A FATIGUE ASSESSMENT METHOD BASED ON WELD STRESSES

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ABSTRACT

In this paper, a method for extending the applicability of structural stress method for fatigue assessment of welded structures is discussed. The structural stress method for plate structures, as currently presented in commonly used design guidance documents, cannot account the effect of weld size and load carrying fillet welds are assessed using a different S-N curve as compared to non-load carrying fillet welds. The current proposal is to linearize the local stress distribution through the plate thickness in the plane of the weld toe and, thus, partially capture the local effect. A bilinear stress distribution is derived from the actual non-linear stress distribution based on equilibrium. A simple procedure is presented to determine the bilinear curve from the nominal weld stress. This is a great advantage in finite element analysis when only nominal base plate stress and nominal weld stresses need to be determined. The same weld stresses can be used also in the analysis of the root cracks. The proposed method was scaled to correspond to the traditional structural stress method using detailed linear elastic fracture mechanics simulations. The method is here applied only to fully load-carrying welds but can also be used for partial load-carrying welds. A symmetric splice plate having a fully loaded fillet weld is presented as an example case. The influence of base plate thickness is also studied.

1 INTRODUCTION

Several fatigue assessment methods have been introduced to assess durability of metal structures under dynamic loading. Methods have evolved as the analysis methods have become more sophisticated and computers have increased in speed and memory capacity. Today, fatigue analyses of complex welded constructions are largely based on numerical methods, e.g., the FE (finite element) method. Fatigue assessment places two conflicting demands on the analysts. The fatigue damage process itself is highly local, thus requiring fine FE meshes. On the other hand, welded structures are frequently large, geometrically complex, have many load points and have difficult to define boundary conditions. These demands are best satisfied with large FE models. Because of this conflict, fatigue assessment is frequently the slowest link in the design process of fabricated structures.

Fatigue assessment methods for welded structures can be based on strain, stress, notch stress or stress intensity factor. Methods can generally be divided to global and local approaches [1]. The nominal stress method can be categorized as global approach, because the local geometric properties of a weld are included in the corresponding detail class and corresponding S-N curve. Structural stress based methods [2,3] omit the detail classes, but the local geometric properties of the weld, e.g., toe radius, weld angle, etc., are still considered to be included in the appropriate S-N curve. In one sense the structural stress method is local even though it cannot specifically account for the notch effect caused by the weld. The effect of local weld toe geometry can be included in analyses using notch stress or notch strain methods. Application of these methods to welded structures is presented, for example, in [1]. The effective notch stress method is one of the methods recommended by the IIW (International Institute of Welding) [6]. Fracture mechanics based method can also be used to determine fatigue strength of the welded structure. The actual weld toe geometry should be considered and an initial crack size must be assumed. The initial crack size used in fatigue analyses is often in the range of 0,1-0,2 mm, but this value can vary depending on the welding operation parameters. Guidelines and successful application of the fracture mechanics in welded structures is given in [4,5,6,7].

The previously mentioned local methods have been shown to be more accurate than the nominal stress method, especially for complex fabricated structures. Performing fatigue analysis for arbitrary welded detail using local methods and finite element method can a challenge for complex structures. Modelling time and memory demands of numerical models expand rapidly when the local geometry is modelled. When compared to other local methods, the structural stress based method significantly decreases the requirement for the mesh size to a fraction from the local methods. If it is only necessary to determine the linear stress distribution through a plate thickness in front of the weld toe, the structural stress can be determined using only a fairly simple element mesh [8,9]. The structural stress based method is included, e.g., in the recommendations of IIW [6], the European standard for steel structures [3] and design guidance documents for pressure vessels [10].

Structural stress or geometrical stress in plate structures is a stress at the weld toe excluding the non-linear peak stress. According to Radaj [11], excluding of the peak stresses can be performed by surface extrapolation or by a linearization of the through thickness stress distribution. Linearization is unambiguously defined. However, the stress determined by surface extrapolation will be affected by the choice of extrapolation points. Suggested extrapolation points are located normally between 0.4 and 2.5 times the plate's thickness from the weld toe [12]. In principal both surface extrapolation and through-thickness linearization should give the same stress value, at least for simple plate structures. If the location of expected fatigue fracture is on a stiffened plate or on a plate edge, the stress gradient is greater and a quadratic extrapolation or extrapolation based on fixed distances from the weld toe is recommended [13].

A linear through thickness stress determination procedure is ideal for shell element models. It is also easily applied for FE models using solid elements. However, even an exact determination of the structural stress does not necessarily guarantee the accurate prediction of fatigue strength [14,15,16,17] Dong et al. [18] introduced a bilinear stress distribution and used these values to determine notch stresses at the weld toe. A relatively fine mesh is required to determine the bilinear stress distribution.

This paper presents a suggestion for improving the accuracy of the structural stress method for load bearing and semi-load bearing welded details. One major goal in the development has been to keep the FE models used in the stress analysis simple. The required mesh should be no more complicated as that used in the traditional structural stress method. As a test case for development, a symmetric splice plate detail subject to tension only loading was chosen.

2 STRUCTURE AND ANALYSIS METHODS

2.1 Welded detail

Fillet welds are extensively used in fabricated steel constructions. Figure 1 shows some typical fillet welded details. The weld in Fig.1 (a) is considered as non-loaded while the other welds in this figure are fully or partially load-carrying. The weld in Fig.1 (c) is fully loaded. The transverse gusset in Fig.1 (b) is often considered as non-load carrying, but in this study it is classified as semi-load carrying. In cases (b) and (d) the degree of loading is dependent on the attachment stiffness and length. As a starting point origin for this study, it has been assumed that the conventional structural stress method as defined by Niemi [19] is sufficiently accurate when the weld size is large compared to base plate thickness.

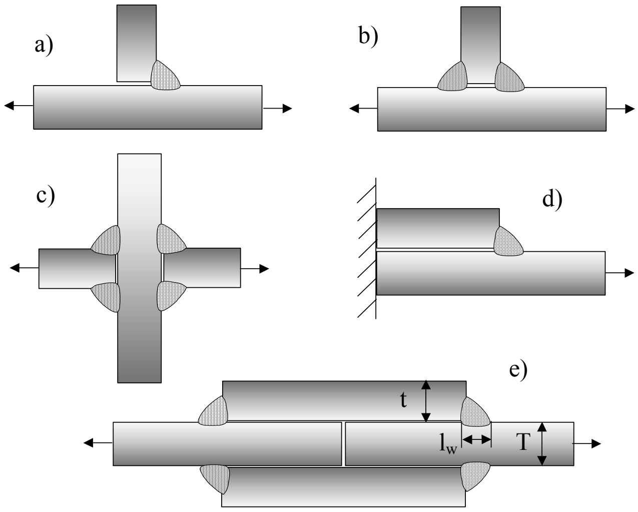

Figure 1: Fillet welds. (a) Non-load carrying, (b) semi-load carrying and (c) load carrying. (d) Fillet welded cover plate. (f) Symmetric splice plate structure used in this study.

Fatigue strength of the details was first assessed using linear elastic fracture mechanics. The fatigue strength at $N_f = 2x10^6$ was estimated and considered as the baseline value against which fatigue strength estimates based on the structural stress were compared. Weld toe radius was modelled as 0.1 mm. A very fine FE mesh with five elements in the toe radius region was used to estimate the non-linear stress distribution for the weld. Stress intensity factors were calculated according to method derived by Albrecht and Yamada [20]. Initial and final crack size were 0.1 mm and 15 mm, respectively. Characteristic crack growth rate constants for steel were used, i.e., C = 3.0×10^{-13} and m = 3 (units MPa√m and mm/cycle).

2.2 Bilinear stress distribution

In the case of the symmetric splice plate used in this study, the structural stress is not dependent on the base plate thickness. Fatigue assessment based only on structural stress, therefore, would show no influence on plate thickness. In reality the through thickness stress distribution at the weld toe is highly non-linear. This is illustrated in Fig. 2 as σ_{nl}. A linear structural stress distribution can be derived from this non-linear stress on the basis of equilibrium. To improve the fatigue life prediction accuracy, the stress distribution is here divided into three linear parts shown schematically in Fig 2. This is similar to the method proposed by Dong et al. [18] for non-symmetric welds. Linearization of the stress distribution determined from FE analysis yields the stress terms S_1, S_2, S_3 and S_4 as shown in Fig. 2. The stress values σ_1, σ_2, and σ_3 as well as the continuity of the bilinear curve at the depth T_1 is solved using equilibrium, Eq. 1.

Solving Eq. 1, however, requires that the depth T_1 must be selected. In practise, a bilinear stress distribution can be determined to any depth T_1. This depth affects the resulting stress value at the late surface. On the other hand, T_1 can be selected so as to calibrate the procedure and produce the desired stress value at the weld toe. Ideally this distance would be some dimension related to the physical dimension of the structure and thus easily determined. Initially, T_1 = 10.6 mm, 15mm and 20mm were investigated. Note that weld leg length is 15 mm and the weld throat thickness is 10.6 mm.

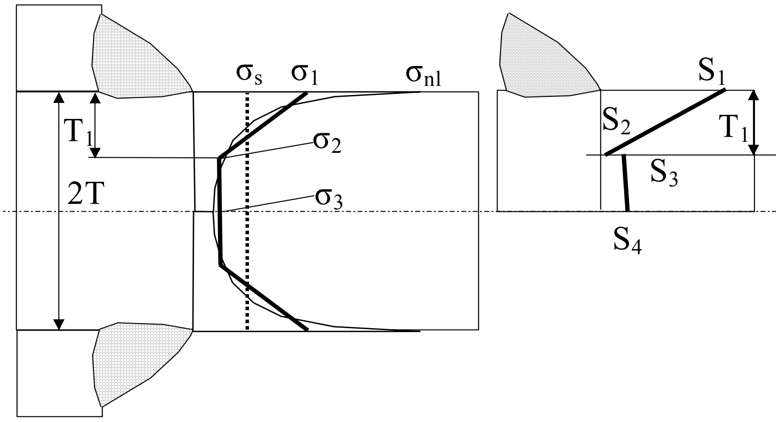

Figure 2: Bilinear stress distribution.

$$2S_1 + S_2 = 2\sigma_1 + \sigma_2$$

$$T_1(S_1 + S_2) + (T - T_1)(S_3 + S_4) = T_1(\sigma_1 + \sigma_2) + (T - T_1)(2\sigma_2) \qquad 1)$$

$$\sigma_2 = \sigma_3$$

It was found that T_1 = 20 mm produced the results most consistent with the fracture mechanics predictions (see Table 1), however, this single depth value was not clearly related to the size of the weld. Furthermore, the stress distribution determination requires a relatively fine FE mesh.

In order to develop a method that only requires coarse FE-meshes, the stress transmitted by the weld is also considered. This value is easily calculated even for coarse meshes or plate element models. With reference to Fig. 3, σ_{weld} is the normal stress transmitted by the weld at the weld throat and the bilinear stress σ_{bl} is determined based on equilibrium between the nominal stress, σ_{nom}, and σ_{weld}. The depth T_1 is assumed equal to l_{weld}. Based on these restrictions, two equations for the evaluating σ_{bl} can be derived depending on the relationship between the weld leg length, l_{weld}, and the plate thickness, T. These are given as Eq. 2.

$$\sigma_{bl} = \sigma_{nom} + \sigma_{weld}\left(1 - \frac{l_w}{2T}\right) \qquad ,l_w \le T$$

$$2)$$

$$\sigma_{bl} = \sigma_{nom} + \sigma_{weld}\left(\frac{T}{2l_w}\right) \qquad ,l_w \ge T$$

The results of the fracture mechanics calculations and calculated fatigue classes using maximum stress of the bilinear curve at weld toe are shown in Table 1. Fatigue strength is assessed based on σ_{bl} and the structural stress design S-N curve recommended by IIW [6], FAT 100. Fatigue strength based on Eq. 2 is given in the bottom row of Table 1. It can be seen that the predicted fatigue strength for all values of plate thickness are in good agreement with the fracture mechanics predictions.

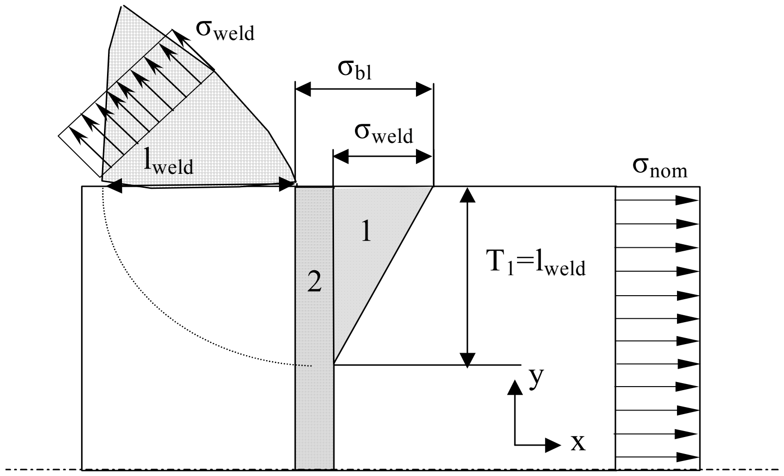

Figure 3: Stress value definitions for the construction of the bilinear curve.

Table 1 Calculated fatigue classes using bilinear curves (σ_{nim} =100 MPa).

T [mm]	stress=0	15mm	20mm	40mm	60mm	100mm
FAT	**100**	**65**	**55**	**32**	**23**	**15**
T1=10.6mm	100	50	40	22	15	9
T1=15mm	100	55	47	26	19	11
T1=20mm	100	0	50	32	22	14
Eq. 2	0	67	55	32	22	14

3 DISCUSSIONS AND CONCLUSIONS

A method has been proposed to determine a bilinear stress distribution through the thickness of a plate in the plane of the weld toe. The method is based on equilibrium and is suited for load carrying welds in relatively thick plates. Simple equations have been developed to compute the bilinear stress at the plate surface. This bilinear stress can considered as a local structural stress and used in same way as traditional structural method. This stress value is used to assess fatigue strength using design curves for non-load carrying welds previously developed within the IIW. This new assessment method will allow all welds, non-loaded, partially loaded or fully load-carrying, to be evaluated using a single S-N design curve.

Fatigue assessments performed with this method for a symmetric splice plate were in good agreement with fracture mechanics based predictions. The base plates in this example were relatively thick. While the fracture mechanics method or other local methods require a very fine FE mesh, the proposed method is also suitable for coarse meshes, which are preferred when large or complex structures are evaluated. The method presented here has been applied only to symmetric fully load carrying welds under tension only loading. The method will also be expanded to unsymmetrical cases and partial load carrying welds. Combined tension-bending load cases are also of interest.

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