Fatigue assessment for selected connections of structural steel bridge components using the Finite Element Method

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Abstract

Fatigue is one of the most common reasons of damage of steel bridges, both the existing and newly designed. Therefore, the procedure for the evaluation of fatigue life is one of the most important procedures in a comprehensive assessment of the load-bearing capacity and operating lifespan of a structure. A reliable fatigue life assessment is, first of all, crucial when estimating the remaining (residual) usability. The components that are the most vulnerable to fatigue damage are the so-called structural notches. This paper presents a fatigue assessment for a selected types of joint used in welded structural components of steel bridges. All the analyses were carried out using Finite Element Method. The obtained fatigue categories were compared against the values recommended in Eurocode 3 and IIW.

Keywords: fatigue, service live, structural notch, steel Bridges, numerical model

1. Introduction

The life expectancy of steel bridges depends mainly on two factors: fatigue, which usually invokes catastrophic failures, and corrosion, which commonly results in degradation-type failures. Fatigue is a form of material damage as a result of the accumulation of micro-damage in the form of scratches and cracks accompanied by repetitive loads, each of which acts statically and does not cause destruction by itself. Fatigue cracking usually forms in the so-called structural notches, which are usually welded joints between deck components [5]. This damage causes a gradual loss of deck stiffness and a rapid degradation of the insulation and pavement, which leads to a reduction in the durability of the entire civil structure and thus an increase in the cost of its maintenance [4].

The occurrence of fatigue damage is influenced by a number of factors. These are related to both the material and geometrical characteristics of the component itself and the variable load. The material and geometrical characteristics include material properties (and especially its ultimate and impact strengths) and the method of shaping the component (the shape of its cross-section, connection type, weld type, weld face treatment method). The latter factors are referred to as a structural notch. Structural notches are where fatigue cracking start to form. In welded plate girder bridges, this type of a notch includes e.g. transverse belt contacts or the location of the change in the stiffness of the belt or welded joint. In addition, in welded structures, a geometrical notch is increased by the introduction of welding stress, the changes in mechanical properties of the material as a result of welding and inner technological flaws in the welds.

2. Fatigue phenomena in steel structures

2.1. Initiation and propagation of fatigue cracking

Bridges are civil structures used under variable loads, which leads to the occurrence of a complex combination of phenomena and structural changes. The micro-cracks occurring due to variable loads gradually develop and accumulate, leading to fatigue cracking.

In the process of fatigue, there are two distinctive phases: (1) the crack initiation, where local effects (gaps) in the material grains (microscopic scale) appear, and (2) the crack development and destruction, where the resulting changes are observed macroscopically.

Fatigue life over time is the sum of the periods of crack initiation and propagation. Contrary to the cracks in smooth notch-less components, the crack initiation period in welded joints is short and almost all of the time is spent on propagation. Therefore, the calculations carried out for welded joints should assume the dominant property of the material, which is the *E*-modulus.

2.2. Fatigue life of welded joints

Currently among engineers, the most popular are the following two methods used to determine the stress in a welded joint, followed by the determination of fatigue life. The first method involves the determination of the nominal stress, and the second one determines strictly local stress in a potential crack initiation point – Figure 1 [1].

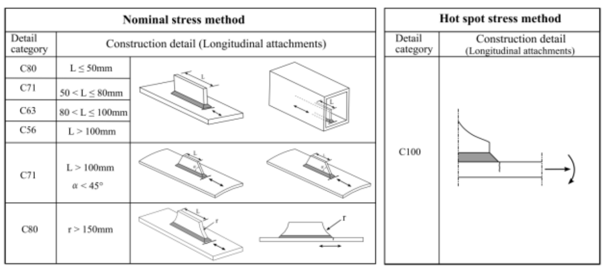

Figure 1: Fatigue class recommendations based on the nominal and the structural hot-spot stress methods [1]

The analysis based on nominal stress is used more frequently when the weld has been classified into groups in accordance with applicable standards [2] and when the stress can be easily determined. The procedures involve a series of coefficients selected based on the nature of and conditions of operation, which significantly simplifies and streamlines the calculation procedures. The detailed recommendations are included in the papers issued by the International Institute of Welding [3]. More than a dozen fatigue (FAT) categories have been specified, which depend on the type of the weld. The determination of the appropriate FAT fatigue class depends on the use of nominal stress range $\Delta\sigma_c$ = FAT (MPa) for fatigue life of $N_f = 2\cdot10^6$ cycles. Structural details are evaluated mostly in risk areas. Therefore, the fatigue life in the range 10^4-$5\cdot10^6$ can be determined from the relation:

$$N_f = \left(\frac{\text{FAT}}{\Delta\sigma_i}\right)^3 \cdot 2\cdot10^6 \quad (1)$$

where $\Delta\sigma_i$ is one occurring stress range for which fatigue is assessed.

Such an approach by the International Institute of Welding assumes that 95% of welded joints can withstand the proposed fatigue life. The obtained fatigue charts are identified by the appropriate characteristic material strength designated for two million cycles. The value of this strength is specified by the FAT fatigue class.

It is a simplification to designate dangerous areas outside the notch areas defined as nominal stress. In the case of fatigue calculations, such a design requires a detailed knowledge in the field of the analysis based on the theory of elasticity or FEM and is prone to a high risk of error. In addition, this method does not take into account any geometric variance of the classified joints, which makes it difficult to apply.

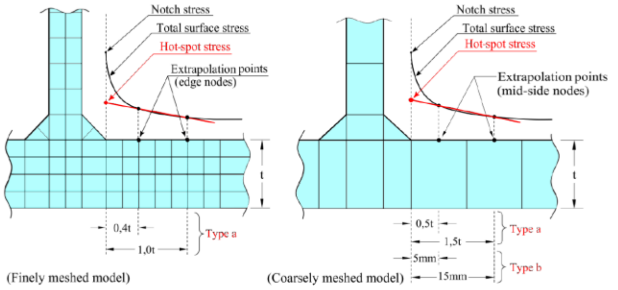

Figure 2: Linear extrapolation of the hot-spot stress from fine and coarse mesh model [1]

The second method is recommended especially in the cases where numerical analysis (FEM) is used. The methodology is also known as the linearization of stress in the critical point (Figure 2 [1]). This method takes into account the changes to cross-sections and the effect of stress concentration in the point of potential cracking, at the same time ignoring the impact of the profile of the weld.

3. Longitudinal non-load-carrying attachments

Longitudinal non-load-carrying attachments are commonly used in bridges. The universal use of this type of attachment has made it one of the most frequent fatigue tested details.

The fatigue life assessment of longitudinal attachments can be only investigated using 3D FE models. Therefore, shell or solid FE models can be used in this case. As the aim of this study is not to investigate different modeling techniques, solid element models are employed to construct the FE models. In this way, the inaccuracies attributed to the finite element analysis can be minimized.

A typical steel with elastic modulus of E = 210GPa and Poisson's ratio of v = 0.3 was defined and assigned to the entire geometry including the welds. It should be mentioned that, since elastic material behavior can be assumed for the fatigue analysis of this kind, only elastic material properties are needed to be defined.

Figure 3 demonstrates the applied loading and boundary conditions for the FE models. The boundary conditions are identical for both ends of the specimens.

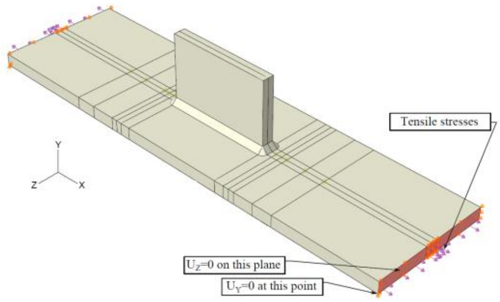

Figure 3: Loading and boundary conditions for the FE models

In the test results the standard deviation is 0.138 and the slope 2.67 evaluated with free linear regression. The characteristic strength is 88.8 MPa. With a fixed slope of 3 the standard deviation becomes 0.150 and the characteristic fatigue strength is 94.2 MPa. Linear extrapolation was also examined for this detail, giving a standard deviation of 0.150 and characteristic fatigue strength of 93.1 MPa. Considering the results, it seems that FAT-category 90 should be used for this detail instead of the FAT100 which is recommended by the IIW [3].

4. Conclusions

The results of the studies make it possible to formulate the following conclusions:

- The hot spot stress method is capable of reducing the scatter caused by the geometrical variations. As a result, one hot spot stress S-N curve can be associated to several details.
- For longitudinal non-load-carrying attachments, the design recommendations according to IIW based on the nominal stress method appears to be consistent with the available test data. However, the recommended FAT100 for evaluation based on the hot spot stress approach seems to be in conservative and should be replaced by FAT90.

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