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Comparison of local stress based concepts — Effects of low-and high cycle fatigue and weld quality

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ABSTRACT

This paper presents a study of the ability for two stress based methods, the effective notch stress method and the structural stress approach, to estimate the fatigue life in the low cycle and the high cycle fatigue regime, considering the weld quality. Two different non-load carrying joint configurations were considered, cruciform joint and T-joint. The conducted fatigue analysis shows that both methods are capable to estimate the fatigue life with good accuracy within the low cycle and the high cycle regime. The effective notch stress generally shows a smaller scatter, it also considers increased weld quality with good accuracy, in contrast to the structural stress approach.

1. Introduction

Products within the transportation industry such as trucks, construction equipment, forestry machines, ships and agricultural machines are often complex welded structures. For these products, fatigue is the most common failure mode which often starts in the welded joints. Design and manufacturing of normal structural applications is already an important task which requires accuracy. In lightweight structural applications however, where thinner and high strength steels are utilized, the increased nominal stress levels and the notch sensitivity for high strength steels compared to mild steels [1] raise the need for accurate fatigue design methods. Due to the variation of the weld profile, size and location of defects and residual stresses initiated during the welding process, the fatigue life of welded joints generally shows a great scatter. This has been verified in multiple studies and it has been incorporated in weld quality standards and recommendations for fatigue design of welded joints [2–5].

Several methods exist which are used for assessing a welded joint in terms of fatigue life. Since failure of a welded joint mainly is determined by the local loading conditions, it is necessary to use local approaches. The IIW recommendations for fatigue design [5] describe the most commonly used local approaches for assessing the fatigue strength of a welded joint:

- Nominal stress method
- Structural hot spot stress method
- Effective notch stress method
- Linear elastic fracture mechanics

The choice of fatigue design method should mainly be based on two criteria, the load level and the expected failure location. The choice is also influenced by the effort and accuracy of the approach, depending on the complexity of the structure. Depending on the

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load level, i.e., the amount of plasticity in the welded joint, different methods are used for fatigue assessment. When there is a high level of plasticity in the weld toe, strain based methods have proven to be more accurate compared to stress based methods, this is usually denoted as low cycle fatigue. For lower load levels, when there is less plasticity in the notches, stress based methods are more adequate. This paper presents a study of the ability for the effective notch stress method and the structural stress method by Dong to assess and predict the fatigue life of normal to high quality welded joints, where failure is expected from the toe side of the weld. The study primarily aims for high cycle fatigue applications, but low cycle fatigue is also considered in order to study the versatility of each method.

2. Weld quality system

Depending on the joint design and loading conditions, different weld discontinuities and imperfections affect the fatigue life differently. A common joint design is a base plate with non-load carrying attachments or stiffeners welded to the base plate, subjected to transversal or longitudinal loading. For this particular joint, critical features are small transition radii and the presence of undercuts. The allowable size and presence of these imperfections are specified with a weld quality level within the new Volvo Corporate weld quality system, see Table 1. Normal as welded quality requirements are denoted VD, high quality as welded joints are denoted VC – e.g., using alternative welding techniques [6] – and post weld improved joints – e.g., where TIG-remelting or HFMI has been utilized – are denoted VB. One important target with the new weld quality system is that the acceptance limits for each defect should reflect the fatigue life. If the quality level is raised one level, the fatigue life should be expected to increase by a factor of 2, alternatively, the allowable stress level should be increased by 25% [4]. It should be noted that the acceptance limits within the weld quality system primarily consider the weld geometry. Effects of an improved stress state in the welded joint are not considered. Applying High Frequency Mechanical Impact (HFMI)-treatment [7,8] significantly enhances the fatigue life of the welded joint by introducing beneficial compressive stresses in the weld toe region. The resulting geometry after HFMI-treatment however, in terms of transition radius and undercut, will not necessarily correlate with the acceptance limits within the quality level VB.

3. Improved weld quality by HFMI

The fatigue life of a welded component is mainly governed by two factors; the shape of the notch which generates a local stress concentration, and the residual stress state. Peeing methods, such as hammer and needle peening, are classified according to IIW [5] as residual stress improvement techniques which eliminate the high tensile stresses in the weld toe region and introduce beneficial compressive stresses. For HFMI-treatment, cylindrical indenters are accelerated against the material with a high frequency (>90 Hz), which is more user friendly compared to hammer peening and the very small spacing between each impact results in a finer surface finish. The treated material becomes highly plastically deformed, which improves the local weld toe geometry as well as the residual stress state in the impacted region [8].

The existing IIW guideline [8] proposes procedures to account for thickness and size effects, yield strength and loading effects such as stress ratio and variable amplitude loading. The procedure to consider these effects depends on the choice of assessment method; the effective notch stress method accounts for size and thickness effects, neglecting effects of yield strength and stress ratio, whereas, in general, the structural stress methods require consideration of all these effects.

4. Fatigue assessment methods

The following section provides a general introduction of the structural stress concept and a more thorough description of the approach used within this study, the structural stress approach derived by Dong. The effective notch stress method will also be given a comprehensive description.

Table 1
Acceptance limits in the weld quality system within Volvo [3].

Discontinuity type	VD (as welded normal quality)	VC (as welded high quality)	VB (post treated)
Transition radius	$R \geq 0.3$ mm	$R \geq 1$ mm	$R \geq 4$ mm
Undercut	$u \leq 0.1\ t$ [max 1.5 mm]	$u \leq 0.08\ t$ [max 1.5mm]	Not allowed
Cold lap	$c \leq 0.5$ mm	$c \leq 0.1$ mm	Not allowed
Inner lack of fusion	Not allowed	Not allowed	Not allowed
Throat deviation	$\leq 0.1\ a$ [max 2 mm] (larger ok)	Not allowed (larger ok)	Not allowed (larger ok)
Clustered pores (inner/outer)	6% / 3%	4% / 2%	2% / 1%