and the crack depth is $a$. The deepest point and two end points of the crack plane are the fronts of the crack plane, and cracks propagate along the length and depth directions at different growth rates because of different SIFs.

Improved modeling of crack growth rate that includes the fatigue crack propagation threshold and crack-closure effect has been proposed by researchers on the basis of Paris' law. With its simple equation form and acceptable calculation accuracy, Paris' law is commonly applied to the fatigue life assessment of welded joints. According to Paris' law, fatigue life $N$ can be obtained by solving definite integrals as follows:

$$N = \begin{cases} \dfrac{a_i^{1-m/2} - a_c^{1-m/2}}{CY^m(\Delta\sigma\sqrt{\pi})^m\left(\frac{m}{2}-1\right)} & (m \neq 2) \\ \dfrac{\ln a_c - \ln a_i}{CY^m(\Delta\sigma\sqrt{\pi})^m} & (m = 2) \end{cases} \tag{1}$$

where $a_i$ is the initial crack length and $a_c$ is the critical crack length.

The fracture mechanics-based method depends on initial crack length and material constants $C$ and $m$. These material constants can be obtained through small-scale specimen tests. Fracture mechanics focuses on the crack propagation behavior of microscopic defects and provides a basis for the estimation of macroscopic mechanical behavior. Consequently, this method is suitable for analyzing the fatigue behavior of tubular joints. According to line elastic fracture mechanics (LEFM) theory, four key factors, namely, initial crack location, initial crack size, SIF, and crack propagation law, need to be clearly defined before evaluating the fatigue life of welded tubular joints.

CHS joints were extensively used in early offshore platform structures. Apart from environmental effects, fatigue damage also influences the CHS joints of offshore platforms when the platforms are exposed to repetitive loading from various sources, such as sea waves and wind. Most of the structural failures of offshore platforms are caused by the accumulated fatigue damage of CHS joints. Extensive research has been conducted on the fatigue performance of CHS joints, and various fatigue design guidelines for CHS joints were issued at the beginning of this century. The HSS approach is usually adopted in the fatigue-resistant design and analysis of CHS joints of offshore platforms because weld toe crack is the dominant fatigue damage mode of CHS joints. The International Institute of Welding (IIW) [5] and the International Committee for Research and Technical Support for Hollow Section Structures (CIDECT) [6] have been developing fatigue design guidelines for welded hollow section joints since 1999. Meanwhile, studies were conducted and design standards were issued by the American Welding

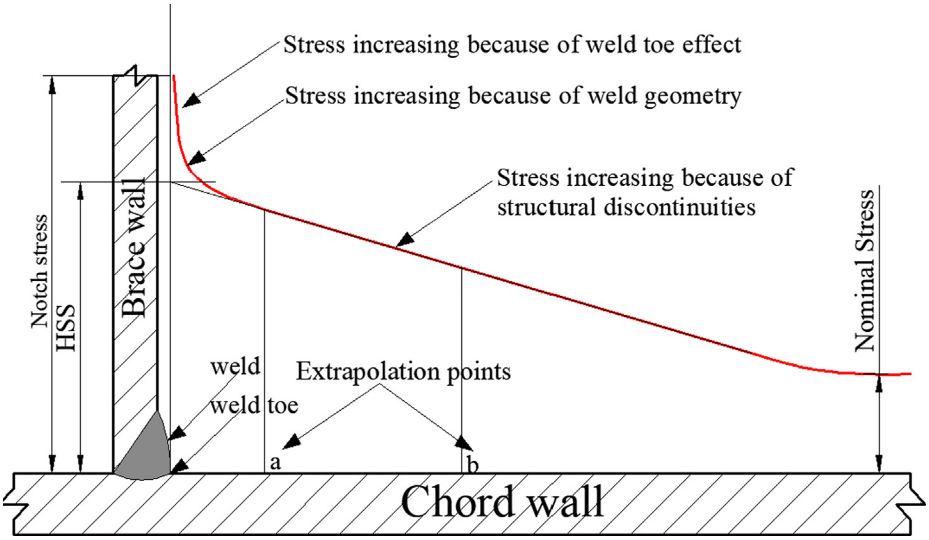

**Fig. 1.** Stress of welded tubular joints.