HIGH CYCLE FATIGUE BEHAVIOUR OF WELDED JOINTS BASED ON NOTCH STRESS INTENSITY FACTORS

B. Atzori[1], P. Lazzarin[2], R. Tovo[3]
[1]Department of Mechanical Engineering, University of Padova, Padova, Italy
[2]Department of Management and Engineering, University of Padova, Vicenza, Italy
[3]Department of Engineering, University of Ferrara, Ferrara, Italy

ABSTRACT

The present paper summarises the application of NSIF approach to stress analysis and high cycle fatigue assessment of welded joints. This approach is based on linear elastic stress analysis of the open sharp corner defined at the weld toe; in that corner the NSIFs evaluate the intensity of the stress singularity similarly to the evaluation of the stress field ahead of the tip of the cracks by means of SIFs.

When the opening angle at the weld toe, as usual in fillet weldments, is equal to 135°, the high cycle fatigue strength of welded joints has been demonstrated to be strongly related to the range of mode I NSIF, if the fatigue loading is mainly perpendicular to the weld bead.

The paper summarises also the most efficient methods for NSIF evaluation and the main topics under investigation concerning fatigue strength assessments of geometrically complex welded joints under uniaxial and multi-axial loads.

1 INTRODUCTION

Among the local approaches, Notch stress Intensity Factors (N-SIFs) have been recently demonstrated to be useful parameters to predict the fatigue behaviour of welded joints, at least when the problem is two-dimensional. Having modelled the weld toe region as a sharp (zero radius) V-shaped notch, two notch stress intensity factors, denoted K_1^N and K_2^N, are necessary to quantify, respectively, the intensity of the linear elastic symmetric and skew symmetric stress components present in the close neighbourhood of the weld toe. Due to weld geometry, such stress components are always present at the weld toe, even under remote uniaxial load, and vary from case to case according to the global geometry of the joint. If also loads not perpendicular to the weldment are considered, the weld toe is loaded by an anti-symmetric stress component that can be evaluated by a third N-SIF, K_3^N, analogous to the mode III (shear) SIF of LEFM. Hence the N-SIF approach is suitable for evaluating the entire stress distribution ahead of any sharp V-notch.

The basic idea in using N-SIFs for fatigue strength evaluation was that of overcoming some difficulties inherent in the fatigue life concept based on fracture mechanics. Since a large amount of the crack initiation time up to a crack size relevant for the engineer, is spent as microcrack propagation, a model based on the integration of any linear elastic da/dN - ΔK or ΔK_{eff} relationship appears unsuitable to predict the short crack propagation life. On the other hand, for engineering applications it is undoubtedly too complex taking into account the behaviour of a short crack and the multiple crack interaction on different planes influenced by loading parameters and statistical variations related to the irregularity of the toe profile.

Initially thought of as parameters suitable for predicting only the fatigue crack initiation phase (Boukharuba [1], Verreman [2]) NSIFs were demonstrated able to predict also the total life fatigue in a number of cases of practical interest (Lazzarin [3], Atzori [4], Lazzarin [5]). This happens simply because a severe notch with a very small toe radius results in a short microstructural initiation life, even without toe “defects”, and in an immediate microcrack propagation. This explains why the influence of the microstructure is weak. Furthermore, most of the life is consumed at short crack depth, within the singularity; and that explains why good correlation is obtained with total fatigue life [5]. In this framework, this contribution aims to summarise the theoretical background and the most significant application of NSIFs to fatigue assessments of welded joints.

2 THEORETICAL FRAMEWORK AND DEFINITIONS OF NSIF

Williams [6] stated that, even in a re-entrant corner, like it happens in the crack case, the Mode I stress field is always singular close to the notch tip. Mode II stress field is also singular but only if the opening angle is less than 102 degrees. Then, in a polar coordinate system (r, ϑ) (see Fig. 1), the stress field is defined within two parameters, a_1 and a_2, and can always be written as the sum of the symmetric field, with the stress singularity of $1/r^{1-\lambda_1}$ type, and the anti-symmetric field, with the stress singularity of $1/r^{1-\lambda_2}$ type:

$$\begin{Bmatrix} \sigma_\vartheta \\ \sigma_r \\ \tau_{r\vartheta} \end{Bmatrix} = \lambda_1 r^{\lambda_1 - 1} a_1 \begin{Bmatrix} f_{1,\vartheta}(\vartheta) \\ f_{1,r}(\vartheta) \\ f_{1,r\vartheta}(\vartheta) \end{Bmatrix} + \lambda_2 r^{\lambda_2 - 1} a_2 \begin{Bmatrix} f_{2,\vartheta}(\vartheta) \\ f_{2,r}(\vartheta) \\ f_{2,r\vartheta}(\vartheta) \end{Bmatrix}. \tag{1}$$

In Eq.(1) λ_1 and λ_2 are the first eigenvalues for Mode I and Mode II, respectively, in Williams' equations [6]. Mode I is always singular, but mode II can be non-singular when λ_2 is greater than 1.0. In order to quantify the values a_1 and a_2, Gross and Mendelson [7] proposed extending the definition of the Stress Intensity Factors, commonly used to describe crack stress fields in Linear Elastic Fracture Mechanics (LEFM), to V-notches. Along the direction with $\vartheta = 0$, the symmetric and the anti-symmetric components are uncoupled: shear stress component $\tau_{r\vartheta}$ depends only on the anti-symmetric loading condition, while σ_r and σ_ϑ are related just to the symmetric one. The expressions for N-SIFs are then:

$$K_1^N = \sqrt{2\pi} \lim_{r \to 0} \left(\sigma_\vartheta\right)_{\vartheta=0} r^{1-\lambda_1}\,; \qquad K_2^N = \sqrt{2\pi} \lim_{r \to 0} \left(\tau_{r\vartheta}\right)_{\vartheta=0} r^{1-\lambda_2}\,. \tag{2}$$

where the constant value $\sqrt{2\pi}$ allows us to have, when $2\alpha = 0$, K_1^N and K_2^N equal to the conventional stress intensity factors K_I and K_{II} of the LEFM.

By introducing definitions (2) into Eq. (1), it is therefore possible to present Williams' formulae for stress components as explicit functions of the N-SIFs. The stress distribution is [3]:

$$\begin{Bmatrix} \sigma_\vartheta \\ \sigma_r \\ \tau_{r\vartheta} \end{Bmatrix} = \frac{1}{\sqrt{2\pi}} \frac{r^{\lambda_1 - 1} K_1^N}{(1+\lambda_1) + \chi_1(1-\lambda_1)} \left\{ \begin{bmatrix} (1+\lambda_1)\cos(1-\lambda_1)\vartheta \\ (3-\lambda_1)\cos(1-\lambda_1)\vartheta \\ (1-\lambda_1)\sin(1-\lambda_1)\vartheta \end{bmatrix} + \chi_1(1-\lambda_1) \begin{bmatrix} \cos(1+\lambda_1)\vartheta \\ -\cos(1+\lambda_1)\vartheta \\ \sin(1+\lambda_1)\vartheta \end{bmatrix} \right\}. \tag{3}$$

For Mode II fracture, the stress distribution becomes [3]:

$$\begin{Bmatrix} \sigma_\vartheta \\ \sigma_r \\ \tau_{r\vartheta} \end{Bmatrix} = \frac{1}{\sqrt{2\pi}} \frac{r^{\lambda_2 - 1} K_2^N}{(1-\lambda_2) + \chi_2(1+\lambda_1)} \left\{ \begin{bmatrix} -(1+\lambda_1)\sin(1-\lambda_1)\vartheta \\ -(3-\lambda_1)\sin(1-\lambda_1)\vartheta \\ -(1-\lambda_1)\cos(1-\lambda_1)\vartheta \end{bmatrix} + \chi_2(1+\lambda_2) \begin{bmatrix} -\sin(1+\lambda_2)\vartheta \\ \sin(1+\lambda_2)\vartheta \\ \cos(1+\lambda_2)\vartheta \end{bmatrix} \right\}. \tag{4}$$

Concerning the mode III stress distribution, N-SIF definition is almost coincident and it deals with the shear stress component involving the "z" direction of the cylindrical coordinate system already shown in fig. 1. The definition of the third N-SIF is then [8]:

$$K_3^N = \sqrt{2\pi} \lim_{r \to 0} \left(\tau_{\vartheta z}\right)_{\vartheta=0} r^{1-\lambda}\,. \tag{5}$$

and related stress components are given by a quite easy formulation:

$$\begin{Bmatrix} \tau_{\vartheta z} \\ \tau_{rz} \end{Bmatrix} = \frac{K_3^N}{\sqrt{2\pi}} r^{\lambda_3 - 1} \begin{Bmatrix} \cos(\lambda_3 \vartheta) \\ \sin(\lambda_3 \vartheta) \end{Bmatrix}. \tag{6}$$

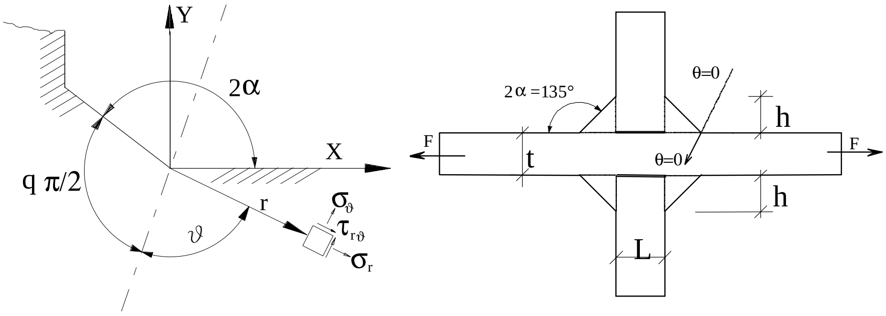

Fig. 1: Coordinate system and geometrical parameters for the analyses of the cruciform welded.

3 NSIF EVALUATION IN SIMPLE GEOMETRIES

A first method for NSIFs evaluation is by means of their definition given in eqs. (2) and (5). Unfortunately this approach requires the analytical knowledge of stress field or an accurate and very refined numerical investigation of local effects, usually by a finite elements method. In practical application such required accuracy is too time consuming for the designer but other approaches are possible too. For welded joints, the N-SIF values can be computed as:

$$K_i^N = k_i \sigma_0 t^{1-\lambda_i} \,. \qquad (7)$$

where σ_0 is the reference stress (e.g., the remote or the nominal tensile or bending stress); $t^{1-\lambda}$ quantifies the size effect and k_i is a non-dimensional parameter that depends on the overall geometry and type of remotely applied load and can be plotted or tabulated in the same way as stress concentration factors. As an example in Ref. [3] these non-dimensional parameters were numerically evaluated for cruciform joint under tensile loading and an example is shown in fig. 2.

Similarly it is possible to state k_i values in a cylindrical bar welded to a flange. In this case tensile and bending loading cause a K_1^N and K_2^N distribution along the weld toe, the torsion load gives a Mode III contribution.

The size effect can be properly taken into account by referring to one of the most significant dimension: the bar diameter or the weld size. For instance, by referring to the bar diameter, the NSIFs can be evaluated as a function of tensile stress for traction and bending loads and of nominal shear stress for torsion loads:

$$K_1^N = k_1\, \sigma_o\, D^{1-\lambda_1}\,; \qquad K_2^N = k_2\, \sigma_o\, D^{1-\lambda_2}\,; \qquad K_3^N = k_3\, \tau_o\, D^{1-\lambda_3}\,. \qquad (8)$$

The shape factors are plotted in fig. 3 as a function of the main geometrical parameters.

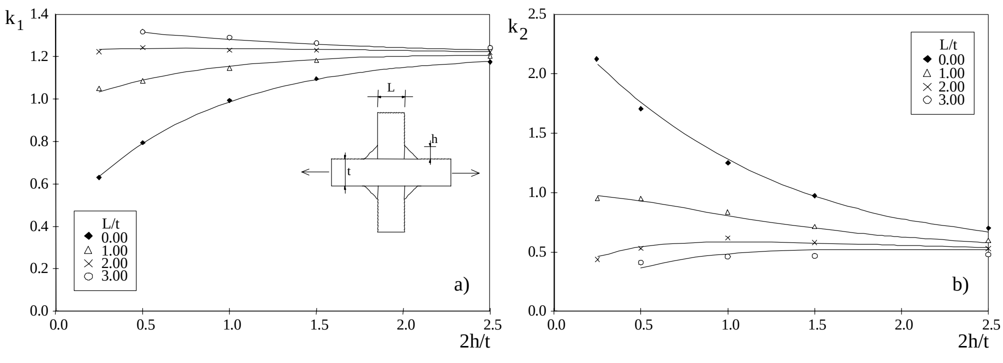

Figure 2. Plots of k_1 and k_2 for non-load carrying fillet welded joints [3].

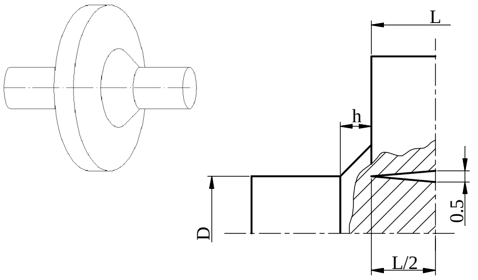

Figure 3a. Fillet welded bar geometry

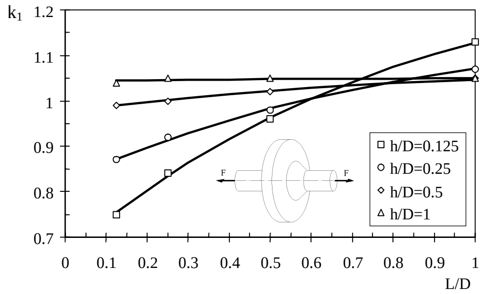

Figure 3b. k_1 under traction load

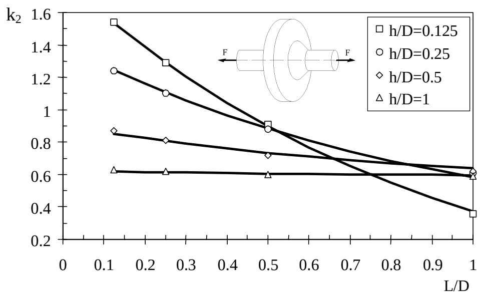

Figure 3c. k_2 under traction load

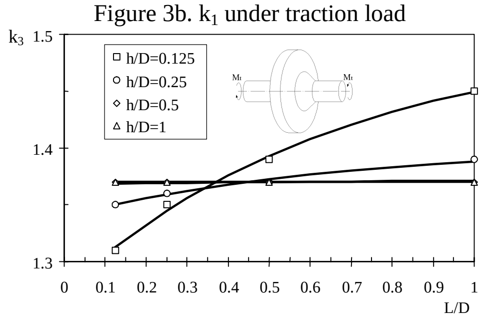

Figure 3d. k_3 under torsion load

4 NSIF-BASED PREDICTION OF FATIGUE LIFE

The research carried out till now has first of all focused on fatigue loading perpendicular to weldment where mode III is zero and the stress field is dominated by mode I being mode II non singular. Collected fatigue strength data from steel and aluminium cruciform welded joints are shown Figure 4. The V-notch angle at weld toes was about 135 degrees, while the main plate thickness ranged from 6 to 100 mm in steel welded joints, from 3 to 24 mm in the aluminium ones. The variation of the transverse stiffeners was even more pronounced (from 3 to 220 mm). Despite the large variability of geometry and materials, two scatter bands of limited width (both given in terms of Mode I N-SIF and related to mean values ± 2 standard deviations) are capable of summarising all experimental data.

5 NSIF ESTIMATION IN COMPLEX GEOMETRIES

As far as complex welded geometries are concerned, it is not possible to perform a very accurate investigation of the local stress and the shape factor can not be defined when the nominal stress is difficult to define or the geometry is complex. In these cases it is easier to evaluate the structural stress by means of shell-based FEM model. Hence the procedure is shown by fig. 5 and

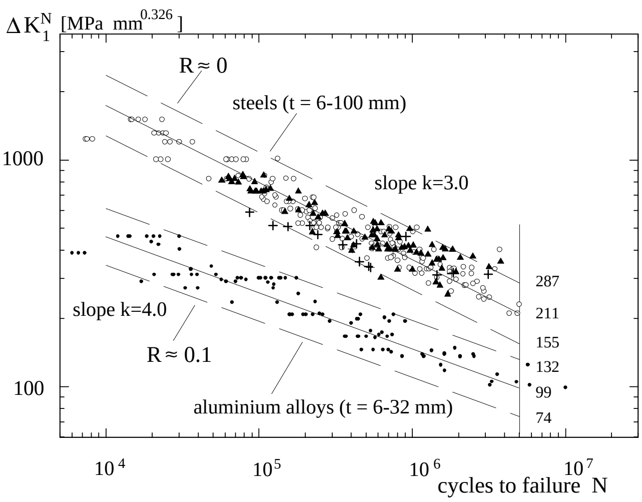

Figure 4. Fatigue strength of cruciform welded joints as a function of the mode I NSIF [5].

the result of a shell model is the membrane and bending stress properly combined give the upper and the lower tensile stress on the main plate together with its variation along direction “x”.

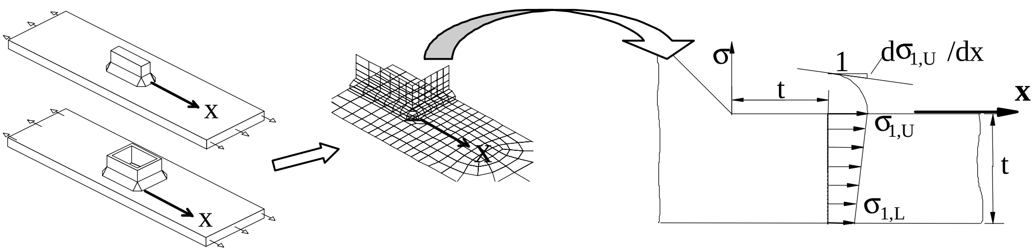

Fig. 5: FE numerical investigation of structural stress in a welded joint

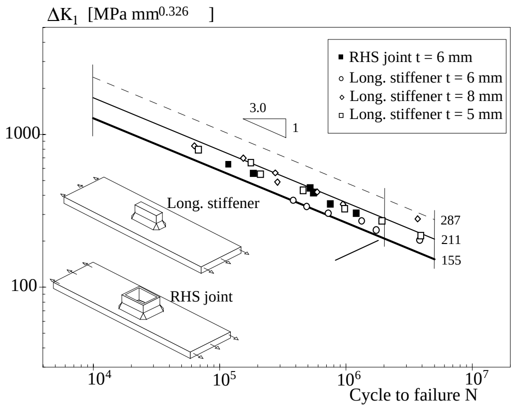

Figure 6: Fatigue life assessments based on local stresses estimated by FE thin-shell analyses [10].

Weld geometry “j”	$D_{1,j,1}$ / $D_{2,j,1}$	$D_{1,j,2}$ / $D_{2,j,2}$	$D_{1,j,3}$ / $D_{2,j,3}$
Single – Fillet	0.815	-0.385	8.996
“SF”	1.857	2.036	-8.986
Single – Penetration	0.973	-0.059	7.455
“SP”	0.915	0.308	-1.335
Double – Fillet	1.116	0.213	6.190
“DF”	0.535	-0.269	1.148
Double – Penetration	1.026	0.132	6.151
“DP”	0.783	-0.059	1.313

Table 1: Coefficients in Eq. (9), when the weld size is close to the main plate thickness.

In the “Hot Spot” procedures the fatigue strength is directly related to structural stress; in NSIF approach the structural stress can be used for the NSIF estimation according to the expression [9]:

$$K_1^N = \left(D_1\, \sigma_{1,U} + D_2\, \sigma_{1,L} + D_3\, \frac{t}{6} \frac{d\,\sigma_{1,U}}{dx} \right) t^{0.326} . \tag{9}$$

Coefficients “D” are generally dependent on weld size and type. When the weld size is equal to the main plate thickness the coefficient are related to the type of weldment (fillet or penetrating) and on the number of weldments on the two sides of the main plate. An example of the results achievable by this simplified procedure is given in fig. 6 where the design scatter band of fig. 4 is compared to the experimental data from longitudinal stiffeners and RHS joints as a function of NSIF range. It is possible to very that the Same NSIF strength curve holds true independently on welded geometry and that the simplified procedure for NSIFs estimation seems to work efficiently.

6 OPEN PROBLEMS AND PLANNED INVESTIGATIONS

The results obtained till now are very promising so that a large amount of research has been set out in order to extend the applicability of the approach to a number of engineering cases. In particular the two most interesting issues are the applicability of the approach to whole fillet weld geometries independently from the weld flank angle and the extension of the approach to multiaxial load conditions.

The NSIFs are endowed by an odd dimensionality, which depends on the V-notch angle. In order to summarise fatigue strength data from welded joints having different weld flank angles (from 110 to 150 degrees), Lazzarin [11] used the mean value of the strain energy in a finite size volume surrounding the weld toes (Figure 7). The critical radius R_C of the elementary volume (simply modelled like a semicircular sector) depends on the welded materials and was found about equal to 0.3 mm for the most common structural (ferritic) steels. The local-energy approach was later applied to T butt welds between tube and flange subjected to combined in–phase bending and torsion (Lazzarin [12]).

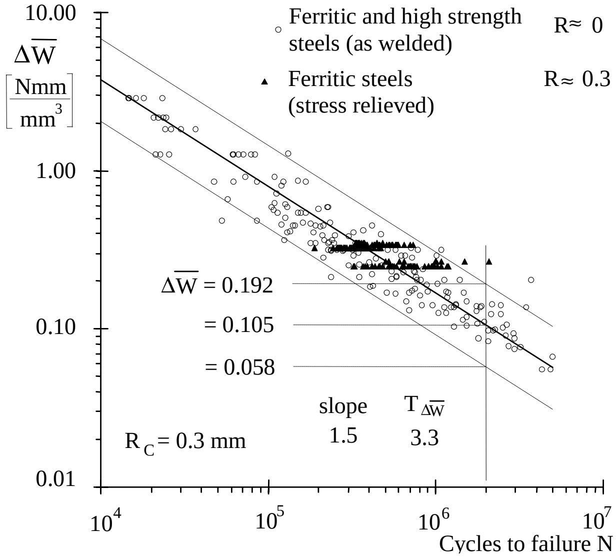

Figure 7: Energy-based scatter band summarising more than 300 data of steel welded joints (Lazzarin [11]).

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