Damage tolerance analysis of aircraft reinforced panels

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ABSTRACT. This work is aimed at reproducing numerically a campaign of experimental tests performed for the development of reinforced panels, typically found in aircraft fuselage. The bonded reinforcements can significantly reduce the rate of fatigue crack growth and increase the residual strength of the skin. The reinforcements are of two types: stringers and doublers. The former provides stiffening to the panel while the latter controls the crack growth between the stringers. The purpose of the study is to validate a numerical method of analysis that can predict the damage tolerance of these reinforced panels. Therefore, using a fracture mechanics approach, several models (different by the geometry and the types of reinforcement constraints) were simulated with the finite element solver ABAQUS. The model was created exploiting symmetries, while the bonding between skin and stiffener was taken either rigid or flexible due to the presence of adhesive. The possible rupture of the reinforcements was also considered. The stress intensity factor trend obtained numerically as a function of crack growth was used to determine the fatigue crack growth rate, obtaining a good approximation of the experimental crack propagation rate in the skin. Therefore, different solutions for improving the damage tolerance of aircraft reinforced panels can be virtually tested in this way before performing experiments.

INTRODUCTION

In aircraft fuselage, aluminum stiffeners are connected to panel in longitudinal and circumferential directions. A particularly significant application is the direct bonding between stringers and the surface of the fuselage skin. The main features of the reinforced bonded panels, concern better damage tolerance and higher stability at different types of loads [1, 2].

The experiments on aluminum panels with bonded stiffeners show that a limit of the aluminum reinforcement is the premature rupture of the reinforcement caused by the load transfer from the skin to the stiffener when the crack runs underneath it. To improve the tolerance to the fracture, the doublers or reinforcement cords should preferably be made of material resistant to fatigue, with high stiffness and static strength [3, 4].

Panels made of a thin metal skins stiffened with bonded reinforcements insensitive to fatigue, can ensure slow crack propagation if not his arrest, and the capability to withstand a large damage, combined with a low structural weight. The effects of this bonded reinforcements or doublers are very difficult to predict numerically or analytically, because of the complex mechanisms of failure:

- separation at the interface between skin and reinforcement around the area of nucleation and propagation of the crack;
- load redistribution between the damaged and undamaged reinforcement;
- fatigue damage of the reinforcement which may cause his premature rupture;
- crack bridging by the doublers thanks if they have a sufficiently high fatigue strength.

In addition, secondary effects, such as residual stresses generated by the bonding process and bending caused by the eccentricity of the load with respect to the neutral axis of the reinforced panel cross-section, increase the complexity of the phenomenon. Reliable predictions of crack growth and residual strength in bonded structures can be based mainly on

empirical considerations. The experimental results which support the numerical analysis reported in this work refer to an experimental investigation carried out by Airbus in a period from 2002 to 2007. Through an extensive campaign of tests, several methods of reinforcement were analyzed, using bonded reinforcements in the fuselage panels. To achieve a quantitative study, in the analysis different types of connection between the reinforcements and the skin were considered.
In the literature, numerical studies on FCP (Fatigue Crack Propagation) in reinforced structures are available. However, if the damage tolerance assessments appear to be practicable in integral reinforced structures [5], the same assessment is not straightforward in differential structures with bonded joints between skin and chords [6, 7] due to the complex mechanisms mentioned previously.

EXPERIMENTS

The panel showed in Fig. 1 has been tested by Airbus (in EADS-IW Laboratories in Ottobrunn, Germany). It is characterized by a skin (1224 mm wide and 1455 mm long) with seven equally spaced bonded stringers. In addition to the stringers, bonded doublers are positioned under and between the stringers in order to provide additional reinforcement. All doublers were placed orthogonal to the direction of crack propagation alike the stringers (see Fig. 1).
The skin, like the doublers, were made of 2024-T3 aluminum alloys with 1,4 mm thickness the former and 0,8 mm the latter. The stringers were "J"-shape extruded profiles made of high strength 7349-T76511 aluminum alloy. The tests were performed by means of a servo-hydraulic INSTRON 8805 machine with a 1 MN load-cell; an anti-bending device was installed to prevent the out of plane deflection of the panel during the test.

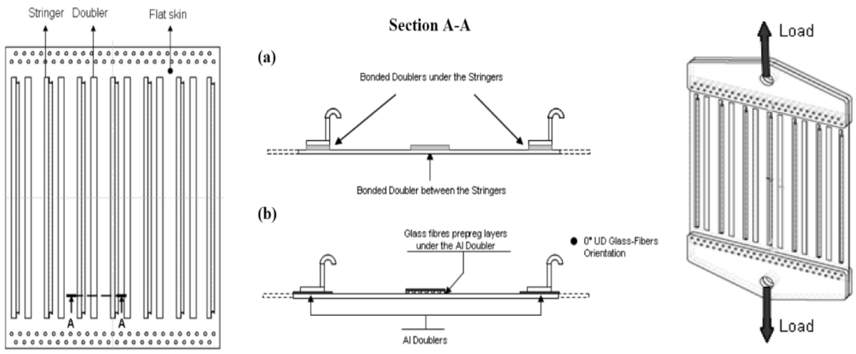

Figure 1: Representation of a "seven stringers" panel with doublers bonded between and under the stringers (a) and with an additional glass fiber reinforcement (b).

In the experiments the fatigue crack propagation was investigated then the panels were provided with a through the thickness machined notch 50 mm long (2a0). The crack was placed across the middle stringer; this stringer and the underlying doubler (when present) were also cut. The loading parameters were the same for all the tested configurations (constant amplitude loading, 280 kN maximum force and 0,1 load ratio). The tests ended when the crack was "four bays" long or in case of panel failure. The crack growth period that the crack spends below the bonded stringer is significant and has been measured during the tests.
The observed crack lengths within the two bays were practically symmetrical: this has permitted to draw the crack propagation curves [a = f(N)] considering the average crack length between the left and right crack tip displacement (see Fig. 2).

MODELING

The method used here is to simulate some of the panels tested by Airbus, using finite element analysis with the ABAQUS software. Only a quarter of the panel was modeled in order to limit the computational complexity. Other two approximations are:
- the propagation occur in the perpendicular direction to that of load application (Mode I);
- the front of the crack is assumed to be straight and modeled with two elements in the thickness (see Fig. 3).

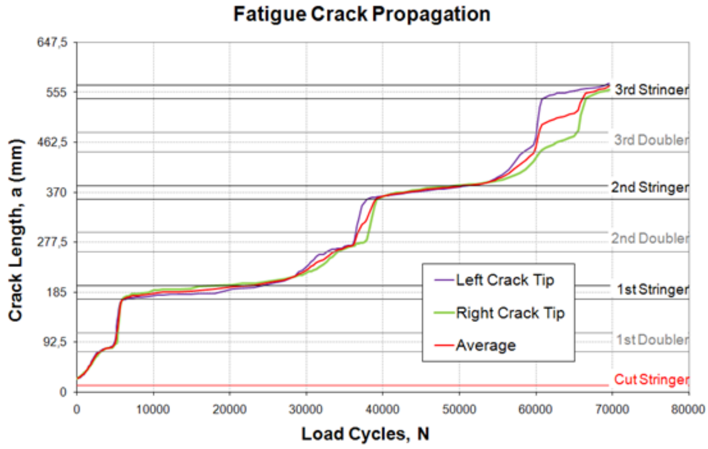

Figure 2: Experimental FCP curve illustration of left and right crack.

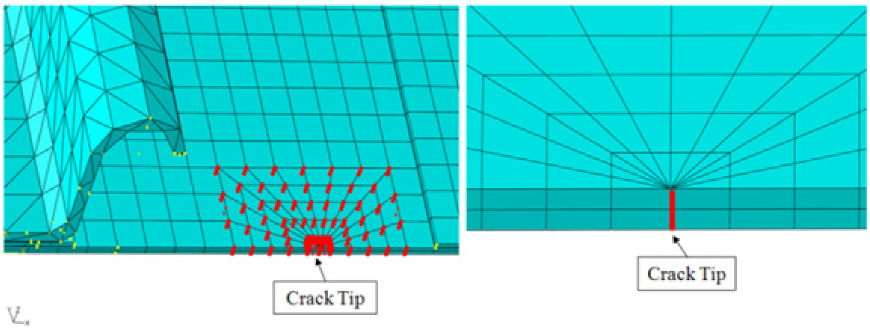

Figure 3: Straight crack tip in the thickness direction of the panel skin-

After a study of convergence based on analysis between various discretization solutions, a modeling with linear solid elements was chosen (see Tab. 1), in this way through a mobile partition with good density of elements near to the fracture tip (see Fig. 3), a good refinement of the results with acceptable computation times was guaranteed.

Element	Characteristics		
	K^1 $[MPa\sqrt{mm}]$	Process Time²	K Deviation³ [%]
Shell Linear	*1771.3*	*5,2*	*3.46*
Shell Parabolic (QPNT)	*1780.5*	*33,1*	*3.99*
Solid Linear	*1780.7*	*7,4*	*4.01*
Solid Parabolic (QPNT)	*1712*	*100*	*0*

[1] Values obtained by the solver taking into account the follow conditions of analysis:
- Same configuration of loads and constraints;
- Same crack length ($a = 42,71\ mm$);
- Same element dimensions in the plane of extension of the skin in the panel;

[2] Normalized values in respect to computation time with modeling elements Solid Parabolic (QPNT)
[3] The deviations was assessed against the best geometric discretization (with Solid Parabolic elements - QPNT)

Table 1: Comparison between the discretization solutions considered in the FE study (QPNT is Quarter-Point Node Technique).

In order to reproduce in the FE the results of the experimental tests, different models were considered, each of which differed in the type of skin-reinforcement coupling. The main differences are due to the modeling of the adhesive properties and to the reproduction of reinforcements rupture (see Tab.2 and Fig. 4).
The Mode I, II and III stress intensity factors are calculated using the contour integral method and they showed a limited variability with the distance of the contour from the crack tip. The KII and KIII parameters assume always values close to zero, therefore the crack propagation is Mode I-dominated. For each size of the defect an average value of the K factor was calculated across the thickness (see Fig. 5).

Model ID	Characteristics				
	Skin	Doublers	Stringers	Adhesive	Stiffeners
1	*Al-Alloy 2024-T3*	*Al-Alloy 2024-T3*	*Al-Alloy 7075-T73511*	-	*Unbroken*
2	*Al-Alloy 2024-T3*	*Al-Alloy 2024-T3*	*Al-Alloy 7075-T73511*	*FM73M0.3*	*Unbroken*
3	*Al-Alloy 2024-T3*	*Al-Alloy 2024-T3*	*Al-Alloy 7075-T73511*	*FM73M0.3*	*Adhesive debonding*
4	*Al-Alloy 2024-T3*	*Al-Alloy 2024-T3*	*Al-Alloy 7075-T73511*	*FM73M0.3*	*Adhesive Debonding + Doublers rupture*
4-NB*	*Al-Alloy 2024-T3*	*Al-Alloy 2024-T3*	*Al-Alloy 7075-T73511*	*FM73M0.3*	*Adhesive Debonding + Doublers rupture*
* Model with the same characteristics of the Model 4, but with the implementation of a No-Bending device with a contact analysis between the skin and a transversal toolbar					

Table 2: FE models developed in this work.

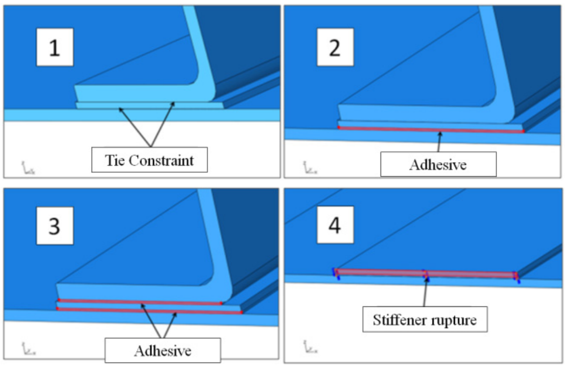

Figure 4: Representation of the different skin-stiffener couplings simulated.

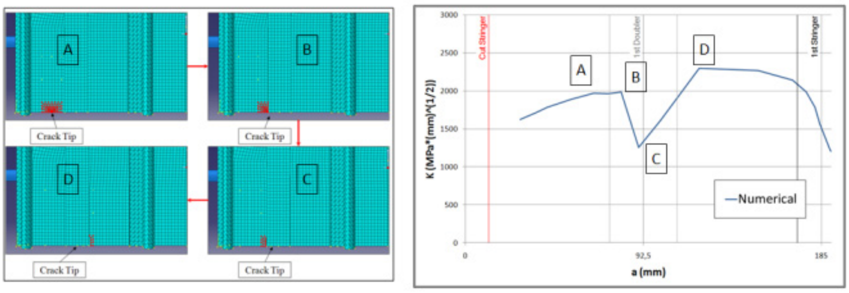

Figure 5: K value in 4 different positions of the crack tip across a doubler and a stiffener.

Geometrically linear analyses were performed to find, for each crack length analyzed, the value of K corresponding to the maximum load of the test. The stress intensity factor range ΔK was then calculated according to the load ratio used in the experiments. To assess the number of cycles to attain a given crack length, the following procedure was considered:

- in the range of interest, the propagation law of the skin material, da/dN-ΔK was approximated with a straight line in a bi-logarithmic plane (Paris model) by the ordinary least squares; the experimental data were taken from AFGROW database [8].
- in the FE model, the K factor calculation was done in steps, that is a model for each specific crack length was made (see Fig. 5). Since the crack growth rate varies significantly near the reinforcements, most of the models were concentrated in those areas;
- the number of cycles was obtained by a numerical integration with a trapezoidal rule:

$$N_{i,i+1} = \frac{1}{2}\left(\frac{1}{C\Delta K_i^{\,m}} + \frac{1}{C\Delta K_{i+1}^{\,m}}\right) a_{i,i+1} \tag{1}$$

were i and i+1 are the limits of a single increment.

After a preliminary comparison between numerical and experimental propagation, the presence of an anti-bending device was reproduced (Fig. 5).

Other details considered after preliminary studies are the effective load ratio at the crack tip, that changes during the crack propagation, and the effect of considering a geometric nonlinearity in the analysis of reinforced panels.

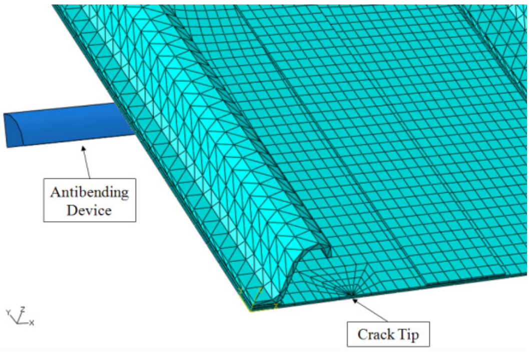

Figure 6: Representation of the anti-bending device developed in the FE modeling of panel 4-NB (No Bending)

RESULTS AND DISCUSSION

At first, the influence of the presence of the adhesive between skin and stiffeners was assessed (Model 02 vs. Model 01). Where adhesive was introduced, the final crack length is reached in a lower number of cycles (see Fig. 7). In Model 03, the separation of the adhesive under the first doubler was modeled and an increase of crack growth rate in the first bay is observed. In the panels 4 and 4-NB, the increase of K factors after the crack runs beyond the first stiffener is caused by the (simulated) rupture of the first doubler (see Fig. 8).

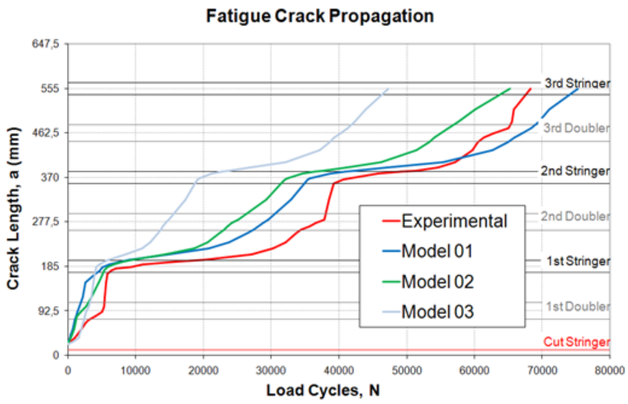

Figure 7: Comparison between experimental and numerical FCP curves (Models 1, 2 and 3).

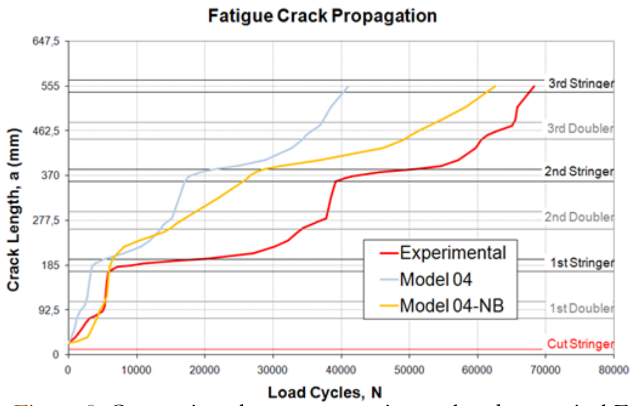

Figure 8: Comparison between experimental and numerical FCP curves (models 4 and 4-NB).

The Model 01 showed the most faithful reproduction of the crack propagation. The absence of the adhesive in the simulation brings in a higher rigidity near the reinforcements that apparently reproduces the stresses in the skin better than the other models. The inclusion of the anti-bending device in the model 04-NB until the second reinforcement leads at a more faithful reproduction of the initial stage of crack propagation.

CONCLUSIONS

In this study, the influence of several parameters that affect the crack propagation rate was evaluated and the focus was aimed at obtaining results comparable with experiments. The effect of type of skin-stiffener coupling has been simulated, with particular interest on the assessment of the presence of the adhesive and the possible debonding. The possibility of first doubler breakage was also considered. Finally, by introducing an anti-bending device, a good correspondence in the first phase of propagation was obtained, differently from the other models simulated.

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