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# Numerical study on fatigue behavior of tubular joints for signal support structures

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ABSTRACT

Welded tubular joints are widely used for the mast arm pole connection in signal support structures. In order to study the fatigue behavior of such welded tubular joints, static loading and fatigue tests were carried out on several full-scale experiments. In order to understand the local behavior and perform parametric study of critical factors such as initial crack location, finite element (FE) models are subsequently built and the numerical simulation results are validated with the experimental test results. Stress intensity factors (SIFs) at the deepest point of fatigue cracks are calculated by the FE method and an empirical equation are examined by comparison. It is found that the numerical simulation results are in good agreement with the experimental test results. The effect of initial crack location on the SIF and the fatigue life are also investigated. The Bowness equation will result in higher SIF value and more conservative fatigue life prediction for the concerned welded tubular joints. The SIFs at the deepest point decrease and fatigue life increases with the increasing initial crack angle.



## 1. Introduction

Traffic signals are widely used at road intersections, crosswalks, and other locations for the purpose of controlling traffic flows. Traffic signal support structures usually adopt steel tubes, which have the advantages of excellent bearing capacity and light weight [1–3].

In the service life of signal support structures, the vibrations caused by vortex shedding, natural gusts, truck-induced gusts, and other effects will probably trigger severe fatigue damages to those structures [4]. Mast arm signal structure collapse in the US has been seen in the past several decades [5]. Some of the accidents happened on highway and the signal mast arm falling over fast moving vehicle poses high threat to drivers. After the accident in Michigan in 1990 [6], AASHTO mandated the revision of the design code for traffic signal structures [7]. Its fatigue problem started to draw more attention from researchers [8–17]. A few experiments have been conducted to study the fatigue strength of welded tubular joints commonly found in traffic signal structures. A typical welded tubular joint is shown in Fig. 1. Those experiments examined a variety of fatigue related design issues for the welded tubular joints in signal structures. Fatigue cracks typically start at highly stressed locations such as weld terminations of specific structural details. The stresses reach peak values near the weld toe of the joints.

The fatigue performance of welded tubular connections is of particular importance for the safety of welded steel tubular structures subjected to repeated loading such as signal support structures. Li and Zhang [1,2] did fatigue testing on six full-scale mast arm welded joint specimens fabricated in accordance with the mast-arm-to-flange plate connection design for signal supports in Maryland. This fatigue detail is commonly used as column-to-base plate or mast-arm-to-flange-plate socket connections in traffic signal supports and is categorized as fatigue category E′ by the AASHTO specification [7]. Fatigue lives of the six identical test specimens are found to vary in tests and show large dispersion although they were subjected to the same loading.

The fatigue design of mast arm signal support structures is similar to that of offshore structures, because they both use tubular joints. A large amount of experimental research in fatigue performance of welded connections has been carried out for offshore structures. However, evidence from the fatigue tests [18] has demonstrated the effect of size on the fatigue strength of welded tubular joints. In comparison with offshore structures, welded joints commonly found in signal support structures exhibit several differences with respect to the welded tubular of joints: joint geometries, member dimensions (both absolute and relative), the loads affecting the joint, and joint fabrication procedures. With the development of fracture mechanics and finite element method (FEM), it is more and more popular to use the fracture mechanics approach for solving the fatigue crack propagation problems. Therefore, finite element analysis (FEA) of prototype welded tubular joints as well as using limited experimental data from previous fatigue test are needed

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**Fig. 1.** A typical welded tubular joint used in signal support structures.

to determine the required fatigue growth behavior especially in local areas for which experimental instrumentation cannot have access to.

Bowness and Lee [19–23] proposed stress intensity factor (SIF, $K$) solutions for T-butt joints. They suggested that the $K$ factor for a T-butt weld (with an attachment) could be obtained by multiplying the $K$ factor for a plain plate (without attachment) with a weld toe magnification factor ($Mk$). They used the $K$ factor solutions for plain plates from Newman and Raju [24], and proposed equations to calculate the $Mk$ factors for the deepest points and crack ends of semi-elliptical cracks. Even though the Bowness equation is widely used in offshore structures, their applicability in traffic signal support structures remains unclear, considering the aforementioned difference between offshore structures and signal support structures.

Lie et al. [25–29] also studied the $K$ calculation for tubular joints. They numerically studied the SIFs of cracked circular hollow section T/Y-joints subjected to different loads, and compared the SIFs estimated using the method in BS7910 [30] with the FE results. Qian et al. [31,32] experimentally and numerically studied the fatigue behavior of tubular X-joints with enhanced partial joint penetration welds. In their numerical study [32], a crack mesh generator, FEACRACK, was used. The SIFs and T-stresses were computed. The effects of crack propagation angle, crack-front profile, and crack interactions on the SIF values were investigated. And, the crack propagation lives for tubular X-joints were estimated. Lie's and Qian's works have solved the K calculation problems and presented crack propagation behavior for tubular joints, which are worthy references for this study, while the crack shapes and joint geometries in this study and their studies are quite different, thus more work should be done.

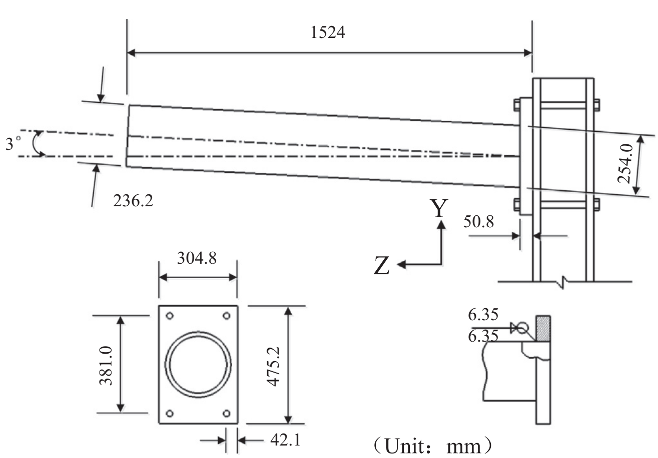


**Fig. 2.** Schematics of test specimen and weld size.

**Fig. 3.** Test setup.

In this study, the fatigue behavior of welded tubular joints for mast arm signal support structures is investigated using both the linear elastic fracture mechanics approach and the FEA method. A brief summary of the experimental test results is first given. The assumption and equation for the fatigue crack propagation are presented. The FE models are subsequently created in a general FEA software and validated with the experimental results. The SIF values obtained by the Bowness equation are compared with the FE results. Finally, the effect of initial crack location on the fatigue behavior of welded tubular joints is discussed.

## 2. Description of experimental test data for calibrating FE model

A full scale steel mast arm tube-to-transverse end plate joint was chosen as the experimental test specimen, which has been widely used as signal support structures in the US. Static loading and fatigue tests were carried out in the Structural Laboratory at the University of Maryland [1,2]. The dimensions of the test specimens and the fillet welds between the end plates and mast arm tube are shown in Fig. 2. The design of six full-scale specimens complied with the cantilevered signal support structures used in the State of Maryland, USA. However, the length of the mast arms was decreased to 1524 mm (5 ft) by keeping only the end segment of the mast arm. Tapered tubes were employed. The diameter at the end of the tube (connecting to the plate) was 254.0 mm (10 in.). The diameter at the loading end was 236.2 mm (9.3 in.). The wall thickness of the tube was 6.35 mm. The angle

**Table 1**
Load amplitudes and ranges in the fatigue tests.

| | Load (kN) | | |
|---|---|---|---|
| | $P_{max}$ | $P_{min}$ | $\Delta P$ |
| WTJ1 | 25.35 | 3.43 | 21.92 |
| WTJ2 | 24.82 | 2.76 | 22.06 |
| WTJ3 | 27.93 | 1.77 | 26.16 |
| WTJ4 | 27.43 | 0.91 | 26.52 |
| WTJ5 | 28.30 | 1.82 | 26.48 |
| WTJ6 | 27.78 | 1.39 | 26.39 |