Effect of initial overload and antibending system on the fatigue behaviour of friction stir welded overlap joints

D. Fersini, A. Pirondi

Dept. of Mechanical Engineering, University of Parma,
Parco Area delle Scienze 181/A 43100 Parma, Italy

Fersini@ied.unipr.it, Pirondia@me.unipr.it

ABSTRACT In a previous work [1], the fatigue behaviour of Al2024-T3 FSW overlap joints has been studied. The fatigue strength of these joints is strongly affected by the presence, at the overlap ends, of two crack-like unwelded zones. The stress intensity factor at the crack tip has been determined using the Franc2d finite element (FE) code, and the lifetime has been then estimated by integrating the material propagation law with the AFgrow software.

In this work the effect of an initial overload and of the presence of an antibending system on the crack propagation rate and on the lifetime of the joints has been investigated. Experimental and numerical results show that lifetime of these joints can be strongly increased with respect to normal conditions.

INTRODUCTION

Friction Stir Welding (FSW) is an innovative solid state welding technique developed and patented at TWI in 1991; this technique results in low distortion and high joint strength compared with other welding procedures, and is able to join all aluminium alloys, including those like series 2XXX and 7XXX that are considered as virtually not weldable with classical liquid state techniques, due to the decrease in strength after resolidification.
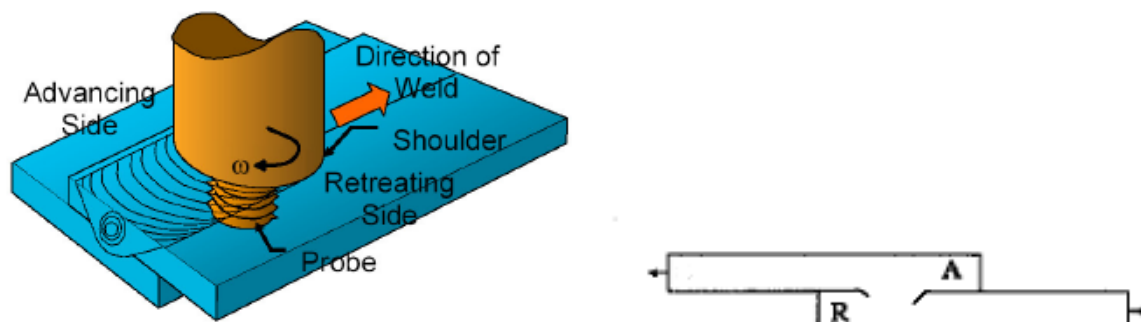

Fig. 1. Scheme of FSW process for overlap joints [1] a),
and unwelded region at overlap sides b).

In FSW, the parts to be joined are approached (see Fig.1) and a rotating tool is pressed on them and then moved along the seam. The tool consists of a cylinder (shoulder) with a profiled protrusion of smaller diameter (probe). The rotation of the shoulder generates a high frictional heat, causing softening of the material, which is then stirred by the probe. The overall effect is the extrusion and forging of the material from the leading side to the trailing side of the tool. Nowadays aluminium pieces with thickness ranging from 0.5 to 75 mm can be joined, at speeds up to 35 mm/s. FSW joints are not symmetric with respect to the seam

due to the rotation of the tool; the side of the weld where translation and rotation speeds have the same direction is called advancing side, while the side where they are opposite with each other is the retreating side.

Several studies have been conducted on friction stir welded butt joints, demonstrating that their strength is very similar to that of base material, and higher than the strength of the joints obtained with traditional welding techniques [2,3,4].

In the last few years, increasing interest has been dedicated to overlap FSW joints in order to verify their capabilities to replace riveted lap joints in aircraft structures, in fact rivet holes are often preferential sites for crack nucleation and provide a path for propagation of multi-site damage. Moreover, in riveted lap joints mastic is necessary in order to achieve pressure tightness, that creates a potential site for crevice corrosion [2].

Therefore, assembling airframes using FSW lap joints in principle could improve mechanical performance reducing weight and extending inspection interval.

On the other hand, FSW butt joints are generally defect-free if welding process conditions (travelling speed and sheet thickness) are properly tuned, while this is generally not the case of overlap joints, where the welded region must be wider than in butt joints to have a correct load transfer and oxides stirring and breaking is more difficult due to the relative orientation of tool and interface.

Besides, two crack-like unwelded zones are present at overlap ends and whose shape can be either straight or deflected of an angle up to 90° at the root of the welded zone (material hooking, fig. 1b). This causes a net reduction of the cross section of the sheet and, in turn, of the strength of the joint especially in fatigue, where the dimension of initial defects affects the lifetime. The effective thickness in the region of material hooking is evaluated using an Effective Sheet Thickness (EST) parameter. [3]

Another typical defect of FSW lap joints is the plate thinning at the retreating side of the weld due to material flow from retreating to advancing side during welding process. [4]

A big effort is being made for developing dedicate tool for overlap joints: different kind of tools (Skew-Stir^{TM}, Flared-Triflut^{TM}, Re-Stir^{TM}, Trivex^{TM} [4]) have been developed in order to minimize material hooking and material softening in heat treatable aluminium alloys due to dissolution and coarsening of the hardening precipitates [4].

With respect to a previous work devoted to the study and numerical simulation of the fatigue behaviour of overlap FSW joints[1], this work is aimed at evaluating the effect of an initial overload and of the presence of an antibending device on the lifetime.

MATERIAL AND EXPERIMENTAL METHODS

Specimen geometry

Figure 2a shows specimens' geometry: the sheet thickness t is equal to 1,6 mm, the width b 20 mm and the overlap length l 20 mm, while the free (unclamped) length is 200 mm. Fig 2b shows the topology of crack-like unwelded region on the advancing side, the crack tip is parallel to the load direction, and this reduces stress intensity factor and potentially increases joint lifetime. Anyway, due to material hooking, the EST of the specimens on the advancing side is equal to 1.3 mm, while the effective overlap length is about 5 mm.
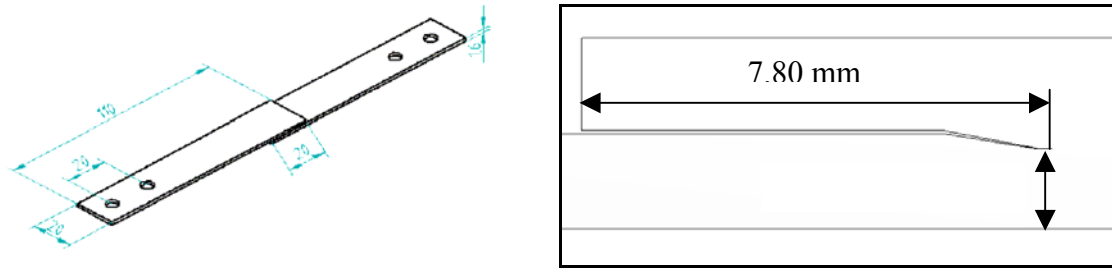
Figure 2. a) *Geometry and dimensions of the specimens used in experimental activity,b) effective sheet thickness (EST).*

Material properties, microstructure and hardness profile
The material (Al2024-T3) is a high strength aluminium alloy, whose mechanical strength is strongly affected by traditional welding techniques. Mechanical properties are reported in Table 1.

Table 1. Mechanical properties of Al2024-T3.

Sheet thickness [mm]	Yield strength, σ_y [MPa]	Ultimate strength, σ_u [MPa]	A[%]
1.6	325	461	11

Tensile tests on overlap joints showed an ultimate strength of 423 MPa if EST is considered, quite close to the value of the base material despite welding and joint geometry, that causes shear and bending, too.
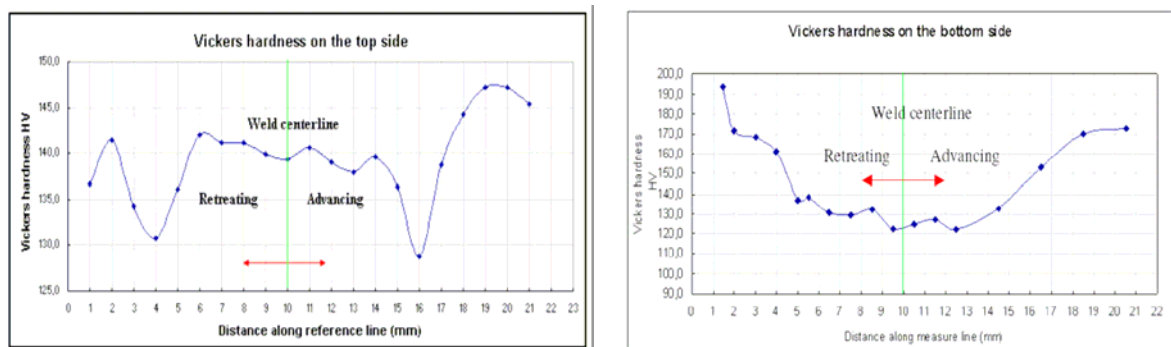

Figure 3. Vickers hardness profile on the top and on the bottom side of overlap region.

Vickers hardness measurement results are shown in Fig. 3 [1]. On the top side of the lap joint Vickers hardness (and so σ_u) has two minimums in the Heat Affected Zones (HAZs) at the sides of the welded zone, while in correspondence of the nugget properties are similar to base material due to recrystallization. On the bottom finally, there is a generalized decrease of mechanical properties in the welded zone in comparison with the base material probably due to thermal flux.
Figure 4 shows the microstructure: in the nugget (e) the grain structure is equiaxed and refined due to mechanically stirring of the tool, in the HAZ (c) the microstructure shows grains elongated in the rolling direction. At the edge of FSW zone there is a transition to the

base material microstructure (d). On the advancing side the transition is very clear, while in the retreating side this transition is smoother due to the lower speed on this side. Fig. 4b shows base material grains elongated in rolling direction. Also second phase black particles are visible (d).
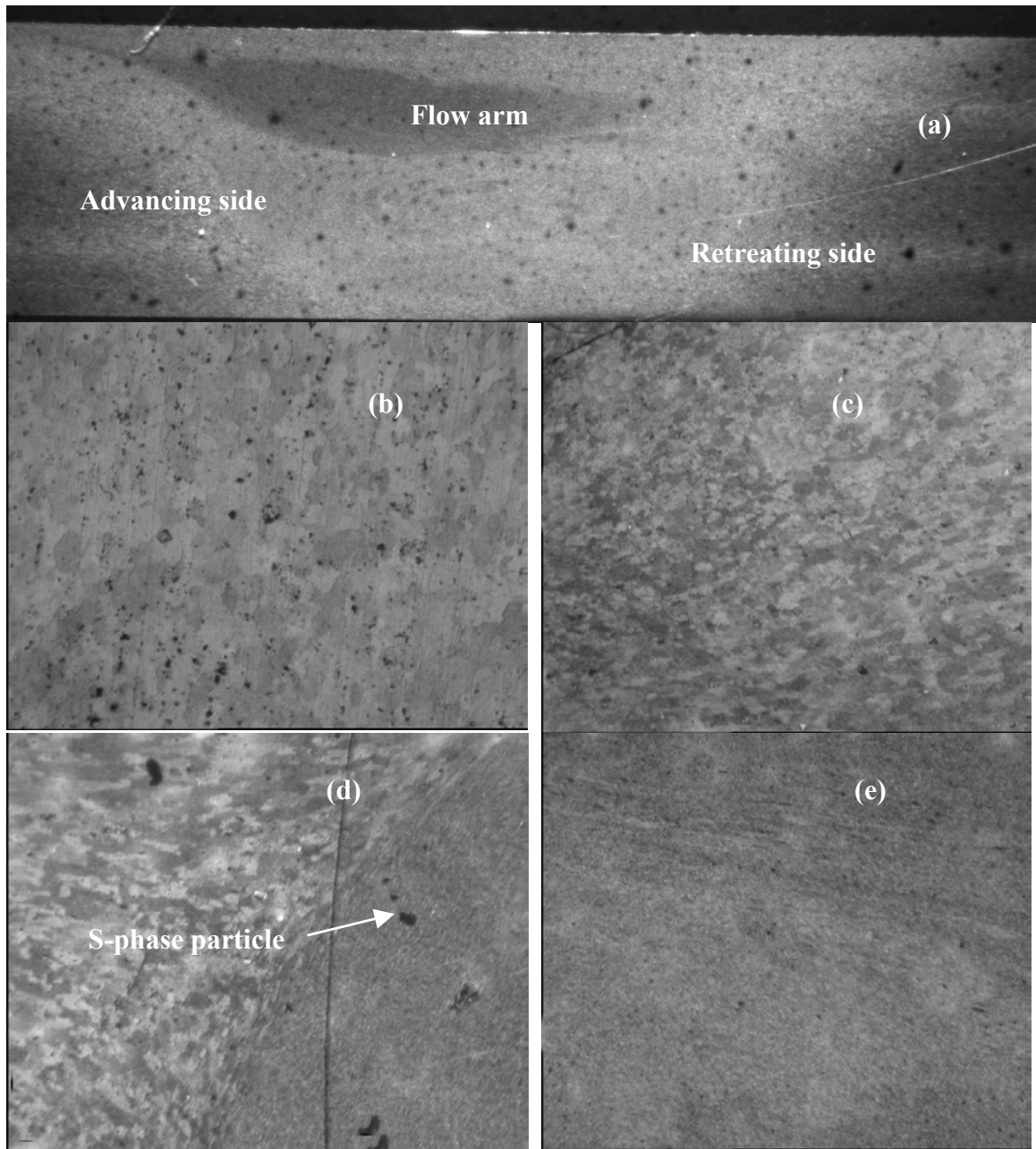

Figure 4 . Microstructure of the joint.

Experimental methodologies
In a previous activity fatigue behaviour with $R=K_{min}/K_{max}=0.1$ has been studied, nineteen specimen have been tested and fatigue limit has been determined using stair case method [1]. In this work, in order to study the effect of an initial overload on the lifetime of the joints two different overload levels have been applied, i.e. 130% and 200% of the maximum load of the cycle , respectively. Additionally, six tests have been carried in order to assess the effect of an

antibending system, shown in Figure 5. The presence of such device limits out-of-plane deformation, hence bending stress, resulting in a lower mode I stress intensity factor.
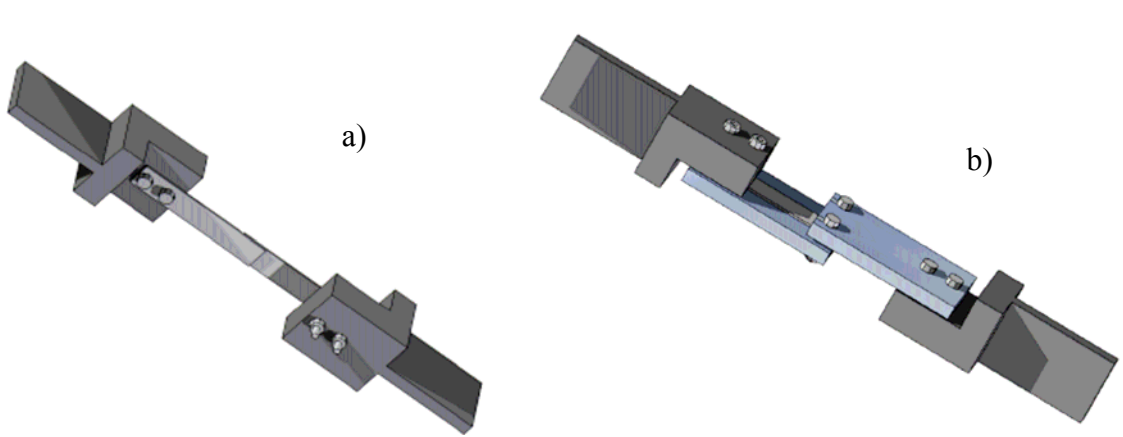

Figure 5. a) Simple locking devices, b) locking devices with antibending system.

Numerical models
The stress state in the joint has been studied using the FE code Franc2d, a two dimensional crack propagation simulator [5]. The crack is propagated in steps where, at the end, the stress intensity factor and the theoretical kink angle are calculated and the mesh in front at the crack tip is redrawn. A detailed description of numerical models and crack propagation procedure is reported in [1]. Figure 6 shows deformed FE model without antibending system and with it, as the antibending system has been modelled as a vertical displacement restraint on the surface.

Due to the mixed mode I/II condition at the crack tip an equivalent stress intensity factor has been used to study crack propagation [7]:

$$\Delta K_{eq} = (\Delta K_I^4 + 8\Delta K_{II}^4)^{0,25} \quad (2)$$

Figure 6. Deformed numerical models without (a) and with (b) antibending system.

The number of cycles to failure was simulated by means of the software AFgrow. The shape factor to be inserted in AFgrow was calculated with Franc2d as a function of crack length. The Nasgro model of fatigue crack propagation of Al2024-T3 has been used in combination with the closure module to account for overload effect [6].
NASGRO crack growth rate equation is implemented in AFgrow as follows:

$$\frac{da}{dn} = C\left[\left(\frac{1-f}{1-R}\right)\Delta K\right]^n \frac{(1 - \frac{\Delta K_{th}}{\Delta K})^p}{(1 - \frac{K_{max}}{K_{crit}})^q} \quad (3)$$

Where C,p,q are empirically derived and f is function of maximum applied stress, flow stress and plane stress/strain constraint factor, ΔK_{th} is the threshold value that is a function of R ratio

and K_{crit} is a function of fracture toughness and of the specimen thickness. For Al2024 properties numerical values available in Nasgro database have been used.

The closure model assumes that a certain load must be applied to open the crack in order to overcome the compressive residual stress in front of the crack tip. The minimum applied load that must be reached before the crack may extend is called opening load. The opening factor CF is the ratio between the opening load and the maximum load and is a function of R ratio:

$$Cf= 1.0 – [(1-C_{f0})(1+0.6R)(1-R)] \quad (4)$$

The closure model uses a single parameter (C_{f0}) to tune the material behaviour, ideally C_{f0} is a material property and ranges from 0.3 to 0.5.

RESULTS

Experimental results for an initial overload are shown in figure 7. The smaller overload did not substantially change the lifetime with respect to non-overloaded tests, while an initial overload equal to two times the maximum load of the following cycle increased notably the duration of the joints.

Numerical results shown in figure 7 show a good agreement with experimental ones and have been obtained by tuning the closure model in AFgrow to a value C_{f0}=0.345.
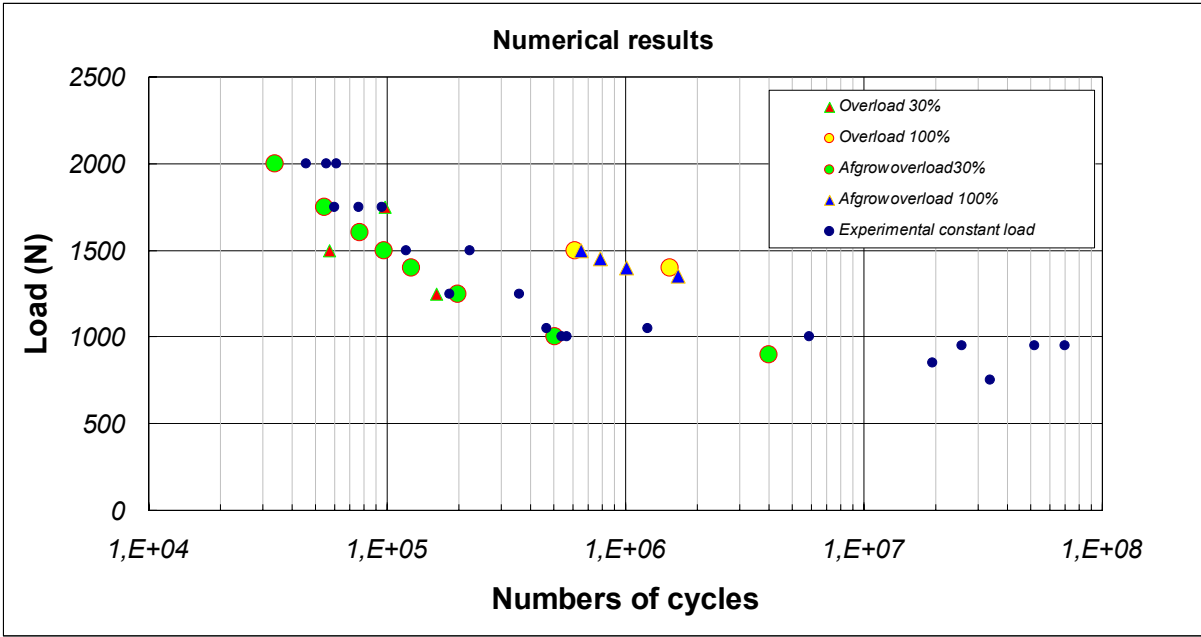

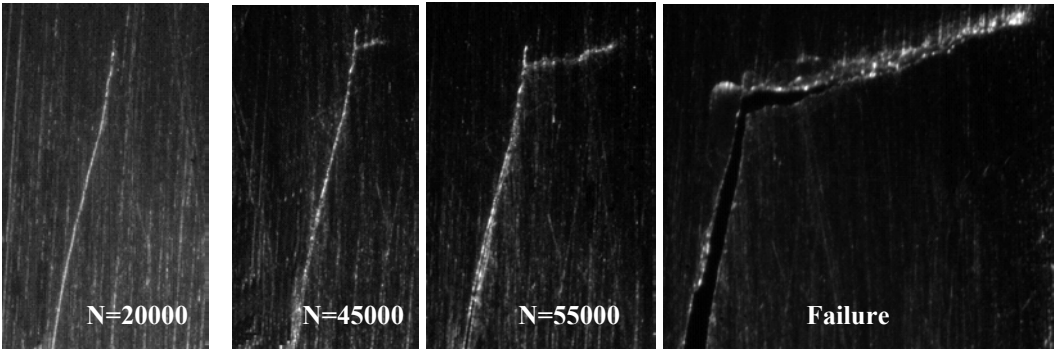Figure 7. Experimental and numerical results in the cases of overload.

Figure 8. Branched crack nucleation and propagation behind the leading crack tip.

It is worth to notice that in the case of absence of initial overload, the crack shows an early stage propagation in shear mode according to Failure mechanism map [1], while in the case of an initial overload, a secondary crack nucleates behind leading crack and propagates in the thickness (fig. 8), probably due to residual stresses that keep crack faces pressed against each other in a region around the leading crack tip.

Figure 9 shows that also antibending system increases both static strength and lifetime of these joints reducing the stress intensity factor at the crack tip. In Table 2 the initial SIF at the crack tip in the cases of absence and presence of an antibending system are compared (applied load of 1000 N): ΔK_{eq} with antibending system is a third of that in the case without, therefore one can expect a factor-of-three improvement in fatigue life. On the other hand, the fatigue strength with antibending system is only about twice of tests carried out without. This discrepancy has been attributed to the fact that the vertical displacement restraint introduced in the FE model to evaluate the stress intensity factor with antibending is probably much more severe than in reality: actually, contact between surfaces of antibending plates and specimen should be modelled in order to obtain a better correspondence with experimental results.

Table 2. Values of SIFs and expected crack deflection at the beginning of propagation.

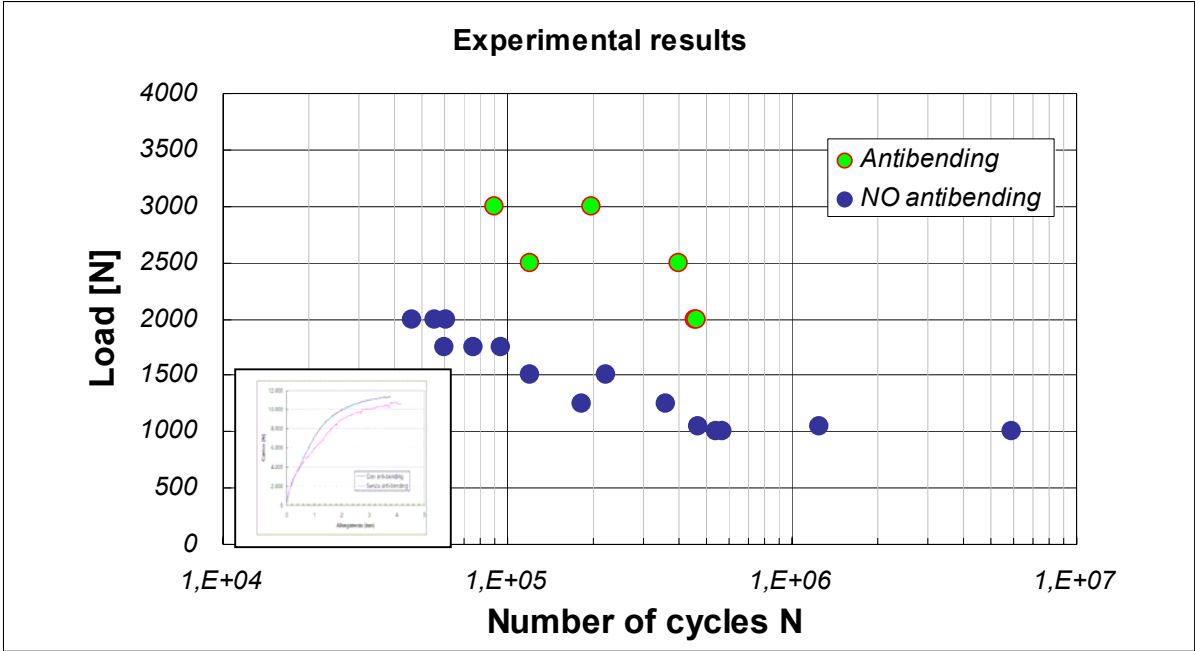|	Mode I SIF MPa√m	Mode II SIF MPa√m	ΔK_{eq} MPa√m	Initial propagation angle
Simple load	1,55	1,74	2.68	54°
Antibending	0,18	0,6	0.9	64°

Figure 9. Effect of antibending system on the fatigue strength of FSW joints.

Conclusion and future developments

The effect of an initial overload on the mixed mode fatigue crack propagation in FSW overlap specimens has been evaluated, experimental results have been compared with those obtained without overload in an earlier work [7], and show a strong increment in specimens lifetime in the case of an initial overload about double subsequent maximum load. A closure model has

been tuned in order to obtain best correspondence with experimental results, resulting in a C_{f0} parameter equal to 0.345.

The role on fatigue lifetime of an antibending device has also been evaluated. In this case numerical results overestimates the experimental fatigue limit. An improvement of the correlation should be possible with a more actual modelling of the contact between antibending plates and specimens, that is under development.

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