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Assessment of the size effect for use in design standards for fatigue analysis

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ABSTRACT

Reduced fatigue capacity of welded structures for larger thicknesses was introduced in design standards approximately 30 years ago. A significant amount of research on this topic was performed during the following years. In general the presence of a size effect was agreed upon. The size effect is considered to be dependent on the plate thickness at the considered hot spot in addition to size of the attachment plate and type of dynamic loading. Only simplified recommendations on the size effect are included in most fatigue design standards. One reason for this is normal scatter in fatigue test data and also somewhat different recommendations based on these data in the literature. This has made it difficult to arrive at full agreement on recommended fatigue analysis procedures. In this paper a review of the background for the size effect in literature and design standards are presented together with a calibration of a fracture mechanics analysis method with fatigue test data. The effect of different parameters contributing to the size effect is illustrated. An attempt has been made to use the calibrated analysis model also to quantify the size effect based on crack growth analyses. Finally some recommendations on size effect to be used in fatigue design standards are presented.

1. Introduction

The thickness and size effect on fatigue capacity of welded structures was first published at a conference on offshore structures in 1979. After this it has been subject to a number of research projects. This research has been related to laboratory fatigue testing and numerical simulation by crack growth analysis using fracture mechanics. A number of papers related to this issue have been presented at conferences and in journals.

Most of the laboratory tests have been performed under cyclic bending load as that has required less capacity of the testing machines than that required for axial testing of thick connections. It is understood that the effect of plate thickness on fatigue capacity is larger in bending than in axial membrane load. In sound structures most of the force transfer in welded joints is by axial force. However, in simple tubular joints also a significant bending stress through the wall thickness is present. It is well known that fatigue test data are showing a significant scatter. This has made it difficult to provide reliable design recommendations that also are resulting in cost efficient structures.

The size effect is related to the size of the main plate and to the size of the attachment such as thickness of a transverse plate at a cruciform joint as indicated for different welded connections in Fig. 1. As the thickness of the attachment increases, more stress is attracted to the weld toe region and a fatigue crack becomes initiated earlier. The size effect is also related to the geometry of the weld toe such as weld toe angle, radius and undercut. This geometry is thus a function of acceptance criteria for fabrication: how much undercut is allowed and what requirements are made with respect to shape of weld at the transition from the weld to the base material.

The effect of the weld toe geometry and the attachment length indicates that a butt weld of limited width will show less size effect than that of a cruciform joint. The effective attachment lengths, L, for some welded joints are shown in Fig. 1. Butt welds are most often subjected to membrane load which also is considered to be less affected by the size effect than for bending loads. Most of the testing for documentation of the size effect has been performed on cruciform joints subjected to bending loads. The size effect is considered to be significantly reduced by grinding the weld toe region such that the weld notch is reduced. The thickness effect may be considered removed by machining the weld such that the weld notch is fully removed. This can be shown by fracture mechanics for a perfect flush grinded weld.

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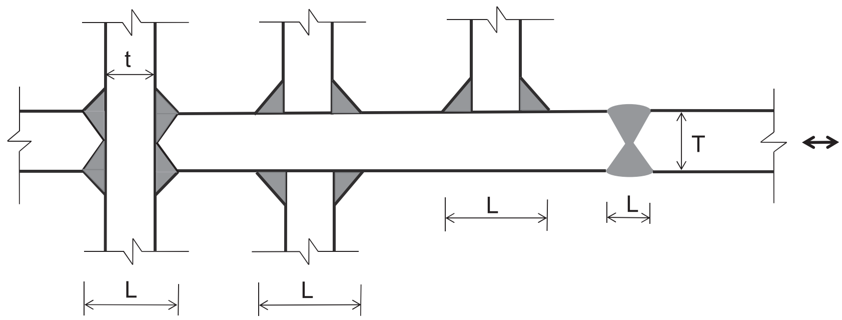

Fig. 1. Illustration of different types of welded cruciform joints and butt weld.

The size effect in many fatigue design standards is accounted for by a modification on the stress range such that the design *S–N* curve for thickness larger than the reference thickness reads, Refs. e.g. ISO 19902 [50], IIW [46], API RP2A [1], IACS [47] and DNV-RP-C203 [25]:

$$\log N = \log \bar{a} - m \log\left(\Delta\sigma\left(\frac{t}{t_{ref}}\right)^k\right) \quad (1)$$

where m is the negative inverse slope of the *S–N* curve, $\log \bar{a}$ the intercept of $\log N$ axis; t_{ref} the reference thickness for welded connections (equal 25 mm in many design standards); t the thickness through which a crack will most likely grow and k is the thickness exponent on fatigue strength as given in design standards.

The effect of the plate thickness on calculated fatigue life as function of thickness and thickness exponent resulting from the above mentioned design procedure is illustrated in Fig. 2. The calculations have been performed for a typical floating platform with a two parameter Weibull long term stress range distribution with shape parameter equal 1.0. A butt weld is analysed as an example (Design *D*-curve according to DNV-RP-C203). A fatigue life equal 20 years without thickness correction is used as reference (total number of cycles $n_0 = 10^8$). The reference thickness is 25 mm. It is observed that the calculated fatigue life is significantly reduced with increased thickness exponent for increasing thickness. It can also be noted that there is a thinness effect below the reference thickness which leads to increased calculated fatigue life for thicknesses lower than the reference thickness (this is not shown in figure). However, this effect is normally not accounted for in design standards for plated structures. It is normally used for tubular joints, Ref. e.g. DNV-RP-C203 [25].

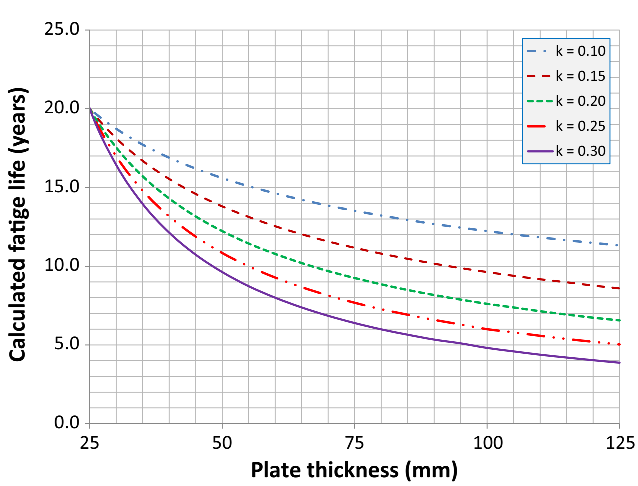

Fig. 2. Effect of plate thickness and thickness exponent on calculated fatigue life.

In general the size effect is included in the design equation to account for a situation that the actual size of the considered structural component is different in geometry from typical test specimens that the *S–N* data are derived from. The mean thickness used to derive *S–N* data corresponds to the reference thickness t_{ref} in Eq. (1). The size effect is considered to account for different sizes of plate through which a crack will most likely grow. It also accounts for size of weld and attachment as explained in Section 2.2. However, it does not account for weld length in components different from that tested such as seam welds in long pipes as described in Section 2.3.

A literature review of the size effect is presented in Section 2 of this paper. A review of the size effect related to *S–N* curves in different design standards is presented in Section 3. A calibration of a traditional fatigue crack model using classical fracture mechanics is presented in Section 4. Then the calibrated analysis model is used to derive crack growth data for different welded geometries in Section 5. The derived crack growth data are transferred to that of an effective plate thickness to be used together with design *S–N* curves. The derived fatigue data are compared with recommendations in existing literature and design standards in Section 6. The results from this give basis for the recommendations in the conclusive section of this paper.

2. Literature review

2.1. Terminology

It may be useful with some explanation of terminology before going into a detailed review of the literature in order to better understand what is meant by a thickness and size effect. In the first papers presented by Gurney [36] and Berge and Engesvik [5] the reduced fatigue capacity due to larger plate thickness was related to the plate thickness on the weld toe side of a cruciform joint through which a fatigue crack would most likely initiate and propagate. This was based on test data where the thickness of the transverse plates in the cruciform joints was of a similar thickness as the main load carrying plates, Ref. Engesvik [28]. This interpretation of the thickness effect with the main load carrying plate as a governing parameter for fatigue design was then introduced in the Department of Energy's guidance notes in 1984. This document became leading for development of many other design standards on fatigue for design of offshore structures such as NS 3472 [72], DNV [31] and API RP2A [1].

Most fatigue testing for assessment of the thickness effect has been performed on cruciform joints. A number of researchers have later indicated that the thickness effect is being reduced when the thickness of the transverse attachment is reduced as compared with the thickness of the main plate, Ref. e. g. Berge et al. [8]. This may simply be explained by less stress at the weld toe as the thickness of the transverse plate is reduced.