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Probabilistic fatigue analysis of shop and field treated tubular truss bridges

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Abstract

This article examines the extent to which post-weld treatment by needle peening can improve the fatigue performance of tubular truss bridges. To do this, the various potential crack sites on several variants of a typical bridge are analyzed using a probabilistic, fracture mechanics-based model. Systems reliability theory is then used to determine the reliability of the entire untreated or treated bridge. The results of this work show that: considering phase effects may result in large reductions in the design stress ranges for these structures, a significant increase in the treatment benefit can be achieved if the treatment is applied after the dead load stresses are introduced, and weld root cracking does not appear to be the critical failure mode for these structures, so long as a strategy of partial treatment is employed.

Keywords: Tubular truss bridges; Fatigue; Post-weld treatment; Needle peening; Probabilistic fracture mechanics

1. Introduction

Bridges consisting of steel tubes welded together to form truss girders have seen increasing popularity in recent years [1–3]. This trend can be explained by the aesthetic merit of these structures and by recent improvements in the cutting and fabrication techniques for tubular structures [4]. Recent research has been conducted to improve our understanding of the fatigue behaviour of tubular bridge joints in view of the significant differences in loading, scale, and geometry that exist between these joints and the more widely studied tubular joints common to offshore applications [4]. With this improved understanding, the search can now begin for ways of improving the fatigue performance of tubular bridge joints, in view of the significant negative impact that this performance is known to have on the economic viability of these structures.

Two ways of improving the fatigue performance of tubular truss bridges have been considered in recent studies: replacing the directly welded joints with cast steel nodes [5,6], and improving the performance of the fatigue-critical welds by post-weld treatment. In order to investigate the latter possibility, large-scale tests have been carried out, which have demonstrated the potential of post-weld treatment by needle peening for this purpose [4]. Although encouraging, several concerns with the use of residual stress-based treatment methods such as needle, hammer, and ultrasonic peening, have limited the extent to which such findings can be translated into practical guidelines. Firstly, concerns exist about the reliability of these methods, in particular under realistic, variable amplitude loading conditions [7]. Secondly, in the large-scale tests reported in [4], it was seen that the benefit of concentrated treatment of the critical crack site, although substantial, was eventually limited by cracking at a less critical, untreated location. In view of these concerns, an analytical study was subsequently initiated to examine the treatment of tubular truss bridges using a probabilistic approach that would consider the actual variable amplitude loading conditions, as well as the influences of the various potential crack sites or *hot-spots* (untreated or treated) on the overall fatigue reliability of the entire structure [8,9].

Herein, the model developed for this analytical study is briefly described. A tubular truss bridge with typical dimensions and loading conditions is then presented. By analyzing several variants of this bridge using the developed probabilistic model, it was thought that the potential benefit of post-weld treatment for improving tubular bridge fatigue performance could be precisely quantified. Typical results of

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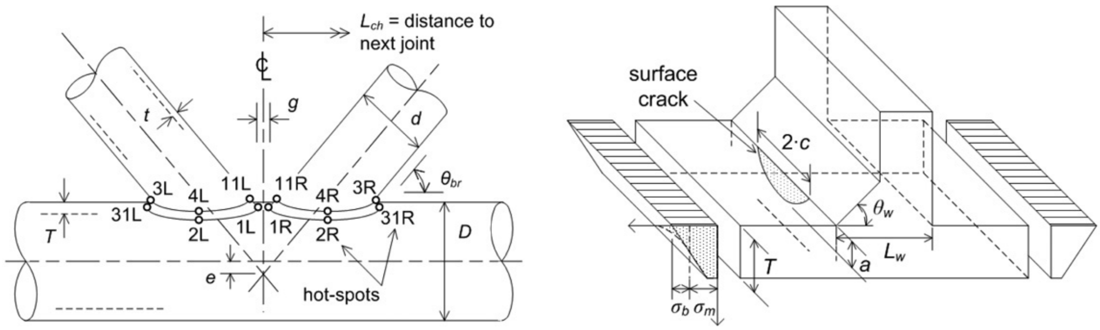

Fig. 1. Tubular K-joint and weld toe models.

the analytical study are then presented and used to determine the treatment benefit for the investigated structure. In addition, a number of related issues are discussed herein including: the effect of considering or ignoring phase effects in the code-based fatigue design of tubular truss bridges, the effect of the treatment timing on the treatment benefit (i.e. before or after the introduction of the dead load stresses), and the possibility that post-weld treatment of the fatigue-critical weld toe will simply result in a shift of the eventual crack location to the untreatable weld root. Based on this discussion, a number of areas are highlighted where further study is needed.

The work presented herein focuses on the post-weld treatment by needle peening of tubular truss bridges comprised of CHS members joined by welded, gapped single K-joints (see Fig. 1). However, it is believed that the employed models are suitable for the fatigue analysis of tubular structures treated using any of the above-mentioned residual stress-based post-weld treatment methods.

Table 1
Statistical variables used in probabilistic analysis

Variable	μ_x	σ_x	Dist.	Units
a_0	0.2	0.045	LN	mm
$(a/c)_0$	0.5	0.16	LN	–
$\text{VAR}_{\text{traffic}}$	1.0	0.15	N	–
VAR_{dead}	1.0	0.10	N	–
VAR_{DOB}	1.0	0.08	N	–
VAR_{SCF}	1.0	0.04	LN	–
VAR_{Mk}	1.0	0.05	LN	–
VAR_{Lw}	1.0	0.10	N	–
$\text{VAR}_{\theta w}$	1.0	0.10	N	–
VAR_{weld}	1.0	0.25	N	–
VAR_{pwt}	0.5	0.10	N	–
LN(C)	−28.80	0.55	N	$\text{LN}((\text{mm/cycle}) \cdot (\text{N/mm}^{-3/2})^m)$
ΔK_{th}	100.0	15.0	LN	$\text{MPa}\sqrt{\text{mm}}$
a_c	$0.5 \cdot T$	–	Det.	mm
f_y	355	–	Det.	MPa
m	3.0	–	Det.	–

2. Probabilistic model overview

2.1. Modelling single potential crack sites

The probabilistic model employed in the analytical study presented herein is based on a previously developed deterministic linear elastic fracture mechanics (LEFM) model [10], modified for the analysis of gapped single circular hollow section (CHS) K-joints (see Fig. 1). The modified model employs a number of design aids developed by others to determine the applied stress intensity factor (SIF) ranges at different crack depths for weld toe cracks at the various potential crack sites or hot-spots on such joints.

The limit state function, $G(\mathbf{z})$, employed in the probabilistic model is founded on the Paris–Erdogan crack growth law, modified to consider crack closure effects and a threshold SIF range, ΔK_{th}, and integrated over the crack depth range, a_0 to a_c. Specifically:

$$G(\mathbf{z}) = N_c - N = \int_{a_0}^{a_c} \frac{\mathrm{d}a}{C \cdot \left(\Delta K_{\text{eff}}^m - \Delta K_{\text{th}}^m\right)} - N \qquad (1)$$

In this expression, N is the actual number of stress cycles and N_c is the number of cycles to failure. In order to conduct analyses under variable amplitude loading conditions, an *equivalent block loading* approach is employed (see, for example: [11]). This approach was found to be superior to using an *equivalent constant amplitude stress range*, in particular for the analysis of the treated crack sites, as discussed in [8].

In Eq. (1) the effective SIF range, ΔK_{eff}, is taken as:

$$\Delta K_{\text{eff}} = \text{MAX}\left(K_{\text{app,max}} - K_{\text{op}}, 0\right) - \text{MAX}\left(K_{\text{app,min}} - K_{\text{op}}, 0\right) \qquad (2)$$

where $K_{\text{app,max}}$ and $K_{\text{app,min}}$ are the maximum and minimum SIFs due to the applied load and K_{op} is the applied SIF at which the crack tip opens upon loading. Specifically:

$$K_{\text{op}} = -\left(K_{\text{res}} + K_{\text{pl}}\right) \qquad (3)$$

where K_{res} is the SIF due to the residual stresses along the crack path and K_{pl} is the crack closure SIF. The uncertainties in the input parameters discussed above are considered by treating these parameters as statistical variables (see Table 1). Of particular interest in this study, the uncertainties in the residual stress distributions due to the welding and treatment processes, $\sigma_{\text{weld}}(b)$ and $\sigma_{\text{pwt}}(b)$, are considered using two variables, VAR_{weld} and VAR_{pwt} (see Fig. 2), which are assigned attributes based on measurements reported in [10,12,13]. Using these variables, the assumed residual stress distribution due to