Fatigue Strength of Welded Lap Joints

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ABSTRACT. *The most advanced structural frames of cars and motorcycles are made of aluminium alloys welded box beams. A recent technological solution for the beams consists of press-formed metal sheets joined by welded lap-joints. Because the frames undergo relevant fatigue loads, the evaluation of fatigue endurance of this kind of connections plays a crucial role during the development of frame. The present research deals with the evaluation of fatigue behaviour of welded lap joints, subjected to tensile and bending loads. Fractographic evidences and numerical analyses showed that fatigue strength is controlled by the presence of defects ad inhomogeneities at the tip of the weld root. In particular these defects, which appear to lie onto the maximum* K_{qq} *path, increase SIF at weld singularity. Such an analysis, together with the statistical description of defects population, allowed to develop a methodology able to predict the fatigue strength of lap-joints. A simple method for SIF based on FEM analyses and structural stresses at the lap-joint is then presented.*

INTRODUCTION

The structural frames of cars and motorcycles are usually made of welded box beams obtained from thin metal sheets. Since the frames are subjected to fatigue loads the evaluation of fatigue strength of welded connections plays a crucial role in the design of the vehicle frame. Traditional technological solutions for obtaining long weld lines are in general based on spot welds, whose fatigue strength can be assessed by FEM structural analyses and by local models which, from the structural loads acting on the spots, analyse fatigue strength with LEFM or 'local strain' approaches [1-2].

A solution which has been increasingly applied in advanced motorbike frames (see Fig. 1) is the application of welded lap joints for box girders made of Al alloy press-formed metal sheets. In this type of welds the joints are mainly subjected to longitudinal, normal and shear stresses due to axial and bending loads and perpendicular stresses due to local bending moments. In terms of longitudinal stresses the lap-joints are not very different from fillet welds and therefore their strength can be assessed in terms of efficiency or local stress methods [1-2]. Stresses perpendicular to weld bead are extremely dangerous for the lap-joints because of the geometrical singularity due to sheet overlap. Several SIF solutions have been published for some simple lap-joint geometries [3-5] and a number of papers have shown the applicability of Linear Elastic Fracture Mechanics for life prediction in failures at the weld root and ideal weld geometries. However, fatigue strength is greatly affected by the presence of inhomogeneities caused by the welding process.

In this paper we address the fatigue strength of lap joints made of an Al alloy subjected to axial and bending loads. Fractographic evidences and numerical investigations have been carried out in order to analyse the effect of defects and inhomogeneities at the weld singular point. This analysis allowed to develop a LEFM methodology able to predict the fatigue strength of lap-joints. A simple application of the method on the basis of structural stress components at the lap-joint is then presented.

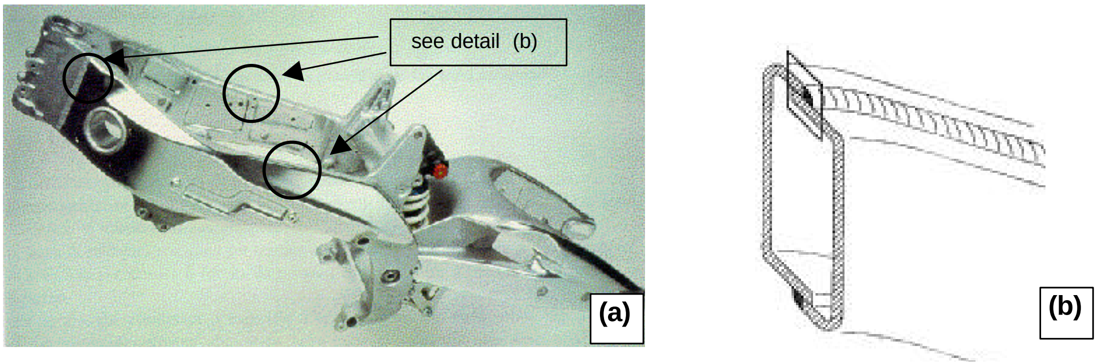

Figure 1. Application of lap joints: a) an advanced motorbike frame; b) a detail of beams obtained by press-formed sheets joined by lap-joints.

EXPERIMENTS

Materials

The lap-joints under investigation were made of AlMg4MnCr sheets (thickness 2.5 mm) joined with a pulsed arc MIG welding: overlap of the metal sheets was 14 mm and the weld bead has a width of 7 mm. Welded sheets were eventually stress relieved.

Base metal tensile properties were: ultimate tensile strength 290 MPa, yield stress 145 MPa. Tensile properties of the welded joint, evaluated with specimens cut along the weld, were: ultimate tensile strength 210 MPa, yield strength 140 MPa.

Base metal was subjected to a series of crack propagation tests for determining fatigue crack growth rate at R=0.1, 0.4 and 0.7 [6]: ΔK_{th} at R=0.1 resulted to be 70 MPa$\sqrt{mm}$.

Fatigue Tests

Specimens were subjected to fatigue tests at R=0.1 under different loading conditions (dimensions of the specimens are shown in Fig.2), namely longitudinal tension σ_{II}, shear $\tau_{//}$ and a nominal tension perpendicular to weld $\sigma_{\perp}$, the two latter being referred to nominal weld leg section (Fig.3). Fatigue strength ratios ($\varphi=\Delta\sigma_{lim}/UTS$) were: $\varphi_{//}= 0.38$, $\varphi_{\tau}=0.32$; $\varphi_{\perp}=0.14$. These values, which for longitudinal stresses are in accordance with typical ‘fatigue efficiencies’ of fillet welds [1], show a very low strength of lap-joints against stresses perpendicular to the joint. It was so decided to better investigate the reasons of this behaviour.

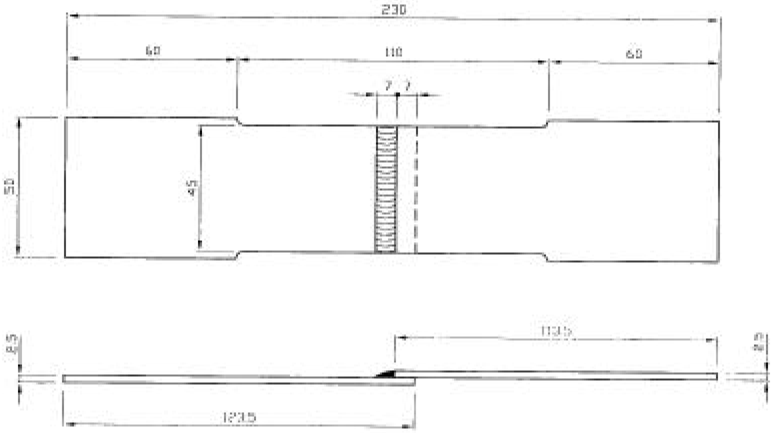

Figure 2. Dimensions of fatigue specimens.

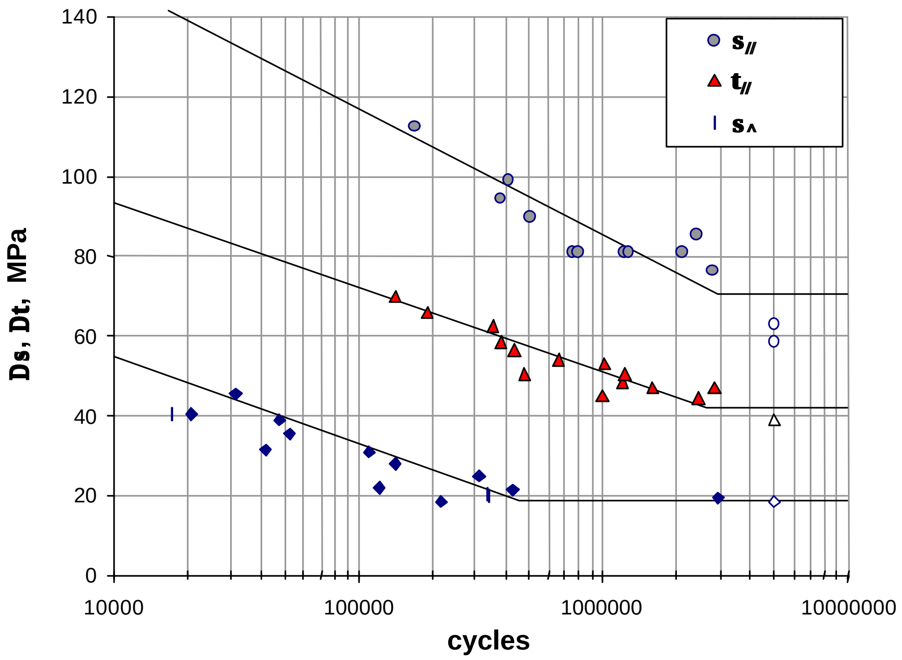

Figure 3. Fatigue test results

Fractographic Analysis

Fractographic evidences showed that fracture occurred on a plane with an angle of approx. 70° with specimen axis (Fig. 4.a). This evidence is in accordance with previous studies describing the presence of a mixed I + II singularity at the overlap tip [3-5].

However, the most interesting feature was the presence of shrinkage cavities and microdefects, that were thoroughly investigated under SEM, which appeared to be aligned along the edge of the weld (Fig. 4.b-c).

Dimensions of defects at weld root were collected and data were analysed with a Weibull distribution: parameters of the distribution were α= 390 μm and β= 3.36. Defect sizes corresponding to 2.5% and 97.5% cumulative probability resulted to be respectively to be 135 μm and 580 μm. By using the 'statistics of extremes' [7], considering an average of 14 defects per specimen, it was possible to estimate the '*characteristics size*' of the maximum defect in a specimen (the defect which is expected to be exceeded once every specimen) which resulted to be 520 μm.

Concerning the shape of defects along the weld edge, if they are assimilated to semi-elliptical flaws, in general their aspect ratio *a/2c* is for most of them below 0.2 (Fig.4.c) so a 2-D approximation for the lap-joint having a defect at its tip has been judged reasonable.

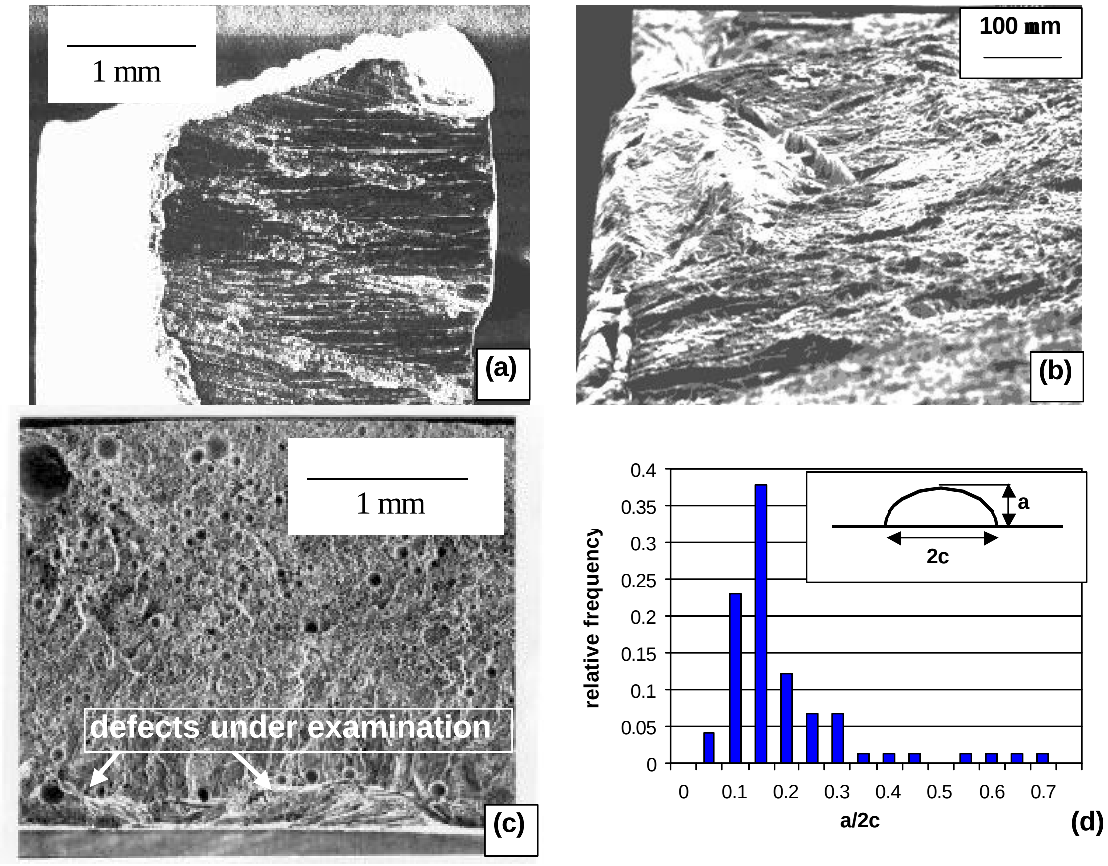

Figure 4. Fractographic evidences: a) propagation plane is inclined due to mixed mode singularity; b) defects are present at the weld root; c) alignment of defects along the weld edge; c) histogram of defect aspect ratio.

ANALYSIS OF LAP-JOINT FATIGUE STRENGTH

SIF analyses for lap-joints in the literature (see for instance Muuki [3], Pook [4], Murakami [5]) show that the lap joint is similar to a crack and it creates a mixed mode I + II singularity. However, since these SIF solutions are valid for geometries different from the one of tested specimens, it was so decided to carry out numerical investigations by using finite element analyses. In particular the analyses addressed the influence of defects at lap-joint tip.

SIF and Crack Path

Analysis of SIF for specimens tested under axial loading was carried out modelling the effective constraints during fatigue tests (Fig. 5.a). Specimen was modelled with plane strain 2D elements, the mesh was focused at the overlap tip adopting 'quarter point' elements with a size of 1 μm (Fig. 5.b). SIFs were derived from singular-field nodal displacements [8]:

$$K_I = \frac{2m}{\mathbf{k}+1}\cdot u_y\sqrt{\frac{2p}{r}}\ ; \quad K_{II} = \frac{2m}{\mathbf{k}+1}\cdot u_x\sqrt{\frac{2p}{r}} \qquad \text{(1 and 1')}$$

where u_x and u_y are crack face displacements and r is distance from the crack tip.

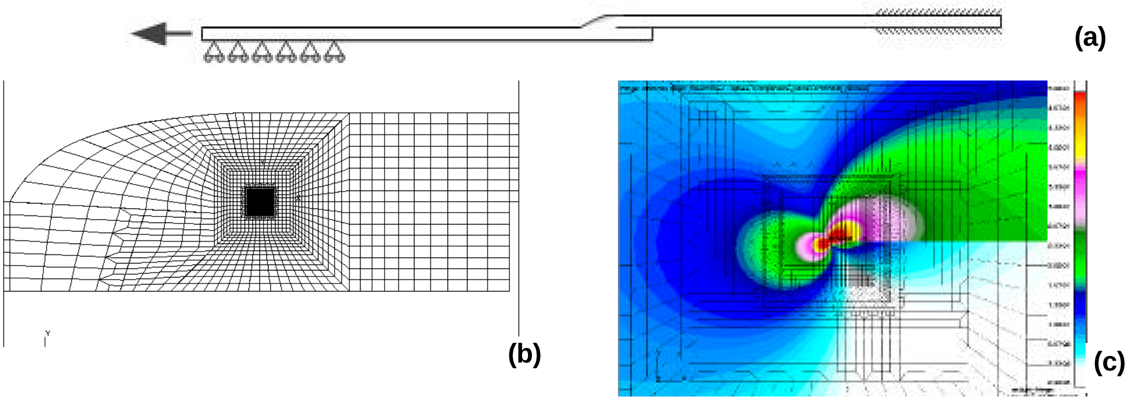

Figure 5. FEM analysis of fatigue specimens: a) load scheme; b) a detail of the mesh; c) Mises stress pattern for the lap-joint without defect.

The analysis was firstly carried out considering a lap-joint without defect (Fig. 5.b). Under the action of a given nominal axial stress, a mixed mode condition is present at weld singularity with a ratio $K_I/K_{II}=0.89$, which is evidence by Mises stress pattern in Fig. 5.c. Crack propagation plane determined by using *'maximum tensile stress'* criterion [8] resulted to be approximately θ=50°. It was then modelled a 50 μm propagation along this propagation angle and the new propagation direction was determined (Fig. 6.a). The procedure was iteratively repeated until a stabilisation of the crack path onto a plane with an angle θ=71° with specimen axis (Fig. 6.a) was found.

This fracture orientation, which is very close to experimental outcomes, corresponds to the direction of minimal distance to weld free surface [9]. Transverse polished sections of the lap joints revealed that shrinkage cavities and defects lie onto a similar path (Fig. 6.b): this is likely related to to weld bead shrinkage stresses.

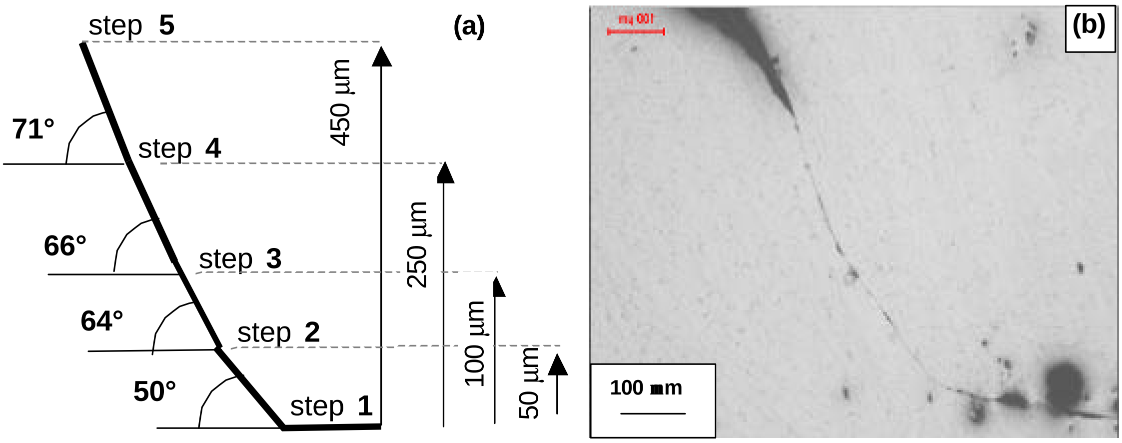

Figure 6. Crack path: a) FEM prediction; b) typical path of a defect at lap singularity.

SIF in Presence of Defects and Fatigue Strength

Previous FEM analyses allowed us to determine SIF at welded joints as a function of defect size – *a* – corresponding to 'maximum tensile stress' criterion. From the results it appeared that small defects at the tip of the singularity have a marked influence on SIF: e.g. a 135 μm defect cause an increment of 135% for $K_{\theta\theta}$.

Fatigue limit was then calculated as the cyclic stress at which $\Delta K_{\theta\theta}$ is equal to crack propagation threshold ΔK_{th}. The results show that taking into account the presence of defects at defect tip has enabled us to obtain a precise fatigue strength prediction. In particular fatigue data points that could appear as 'erratic data' in reality represent the lower bound of fatigue properties because of the presence of large defects.

SIF AND STRUCTURAL STRESS

Stress intensity factor solutions for lap-joints in the literature are valid only for simple load cases and it is in general difficult to transfer them to real structures. The same can be also said for trying to transfer fatigue strength data obtained for the 'nominal' $\sigma_{\perp}$.

If we analyse the internal actions onto the clamped specimens, it can be seen that, if the welded joint is assimilated to a small structural element connected to the two beam

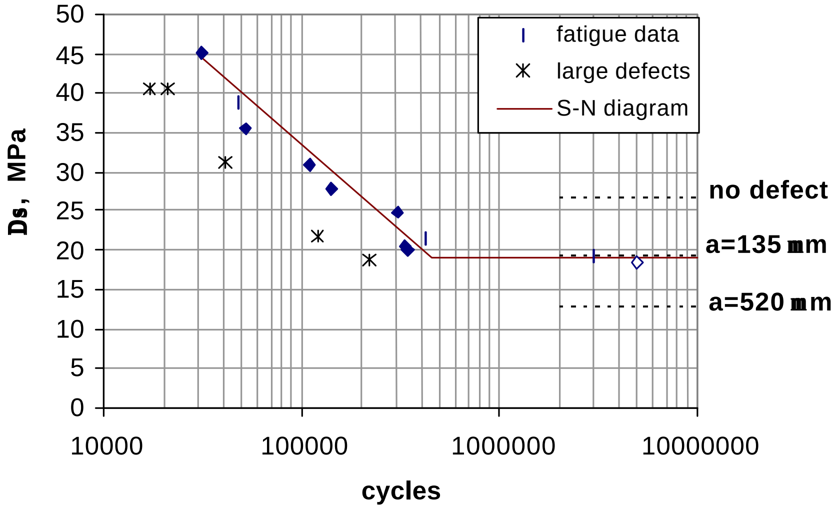

Figure 7. Prediction of fatigue strength for specimens under $\sigma_{\perp}$.

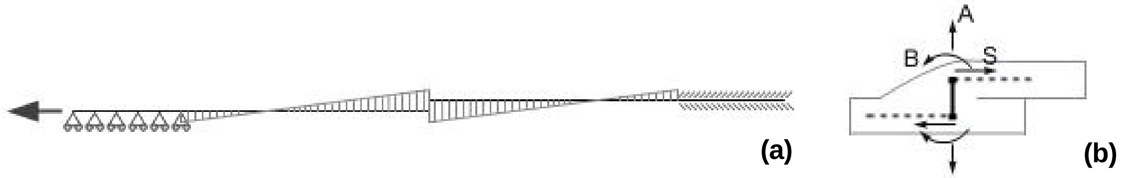

Figure 8. Structural model of the lap-joint: a) bending moments onto the clamped specimen; b) the lap-joint assimilated to a structural element.

representing the sheets joined by the lap-joint, it is essentially loaded by a bending moment B, a shear S and an axial load A (Fig. 8).

It could then be said that the SIFs in mode I and mode II in any load condition are a superposition of the effect of single loads, in particular:

$$K_I = K_{I,b} \cdot B + K_{I,s} \cdot S + K_{I,a} \cdot A \qquad (2)$$

$$K_{II} = K_{II,b} \cdot B + K_{II,s} \cdot S + K_{II,a} \cdot A \qquad (2')$$

In order to determine the contribution factors due to single loads, K_I and K_{II} were calculated by the 2D mesh of the specimens in 3 simple load cases (Fig.9). The loads onto the 'lap-joint' element were calculated by simple beam calculations and plugged into two linear systems:

$$\begin{cases} K_{I,1} = K_{I,b} \cdot B_1 + K_{I,s} \cdot S_1 + K_{I,a} \cdot A_1 \\ K_{I,2} = K_{I,b} \cdot B_2 + K_{I,s} \cdot S_2 + K_{I,a} \cdot A_2 \\ K_{I,3} = K_{I,b} \cdot B_3 + K_{I,s} \cdot S_3 + K_{I,a} \cdot A_3 \end{cases} \quad \begin{cases} K_{II,1} = K_{II,b} \cdot B_1 + K_{II,s} \cdot S_1 + K_{II,a} \cdot A_1 \\ K_{II,2} = K_{II,b} \cdot B_2 + K_{II,s} \cdot S_2 + K_{II,a} \cdot A_2 \\ K_{II,3} = K_{II,b} \cdot B_3 + K_{II,s} \cdot S_3 + K_{II,a} \cdot A_3 \end{cases} \text{(3 and 3')}$$

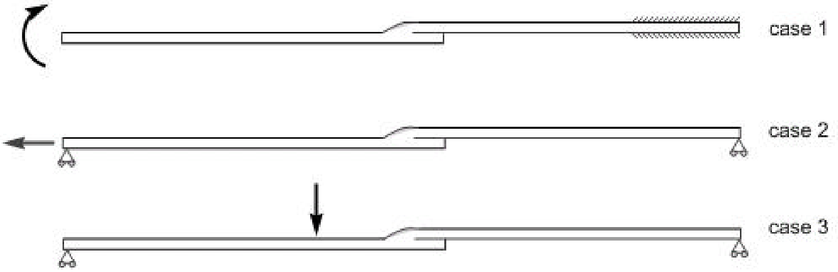

Figure 9. Load cases analysed for determining coefficients of Eq. (2) and (2').

The analysis resulted in a SIF calculation for the clamped specimen with a 6% precision (see Tab. I). Moreover the analysis showed that the effect of axial load into the 'lap-joint' element is neglibible. The point to be remarked is that calculation of SIF by eq. (2-2') allows the user to calculate fatigue strength also in a complex structure, as the one shown in Fig. 1.

This part of the research has finally led to a comprenhesive model [10], which is in good accordance with Chang&Muki solutions, for SIF at a lap-joint as a function of its geometry and loading.

Table 1. SIF for the clamped specimen under a nominal stress $\sigma_\perp$ = 1 MPa

	2D FEM analysis	Beam theory + Eq. (2-2')	Error
K_I [MPa√mm]	1.355	1.437	6%
K_{II} [MPa√mm]	1.525	1.598	4.7%

CONCLUSIONS

This research has addressed the analysis of fatigue strength of welded lap-joints subjected to loads perpendicular to the weld. The results can be so summarised: i) SIFs at the tip of lap-joints are strongly enhanced by the presence of shrinkage cavities at the weld root; ii) fatigue strength of lap-joints can be calculated in terms of the cyclic stress at which $K_{\theta\theta,max}$ at weld root is equal to ΔK_{th}; iii) in a complex structure K_I and K_{II} at the lap-joint singularity can be calculated as a linear superposition of the effects of bending and shear onto the welded joint.

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