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Effects of plate stiffness on the fatigue resistance and failure location of pipe-to-plate welded joints under bending

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ABSTRACT

A series of tests have been carried out using specimens made of a tube, having a thickness of $t = 10$ mm, joined to a plate by fillet welding. Two different kinds of specimen were employed, differing in the plate geometry (stiffness). Both kinds of specimen were tested under bending (prevalent load) and shear loading in as welded conditions.

Different initiation regions for the fatigue cracks were found and significantly different fatigue resistances were obtained for the two geometries in terms of the nominal stress approach (or in terms of applied load vs cycles to failure). Two local methods for the fatigue life assessment were then applied to independently analyse the experimental results: the fictitious notch rounding approach proposed by Radaj, which is also recommended by some international standards and the more recently proposed peak stress method, which is based on the NSIF concept.

It is shown that the nominal stress method, which is by far the simplest method among those recommended in standards for analysing the joint under study, fails to explain the observed different endurances. On the other side, the methods based on local stresses account for the different joint stiffness and provide a reduced scatter in the results. However, even if local approaches, accounts for differences in the structural behaviour of the joint, the knowledge of the actual geometry of the weld need to be accounted for, in order to be able to identify the fatigue crack initiation region.

For a design purpose, a safe prediction of the fatigue endurance of the joint can be obtained by all the analysed methods, if the corresponding recommended design curve is used.

1. Introduction

The fatigue life assessment of welded joints is still an open and debated subject. One of the main features of the welding process is that localised high temperatures are reached and, as a consequence, the material microstructure (i.e. grain size, secondary phases, microstructural defects, etc.) and the mechanical properties (e.g. yield strength, hardness, etc.) in the fused zone and in the heat affected zone are modified. Some micro and macro geometric discontinuities (such as e.g. inclusions, porosity, undercutting) may also be introduced by the welding process itself and high residual stresses are generated in proximity of the weld seam. The variability typical of the welding process when combined with the localised nature of damage initiation, usually, gives raise to relevant scatter in fatigue test's data. For these reasons the fatigue assessment of welded joints is complex and different analysis methods have been proposed in standards [1–4] and, more generally, in the technical literature (see e.g. [5–15]).

Dealing with welded joints, there are different potential regions where the fatigue crack responsible of the final failure may initiate, namely the weld root and the weld toe. Despite of that, some of the methods that are recommended in standards, such as the nominal stress approach, does not consider the local geometry of the weld and, consequently, do not differentiate on the initiation region. In addition, some of the proposed local methods, such as the hot spot (or structural stress) method, only consider the case of failures from the weld toe. To this regard, it is also infrequent that papers available in the technical literature from different authors report different initiation regions for the same kind of specimen, material and loading conditions (see e.g. [16–20]).

In the present work the effect of the plate geometry on the fatigue crack initiation region and on the observed fatigue endurance in a frequently employed welded joint, i.e. the pipe-to-plate joint, is discussed. For this reason a dedicated experimental campaign was conducted, extending the database of experimental results already presented in previous works by the authors [16,21]. The

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newly employed specimens differ from the previous ones in terms of plate stiffness (Fig. 1). However, if the nominal stress method is considered, the specimens belong to the same structural detail (see [1,2]).

The fatigue strength of the analysed flange-tube welded joints has been discussed in [17–19], for the case of fillet-welded joints is and in [7,9,20] for the case of bevel butt welded joint. However, in none of those works the stiffness of the plate is explicitly regarded as a significant parameter in terms of the fatigue strength of the joint.

The discussion of the results is based on three endurable stresses obtained by different analysis methods, i.e. the nominal stress approach, which is by far the most simple and used method when applicable, and two local stress methods: the already well established fictitious notch rounding radius [22–24] and the more recently proposed peak stress methods [25,26]. The capability of the different methods, which are based on quite different theoretical background, in interpreting the experimental endurances is also discussed in terms of scatter band and prediction of the crack initiation region.

2. Evaluation of the fatigue strength of welded joints by the nominal stress, the fictitious notch rounding radius and the peak stress method

In this work both global and local methods have been used for the fatigue assessment. The nominal stress method [2] belongs to the former category and, if a nominal stress can be defined, is by far the most simple and most widely used method. For this reason it is also referenced in standards [1] and is the usually preferred method for engineers working in the industry. Furthermore two local methods have been used: the notch stress method (see e.g. [2,23]) and the peak stress method [25]. A brief review on their theoretical background is presented in the following.

It is worth to note that both the local methods here reviewed assumes a sharp V notch with a null tip radius at the most solicited region, i.e. weld toe or root. This is a widely used assumption for design purposes, since it is a conservative hypothesis and, in addition, is an easy way to bypass the difficulties related to the evaluation of the actual notch tip radius.

2.1. Nominal stress method

This method is recommended by both the *International Institute if Welding* (IIW) [2] and by the Eurocode 3 [1]. According to this method, the nominal stress on the weld section is calculated according to common stress formulas, based on beam theory. In the present case, due to the length of the tube, the applied load results in a prevalent bending component at the weld critical section. Therefore, the nominal stress can be evaluated by Eq. (1), where M_b is the bending moment, W_x is the strength modulus of the weld section, which is defined with reference to the weld throat size.

$$\sigma_n = \frac{M_b}{W_x} \tag{1}$$

It is worth noting that only nominal dimensions of the weld seam (weld throat) are taken into the calculation and there is no account for the actual joint geometry, meaning that the effect of all the fatigue relevant parameters should be included in the fatigue class of the structural detail [27]. It can be easily understood that, by using this method, the fatigue life assessment is as reliable as the structural detail is similar to one of the details covered by the code. In the present case both the test specimens A and B (Fig. 1) can be referred to structural detail number 423 as classified by [2], with no distinction.

2.2. Fictitious notch rounding radius

Fatigue assessment through the use of a fictitious notch radius was developed by Neuber [28] based on the idea of averaging the linear elastic stress over the micro-structural length in the ligament of the notch.

$$\overline{\sigma} = \frac{1}{\rho^*}\int_0^{\rho^*} \sigma(x)dx \tag{2}$$

The average stress ($\overline{\sigma}$) is used as a fatigue effective stress. Due to limitations in numerical calculation methods at that time, Neuber formulated the procedure of fictitious notch rounding, where the averaged stress on the actual notch with a radius ρ is substituted by the maximum stress on a fictitiously enlarged notch radius, termed ρ_f in Eq. (3). Here the support factor (s) is an analytically derived factor that depends on the stress state at the notch tip and on the failure hypothesis (see e.g. [29,30]).

$$\rho_f = \rho + s\rho^* \tag{3}$$

For welded joints, Radaj [23] assumed the notch to be V-shaped with tip radius equal to zero ($\rho = 0$), which is always a conservative hypothesis. He also obtained $s = 2.5$ and the micro-support length $\rho^* = 0.4$ for steel. Then, the fictitious radius resulted $\rho_f = 1$ mm, which is called reference radius.

This procedure has been successfully applied for decades in the fatigue life assessment of joints with a thickness $t \geqslant 5$ mm and is one of the methods recommended by the *International Institute of Welding* (IIW) [2].

2.3. Peak stress method

The peak stress method (PSM) was originally proposed by Nisitani et al. [31] for notched specimens. More recently Meneghetti et al. have proposed its use also for the fatigue life assessment of welded joints [25,26] and have extended its application in case of three dimensional problems.

$$\Delta\sigma_{eq,peak} = \sqrt{f_{w1}^2\Delta\sigma^2_{\theta\theta,\theta=0,peak} + f_{w2}^2\Delta\tau^2_{r\theta,\theta=0,peak}} \tag{4}$$

The basic idea behind the PSM is to estimate the stress intensity factor (NSIF) with a Finite Element (FE) model, which is characterised by a coarse free mesh. Also in this case the notches are assumed to be V-shaped with a null tip radius. The mode I and II elastic stresses obtained from such model are then linked to the desired NSIFs by the simple Eq. (4). In that equation, $\Delta\sigma_{\theta\theta,\theta=0,peak}$

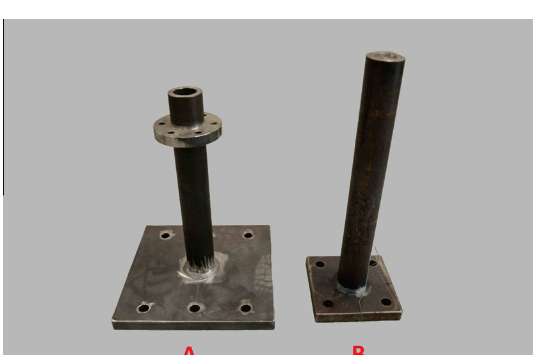

Fig. 1. Tested specimens. Type A specimen with the larger plate (on the left) and type B specimen with the smaller plate (on the right).