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Numerical predictions of the fatigue life of aluminium welded joints

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Abstract

The fatigue life of arc welded joints made of aluminium alloy has been investigated by means of the implicit gradient method. This approach is suitable for estimating the fatigue life of welded joints characterised by different opening angles of the fillet weld and different thicknesses. The main fatigue data are related to cruciform joints, rectangular hollow section T-joints and bead removed joints. Using the principal stress as the local equivalent stress and a notch tip of the weld toe radius equal to zero, the paper analyses about two hundred experimental data taken from the literature and proposes a universal scatter band in the range of 10^4 to $5{\cdot}10^6$ cycles. This scatter band has an inverse slope around 4 and, at high cycle fatigue, the strength is about half that of steel joints. However, the scatter band is similar to welded joints made of steel previously analysed.

Keywords: Fatigue life; Aluminum; Welded joints

1. Introduction

The basic idea of local approaches to assess the fatigue life of welded joints is to consider the value of actual physical quantities linked to the stress field in the neighbourhood of the area where the fatigue crack will nucleate [Radaj and Sonsino (1998), Baumgartner et al. (2015), Karakas et al. 2008, Lazzarin and Zambardi (2001), Berto and Lazzarin (2009), Meneghetti (2008), Susmel and Taylor (2011), Marulo et al. 2017]. A strong simplification is usually introduced by considering the weld as an open notch with a linear flank and null notch tip radius [Lazzarin and Tovo (1997), Livieri and Lazzarin (2005)]. So that, the stress field ahead of the notch tip has to be considered as singular [Williams

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(1952)] and a fatigue limit strength of the material cannot be introduced. On the other hand, from an engineering point of view, a smoothing of the peak stress can be introduced by using the structural hot spot stress method developed for calculating the fatigue life of welded tubular joints in the offshore industry [see Marshall 1992]. Later, the IIW published new recommendations containing four fatigue design approaches, including the hot spot approach [Niemi 1995, 2006].

The idea that material damage is mainly due to the fatigue behaviour of a wide zone around the notch tip is also considered by Pijaudier-Cabot and Bažant (1987), by Weixing (1993) and in the implicit gradient method [Peerlings et al. (1996)]. This approach has been proposed as a design method for welded arc structures made of steel [Tovo-Livieri (2007), Livieri-Tovo (2018)]. Many experimental series, very different in terms of thickness and geometry (for example with a thickness ranging from 3 mm to 100 mm), were analysed by means of a numerical technique and obtained a Woehler master curve suitable for the evaluation of the fatigue strength of welded joints under mainly mode I loadings. One of the strengths of this procedure is the ability to represent welded joints in a three-dimensional form without necessarily performing exemplifications in the shape, weld tip radius and flank angle as proposed in [Tovo-Livieri 2001].

This paper, by means of the implicit gradient method, will examine the fatigue behaviour of welded aluminium joints taken from the literature (mainly cruciform joints, T-joints and bead removed specimens). The procedure used for steel welded structures was utilised also for aluminium alloy. In this case, a different characteristic length relating to the material proprieties was proposed and the fatigue scatter band for aluminium alloy was presented.

Nomenclature

σ_{eff}	effective stress
σ_{eq}	equivalent stress
σ_n	nominal stress
$\sigma_{eff,max}$	maximum effective stress
Δ	range
∇^2	Laplace operator
2α	opening angle
c	characteristic length
FE	finite element
R	nominal load ratio
t	thickness
N	fatigue life, cycles to failure
V	volume
K_1^N	mode I Notch Stress Intensity Factor (NSIF)

2. Basic equation

The effective stress, $\sigma_{eff,}$ relates to the local stress fields generated by a stress raiser such as a sharp V-notch and can be analytically obtained by using the implicit gradient method by means of Eq. (1):

$$\Delta\sigma_{eff,max} = \frac{m_v}{c^{1-\lambda_1}} \Delta K_1^N \tag{1}$$

where m_v is a non-dimensional parameter that depends only on the opening angle and λ_1 is Williams' eigenvalue of mode I (for 2α=0 and 135°, λ_1 assumes values of 0.5 and 0.674, respectively). For a generic opening angle, the mode I Notch Stress Intensity Factor (NSIF) K_1^N can be obtained from an asymptotic FE analysis [Lazzarin and Tovo (1998)].

If the NSIF is not known, the effective stress σ_{eff} can be calculated numerically, point by point, by solving the Helmholz differential equation in volume V of the component by imposing Neumann as the boundary conditions [Peerlings et al. (1996) and (2001)]:

$$\sigma_{eff} - c^2 \nabla^2 \sigma_{eff} = \sigma_{eq} \quad \text{in} \quad V \tag{2}$$

In Eq.(2) it is implicitly assumed that fatigue damage is due to the average, evaluated on the whole component, of a physical quantity called equivalent stress σ_{eq}, which is considered to be directly linked to fatigue damage [see Pijaudier-Cabot and Bažant (1987), Tovo and Livieri (2007-8)].

The characteristic length *c* is an intrinsic parameter assumed to be related to the material and to have the physical dimensions of a length, ∇^2 is the Laplace operator. In this work, σ_{eq} coincides with the first principal stress evaluated with finite elements for linear elastic material. A non-linear behaviour could be introduced without particular problems (see Tovo et al. (2008 b), Livieri et al. (2016)) as well as a multiaxial fatigue criterion [Cristofori et al. 2009 and Capetta et al. 2011].

Eq. (2) can be solved by means of FE analysis by using the mesh utilised for the calculation of the Cauchy stress tensor under linear elastic hypothesis of the material. Furthermore, an elasto-plastic material can be considered, as proposed in Livieri et al. 2016.

For arc welded joints made of steel, in previous works [Tovo-Livieri 2007 and 2008] the fatigue scatter band was evaluated between 10^4 and $5{\cdot}10^6$ cycles to failure in terms of maximum effective stress variation $\Delta\sigma_{eff,\,max}$. The inverse slope is about 3 and the T_σ ratio between the scatter bands related to the mean values plus/minus 2 standard deviations is 1.85. The scatter band is independent of the geometry of the joints and can be used to estimate the safety factor of welded joints or to estimate fatigue life in terms of nominal stress [Livieri-Tovo 2017].

3. Fatigue analysis of aluminium welded joints

This paper analyses the fatigue behaviour of welded joints made of aluminium alloy. Table 1 shows the characteristics of a series previously analysed in terms of strain energy density and qualified by an opening angle of 135°, as represented in Figure 1 for different types of welded joints or butt weld joints after bead removal [Livieri-Lazzarin 2005].

Table 2 reports the new series of aluminium alloy welded joints which is analysed in this paper. The opening angle is reported in the table as well as the three-dimensional model used for making the mesh in the FE analysis.

The evaluation of the characteristic length *c* is of fundamental importance for the fatigue life assessments. The *c* value can be evaluated in different ways but due to fatigue scatter, a difference can be observed from various algorithms. If we take into account all welded joints in tables 1 and 2, for a given value of *c*, a scatter index can be evaluated such as the sum of the quadratic difference between the average value estimated with a statistical analysis and the experimental ones. The analytical model for predicting fatigue life should be the classic linear model in a double logarithm scale (Woehler curve). Thus, the scatter index Π can be defined as

$$\Pi = \sum(x - \bar{x})^2 \tag{3}$$

where x is the predicted logarithm of cycle to fatigue obtained by means of a linear regression in a double logarithm scale of cycle to fatigue *N* against the range of the maximum effective stress $\Delta\sigma_{eff,max}$. $\bar{x}$ is the logarithm of the experimental value of cycle *N*. For the welded joints in table 1, Eq. (1) was used, while for the joints in table 2 a three-dimensional numerical solution was considered. However, the $\Delta\sigma_{eff,max}$, can always be written in the former case indicated by Eq. (1) as a function of the nominal stress so that the scatter index Π can be expressed numerically as a function of *c* (see Tovo-Livieri 2007).

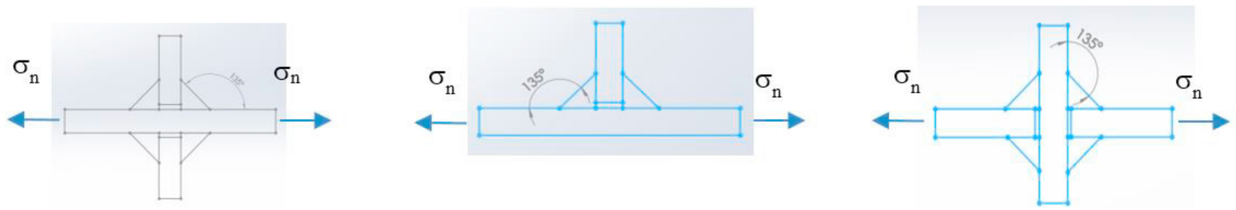


Fig. 1. Welded joints in table 1 under remote uniform stress σ_n.

Figure 2 reports the scatter index Π versus the *c* parameter evaluated for all experimental data. In the figure, the minimum value of the scatter index is close to 0.15 mm. Such a value is considered as the characteristic length of the welded joints made of aluminium alloy. A value of *c* equal to 0.2 was calculated for the steel joints. After establishing the *c* parameter, the numerical procedure for evaluating the effective stress σ_{eff} for aluminium alloy follows the same procedure used for steel welded joints provided that a different value of *c* is used to solve Eq. (2).

Figure 3 shows the scatter band of aluminium welded joints in terms of the range of maximum effective stress. The slope is 3.7 and the scatter index T_σ related to two different probabilities of survival P_S (defined simply as $T_\sigma = \Delta\sigma_{eff,\max,\ Ps=2.3\%} / \Delta\sigma_{eff,\max,\ Ps=97.7\%}$) is practically the same for steel and aluminium welded joints (1.97 versus 1.96). The experimental data in tables 1 and 2 fall inside the scatter band with good accuracy.

Table 3 summarises the numerical value of the two scatter bands for welded joints made of steel or aluminium alloy.

Finally, Figure 4 shows a comparison between the two scatter bands of all experimental data analysed in this paper.

Table 1. Geometrical and fatigue strength properties of aluminium welded joints (Nominal load ratio R≈0.1)

Refs	Geometry	$\Delta\sigma_{n,50\%}$ [MPa]	$\Delta K^{N}_{1,\ 50\%}$ MPa mm$^{0.326}$
Maddox, 1995	C-NLC	59.3	103.2
Maddox, 1995	C-NLC	45.3	97.8
Maddox, 1995	C-NLC	40.5	108.6
Maddox, 1995	C-NLC	29.1	97.7
Maddox, 1995	C-NLC	40.9	105.0
Maddox, 1995	C-NLC	38.0	94.1
Meneghetti, 1998	T-NLC	43.1	89.7
Ribeiro, 1995	T-NLC	53.0	110.3
Ribeiro 1995	C-LC	28.0	108.8
Jacoby, 1961	C-LC	26.3	122.5
Ohno, 1985	Bead removed	86	-
Person, 1971	Bead removed	92-107	-

Key: Type of joint: C-NLC = cruciform joint with non-load carrying fillet weld; C-LC = cruciform joint with load-carrying fillet weld; T-NLC =T-joint with non-load carrying fillet weld; SL = single lap joint;

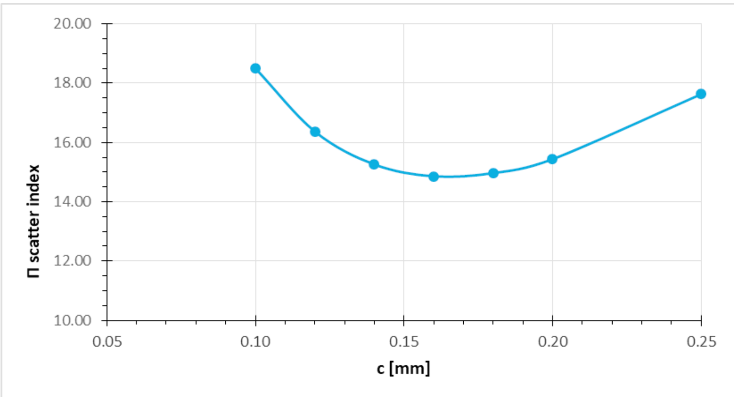


Fig. 2. Scatter index as a function of the *c* characteristic length

4. Conclusions

The main conclusions of this paper can be summarised as follows:

Table 2. Geometrical properties of aluminium welded joints (Nominal load ratio R≈0.1)

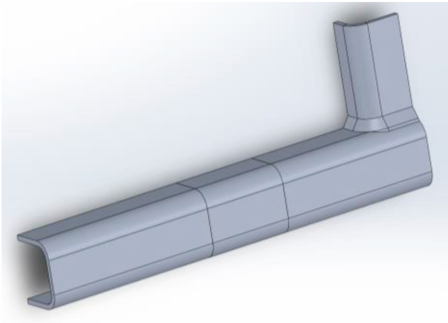
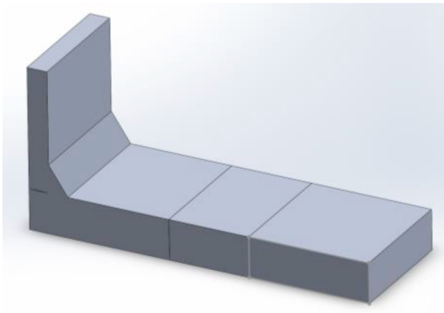
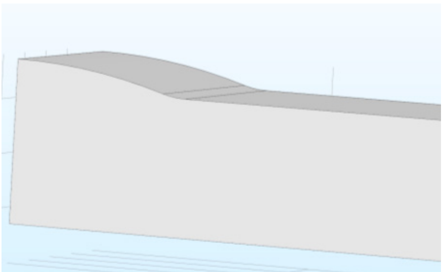
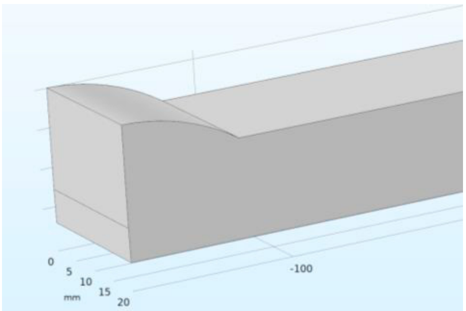
Refs	3D model	Type of joint, type of loading and opening angle	Thickness of main plate [mm]
Macdonald-Haagensen 1999-2009		Hollow section T-joint Axial loading, chord four-point bending chord In-plane bending branch 125° and 135°	3
Sidhom et al. 2005		T-joint four-point bending 124°	10
Brandt et al. 2001		Butt weldment Axial loading 148°	25
Brandt et al. 2001		Butt weldment with incomplete penetration Axial loading 0°	25

Table 3. Reference value of the effective stress of the two fatigue scatter bands at $5 \cdot 10^6$ cycles to failure

Weld type	97.70% [MPa]	50% [MPa]	2.30% [MPa]	k
steel	111	156	219	3.0
aluminium	54.5	76.6	106	3.7

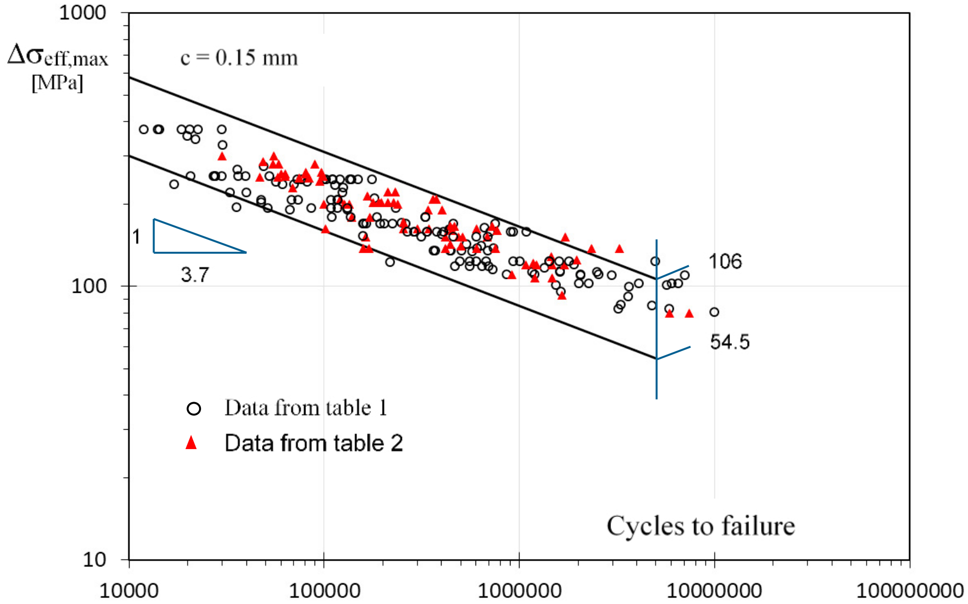


Fig. 3. Scatter band for aluminium welded joints in terms of maximum effective stress range (scatter bands related to mean values plus/minus 2 standard deviations)

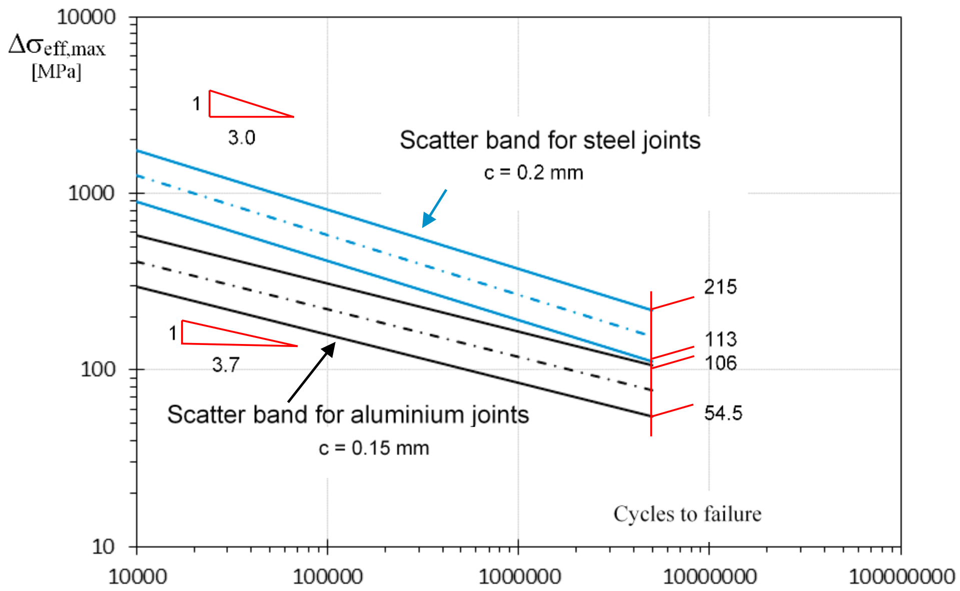


Fig. 4. Scatter bands for steel and aluminium welded joints in terms of maximum effective stress range (scatter bands related to mean values plus/minus 2 standard deviations)

- A scatter band was obtained in terms of the effective stress range by analysing aluminium welded joints with the main plate thickness ranging from 3 to 25 mm.
- The scatter band allows the designer to predict the fatigue life of aluminium welded joints without changing the procedure with respect to the algorithm proposed for welded joints made of steel. The characteristic length for aluminium alloy reduces to 0.15 mm (0.2 mm for steel joints).
- In the case of welded T-joints subjected to bending or tensile loading, the actual critical point was well predicted by the proposed approach.

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