MODELING OF FATIGUE CRACK GROWTH IN MONOLITHIC INTEGRAL STIFFENED PANELS TAKING INTO ACCOUNT RESIDUAL STRESS

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ABSTRACT

The main and primary structures in airframes are composed by stiffened panels in order to have a high specific strength. Different manufacturing processes are under study for improving this type of structures, aiming at decreasing the panel weight without compromising the global safety. In this paper stiffened panels produced by three different manufacturing processes are studied as regards their behaviour in the presence of crack, evaluating the damage tolerance of different solutions. For this purpose, numerical models using Linear Elastic Fracture Mechanics concepts are developed to simulate the fatigue behaviour of the cracked panels tested. Finite element models of the stiffened panels were made using 3D elements to determine Stress Intensity Factors (SIFs) using the modified virtual crack closure technique and taking into account the residual stress redistributions promoted by the welding processes. These SIF calibrations were applied in a fatigue crack growth law for fatigue life determination. In addition, the effect of the residual stress on the load ratio at the crack tip was estimated and incorporated into the crack growth law. The residual stress effect can significantly deteriorate or improve the fatigue life of these stiffened panels, depending upon the location of the initial crack and the intensity and type of residual stresses. Longer fatigue life is obtained when the crack starts to grow in areas with higher compression residual stresses. The results obtained were compared with experimental data for validation of the numerical models.

KEY WORDS: Fatigue crack growth; Forman law; residual stress; stiffened panels.

1. INTRODUCTION

Economical and environmental concerns force the decrease in operational costs and environmental impacts and are drivers for the development of new solutions for aeronautics [1]. In the case of airframes, the main interest is the decrease of the global weight without compromising safety. For this purpose new technologies start to be applied as in the aircrafts Boeing 787 or the Airbus A350WXB aircrafts, where the traditional material for the airframe, aluminium, was substantially replaced by carbon fibre reinforced polymer (CFRP). Nevertheless, due to the problems of the large scale application of CFRPs in airframes, as stress concentration, final cost, maintenance and aging, other alternatives using aluminium alloys are being investigated.

New manufacturing processes can replace the riveting processes creating a leaner joint and with an improvement of mechanical properties. Examples of these joining processes are the friction stir welding (FSW) and laser beam welding (LBW). In addition, new aluminium alloys with lower density and higher mechanical properties can add an additional improvement to the airframe structures. The combination of these new aluminium alloys with new manufacturing processes can bring competitive airframes, with a reduced number of parts, higher maintenance intervals, less lead times and less global weight for the structure.

Al-Li [2] and Al-Sc [3] are examples of alloys with better material properties than the AA2024, with better weldability and suitable to be joined with welding processes as LBW, FSW and electron beam welding.

The application of new processes and materials in airframes requires an extensive study in order to take into account effects that were not considered in riveted structures, as the continuous paths for the crack growth from the skin to the stiffeners and the residual stress fields promoted by the welding processes.

The residual stresses originated by the application of welding processes in stiffened structures considerably affect their fatigue behaviour. The residual stresses arise due to the thermal gradients originated by the welding process. In the FSW process, in addition to the thermal field the mechanical work also promotes residual stresses. These residual stress fields could increase or decrease the fatigue life of the structures if they are compressive or tensile, respectively.

This paper presents a methodology, based in the Linear Elastic Fracture Mechanics (LEFM) concepts, to determine fatigue life of integral structures with residual stresses. ABAQUS finite element models were used together with the Modified Virtual Crack Closure Technique (VCCT), [4], and the J-integral technique for stress intensity factor determination of cracked stiffened panels subjected to mode I loading.

Following the stress intensity factor calibration, crack growth laws were used to determine the fatigue life of the panel considering the effect of residual stress.

The methodology proposed was developed under the frame of an European project, Innovative Fatigue and Damage Tolerance Methods for the Application of New Structural Concepts - DaToN [5], where panels with two stiffeners was manufactured by three different processes: high speed machining (HSM), LBW and FSW, using two aluminium alloys AA2024 and AA6056 and with different heat treatments. These panels were experimentally tested by various institutions. The acquired results were compared with the numerical models in order to validate the methodologies used.

2. EXPERIMENTAL PROCEDURE

A base geometry of the stiffened panel was selected for this benchmark. Panels were manufactured with three different processes and with two different materials. Panels are flat with 450 mm width and two simple stiffeners of rectangular cross section. Figure 1 shows the cross section of the panel with dimensions and location of the initial crack.

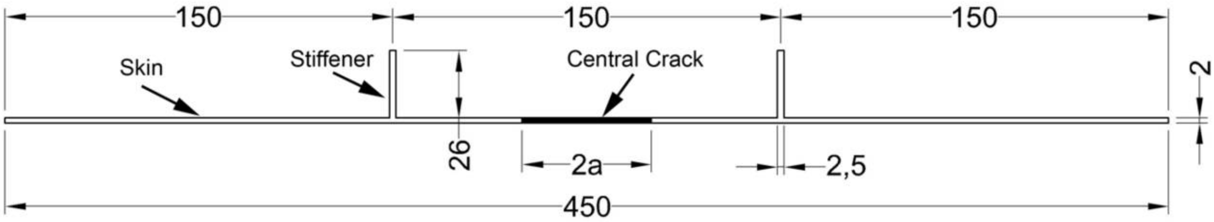
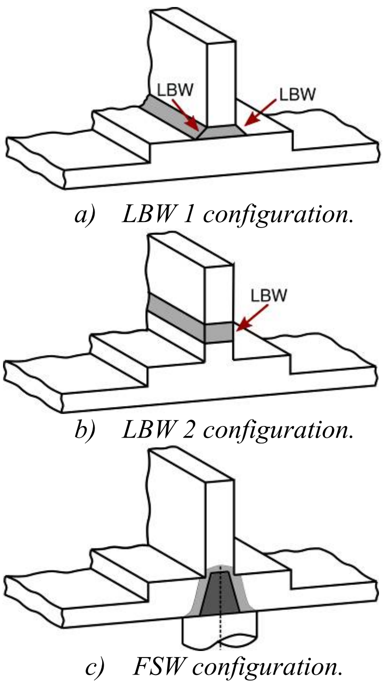


Figure 1. Cross-section of the stiffened panel and the crack location.

The HSM panels are produced from a block of aluminium with 40 mm thick that was machined until get the final shape of the panels. For LBW and FSW, the stiffeners were welded to a plat plate. For the LBW process two different configurations were used and are presented in Figure 2 a) and 2 b). In the stiffened panel produced by FSW, the stiffeners were welded with a tool that crosses all skin and mix the material from the stiffener with the skin, as shown in Figure 2 c).



a) LBW 1 configuration.

b) LBW 2 configuration.

c) FSW configuration.

Figure 2. Welded panels, the different configurations.

Besides the manufacturing processes and joining configurations, different materials and heat treatment conditions were used to manufacture these panels:

- AA2024-T3;
- AA6056-T6;
- AA6056-T4 and post welding treatment (PWHT) to T6 condition.

For each configuration, the specimens were tested, in order to measure the crack growth, in the situation of an applied constant cyclic load for two different load ratios (R) with different maximum loads:

- R=0.1 → σ_{max}=80 MPa;
- R=0.5 → σ_{max}=110 MPa.

In the experimental program, besides the crack growth with constant load, some panels were used to test the crack growth with a flight load spectrum and other used to measure the residual stress using a destructive method, the cut method, where the residual stress are measured by strain gages that measure the residual stress release after a cut. The method was applied by Pisa University, partner of DaToN project, in 7 panels produced by the different processes and for the both materials, [6]. These panels were cut in the middle, transversally to the stiffeners, and the final strain achieved after the cut was measured with strain gages along the cutting line on both surfaces, obtaining the residual stresses acting parallel to the stiffeners. In order to not influence the residual stress state by the cutting process, the cut was done on a milling machine.

3. NUMERICAL PROCEDURE

The numerical procedure adopted to model the crack growth in these panels is based on LEFM theory where SIFs were calculated from FE elastic models.

A finite element model corresponding to half of the specimen geometry was made using the symmetry of the DaToN panel and including part of the griping system for better load distribution at the top of the panel, Figure 3.

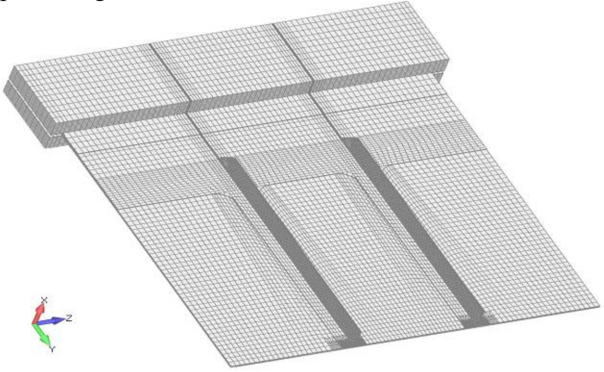


Figure 3. Mesh of the FE models of the stiffened panel.

The elements used in this model are parabolic solid elements with 20 nodes (C3D20) and 15 nodes (C3D15), from the ABAQUS element library, [7]. The global model has 47978 elements and 230287 nodes. The residual stress was applied as initial condition in the FE models.

In order to apply the residual stress data from the experiments in the three-dimensional finite element models, information along the thickness is required. This information was obtained using linear interpolations from the known points on surface. Employing an interpolation algorithm based on a Delaunay triangulation [8] the values along the thickness, were estimated

To increase the accuracy of these models, the centroid of each element was calculated and the residual stress was interpolated into these centroids. A detail of the initial stress (uncracked panel) in a contour map is presented in Figure 4 for the panel produced in AA6056-T6 with the FSW process. After this initial condition, the remote load and the boundary conditions that define the crack size were applied.

To determine the stress intensity factor calibration (SIF in function of the crack length) for each configuration the crack growth was simulated in a step, adapting the boundary conditions corresponding to each crack length.

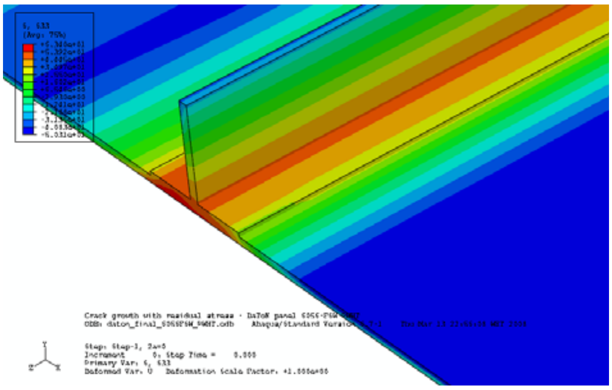


Figure 4. RS applied in the FE models of the stiffened panel (detail)

VCCT was proposed by Rybicki and Kanninen, [9], in order to calculate the energy release rate (G) based on the calculation of the strain energy release rate (U). The energy release rate when a virtual extension of crack length is imposed (Δa) can be approximated by:

$$G = \frac{\partial U}{\partial a} \approx \frac{U_{a+\Delta a}}{\Delta a} \qquad \text{..(1)}$$

However, this procedure requires performing two finite element simulations, one to determine the reaction loads and another to determine the displacements in order to obtain the energy release rate. This procedure could be hard working and time consuming in large finite element models.

A modification of VCCT was presented by Krueger in 2002, [4]. This modified technique presupposes that if the nodal displacements are measured, near the crack before and after grow the crack length to $a+\Delta a$, for nodes equidistant to the crack tip, the nodal displacements are identical. This assumption allows computing the energy release rate using only one finite element analysis for each crack length. For 3D parabolic finite elements, the determination of the energy release rate with the modified virtual crack closure technique can be determined using the nodal loads and nodal displacements; however it requires to consider the different weights of the nodes in the middle and in the corner of the element. As example, for a parabolic element with 20 elements, the mode I, considering the notation presented in Figure 5, the equation used to determine the energy release rate for the node at the crack surface (node 3) is:

$$G_I = -\frac{1}{2\Delta a \cdot \Delta b}\Big[F_{z_3}\left(u_{z_{1*}} - u_{z_1}\right) + F_{z_4}\left(u_{z_{2*}} - u_{z_2}\right) + \frac{1}{2}F_{z_6}\left(u_{z_{5*}} - u_{z_5}\right)\Big]$$

(2)

where F_z is the nodal force in the z direction, u_z is the displacement in z direction and Δa and Δb are the element dimensions. For the nodes positioned in the middle of the element, in this case node 6:

$$G_I = -\frac{1}{2\Delta a \cdot \Delta b}\Big[\frac{1}{2}F_{z_3}\left(u_{z_{1*}} - u_{z_1}\right) + \frac{1}{2}F_{z_4}\left(u_{z_{2*}} - u_{z_2}\right) + F_{z_6}\left(u_{z_{5*}} - u_{z_5}\right) + \frac{1}{2}F_{z_9}\left(u_{z_{7*}} - u_{z_7}\right) + \frac{1}{2}F_{z_{10}}\left(u_{z_{8*}} - u_{z_8}\right)\Big] \qquad (3)$$

For the corner nodes inside the crack tip, as the node 9, the energy release rate will be:

$$G_I = -\frac{1}{2\Delta a \cdot \Delta b}\Big[\frac{1}{2}F_{z_6}\left(u_{z_{5*}} - u_{z_5}\right) + F_{z_9}\left(u_{z_{7*}} - u_{z_7}\right) + F_{z_{10}}\left(u_{z_{8*}} - u_{z_8}\right) + \frac{1}{2}F_{z_{12}}\left(u_{z_{11*}} - u_{z_{11}}\right)\Big] \qquad (4)$$

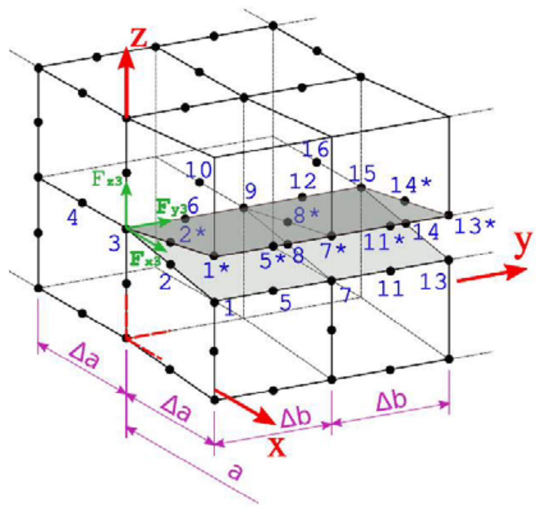


Figure 5. FE crack tip model

The results of stress intensity factors were estimated for 37 crack lengths for the different manufacturing processes, the values for each configuration are presented in Figure 5.

These three equations are able to determine de evolution of the stress intensity factor along the crack front, in mode I. Similar equations for the determination of SIFs in modes II and III can be derived from presented equations exchanging the nodal loads and nodal displacements by the ones associates to the desired mode of deformation.

The determination of the fatigue life from the stress intensity factor calibration is done using the fatigue crack growth laws that describes the number of cycles in function of the crack length using the material parameters and the stress intensity factors. The determination of the number of cycles in function of crack length is done by the integration of power laws.

Several laws may be used to estimate fatigue crack growth as Paris; Walker, Forman, Terada or NASGRO. In this work the Forman law was used for the panels produced in AA6056-T6, because this law considers the load ratio (R) variation at the crack tip and it is possible to fit this law to the available material data for different load rations with reasonable accuracy.

The Forman law, [10] is:

$$\frac{da}{dN} = \frac{C_f \Delta K^{m_f}}{\left(1 - R_{eff}\right) K_c - \Delta K} \qquad (5)$$

where C_f, m_f and K_c are material constants and R_{eff} is the effective load ratio at crack tip.

As the crack law are power laws, are particularly sensitive to material characterization. Therefore, the crack growth parameters were obtained from the same material that are produced the panels. The welded panels were obtained from 4 mm thick sheets and the HSM panel was machined from a block of 40 mm. Because the materials applied in the manufacturing had different thickness, fatigue crack growth characterization was done for both material panels, [11].

An algorithm was developed to estimate the Forman law parameters, optimized for R=0.1 and R=0.5.

The Forman constants can be linearized with the logarithmic values from experimental measurements and fixing a value of K_c (that can be determined by the asymptote of the experimental data for high *da/dN* values) and for different load ratios, as presented in the next equation:

$$\log\left(\frac{da}{dN}\cdot\left[\left(1-R\right)K_c - \Delta K\right]\right) = \\ = n_F \log\left(\Delta K\right) + \log\left(C_F\right) \qquad (6)$$

The value n_F is determined using the least mean squares technique and the C_F value using the minimisation of the error between the Forman law and the experimental points.

Figure 6 shows the fitting obtained for the Forman law parameters. The material parameters applied in the integration of the Forman law were:

- C_F= 2.9022E-07
- n_F= 2.3510
- K_c= 3000

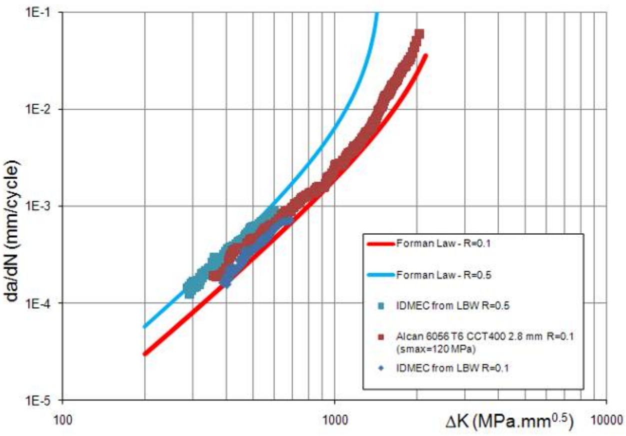


Figure 6. Forman law parameters determination.

4. RESULTS AND DISCUSSION

The results of stress intensity factors for the stiffened panel were estimated for 37 central crack lengths and for the 8 models, the values for each configuration are presented in Figure 7. In addition, the crack bifurcation, when the crack reaches the stiffener was modelled.

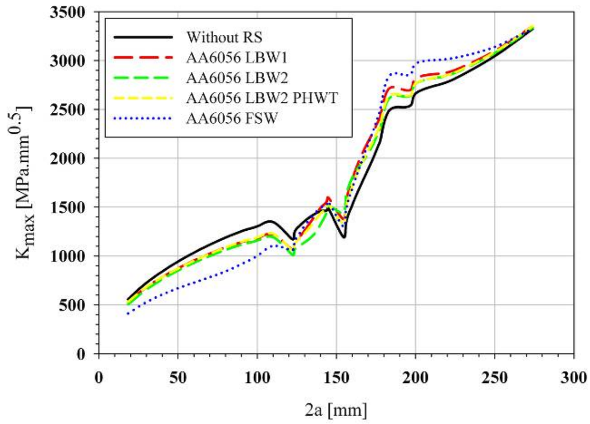


Figure 7. SIFs in function of crack length.

The stiffener influence in the retardation of the crack is noticeable, however the first decrease of the crack length is due to an increase of the skin thickness. It is perceptible from this figure that the FSW promotes a lower stress intensity factor in the middle of the specimen due the compressive residual stresses. In the case of the LBW, the effect is more concentrated in the weld zone generating higher SIFs.
Due to the residual stress field in the panels, the effective load ratio (R_{eff}) at the crack tip will is not the nominal. Thus, effective load ratios can be determined using the SIF solutions and equation 7:

$$R_{eff} = \frac{K_{\min} + K_{res}}{K_{\max} + K_{res}} \tag{7}$$

where the K_{min} and K_{max} are determined from the FE models and K_{res} is determined using the reference of a panel without RS (panel HSM). Figure 8 shows the evaluation of the R_{eff} at the crack tip in function of the crack length. The compressive residual stress field due the FSW process is intensive generating negative load ratios. These negative load ratios are also presented in the LBW panels although not so severe. When the crack tip reaches the stiffener, the residual stresses are in tension increasing the load ratio but now in positive values.

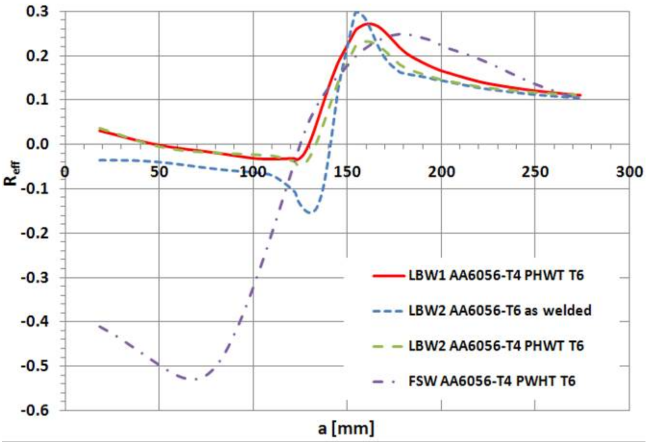


Figure 8. Effective load ratio at the crack tip.

The SIFs and R_{eff} calibrations were applied in the Forman law, equation 5, in order to determine the remaining fatigue life of the different panels by integration. For this integration of the Forman law an algorithm in MATLAB was developed where the variation of the SIF, *ΔK(a)*, and the efective load ratio, $R_{eff}(a)$, as a function of the crack length is considered. The effective load ratio was calculated using the SIF models with and without load ratios.
The results obtained for the load ratio R=0.1 (σ_{max}=80 MPa) are presented in Figure 9 and for the load ratio R=0.5 (σ_{max}=110 MPa) are presented in Figure 10.

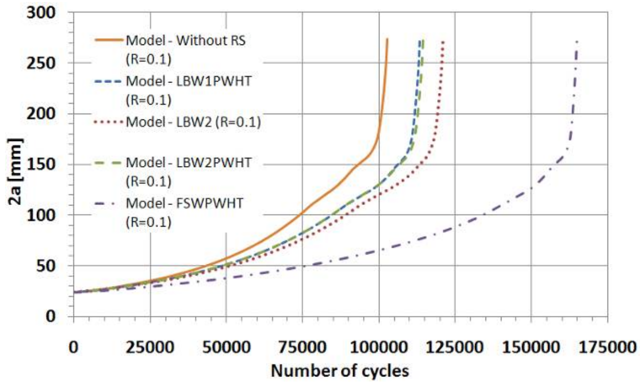


Figure 9. Fatigue life of the panels for the condition of a load ratio R=0.1 and σ_{max}=80 MPa.

As aspected, the higher compressive residual stresses in FSW panels promotes higher fatigue life. The HSM panel, whitout residual stresses, have the lower fatigue life, however should be taken into account that the crack starts to growth in a compressive RS field, if the cracks starts near the stiffeners, where tensile RS are present, the fatigue life will be lower for welded panels.
The difference between the fatigue life for the two load ratios is not large, however the stress amplitude during the test for R=0.5 is lower than for R=0.1.

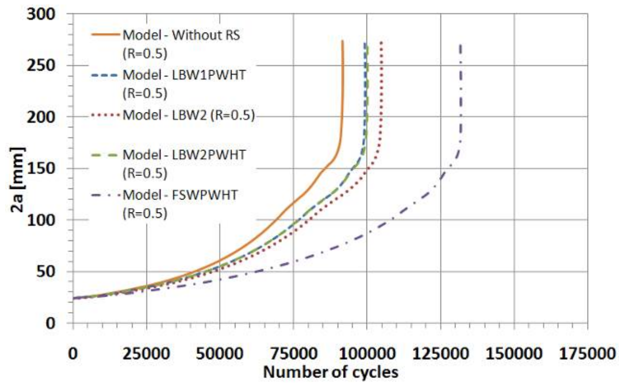


Figure 10. Fatigue life of the panels for the condition of a load ratio R=0.5 and σ_{max}=110 MPa.

In order to validate the numerical models, the results were compared with experimental results for the manufacturing processes, heat treatments and load conditions.
Figures 11 and 12 shows two of these comparisons. generallygood agreement was found, including exceptional agreement in the case of Figure 11, and reasonable in Figure 12. The crack growth have always some variance even in the base material with controlled test conditions, therefore discrepancies about the 20%-30% is expectable due the nature of this phenomenon. In this research is also noticed the sensitivity of the calculated fatigue life to the crack growth law parameters; minor variations produce substantial differences in the fatigue life. It is suggested, when possible to measure the material parameters from similar lots of material. The residual stress quantification is also extremely important in order to obtain accurate models.

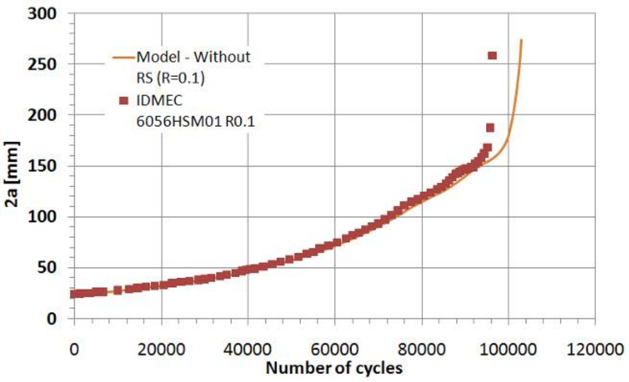


Figure 11. Comparison between numerical and experimental results, panel HSM AA6056, R=0.1 and σ_{max}=80 MPa.

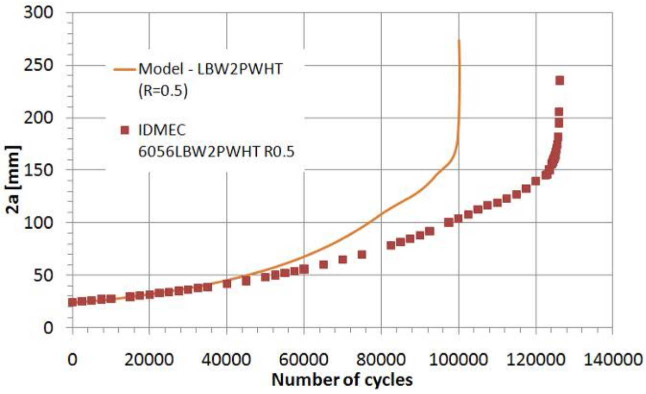


Figure 12. Comparison between numerical and experimental results, panel LBW 2, AA6056 PWHT, R=0.5 and σ_{max}=110 MPa.

5. CONCLUSIONS

Lightweight constructions may be optimized by reducing the number of parts, simplifing the joints, reducing weight and costs. However, the behavior of integral structures under service conditions needs to be addressed carefully.

Some of the new joining processes (welding processes) promote residual stresses that can be beneficial or detrimental for the fatigue life, depending on the location of the crack. Therefore, new approaches are required to design these structures concerning their fatigue life. In order to understand the impact of the application of these processes, a project was developed with the main purpose of studying their effect in the fatigue behavior of stiffened panels and to develop tools to model their behavior in order to predict their fatigue life when a crack arises in the structure.

With the residual stress measurements it was possible to determine and model their influence in the fatigue life of panel. With the finite element models, the redistribution of residual stresses and the stress intensity factors for different crack lengths are calculated. Afterwards, with the experimental data of the fatigue crack growth rates for the alloy AA6056-T6 in standard specimens the Forman law parameters were calculated. With these parameters and with SIF calibrations the Forman law was integrated considering the effective load ratio at the crack tip due the residual stresses. The comparison of numerical simulation with experimental results shows good aggreement and demonstrates the possibility to predict the fatigue life in this type of stiffened panels. It was confirmed that the compressive residual stress may be beneficial for the fatigue life of structures; however if the crack starts in the tensile residual stress zone it will propagates at a higher rate being detrimental for the integrity of the panel.

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