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OPTIMISATION OF WING-FUSELAGE ATTACHMENT LUG

OPTIMIZACIJA UŠKE ZA VEZU KRILO-TRUP

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- lug
- extended finite element method (XFEM)
- wing spar
- fatigue life

Ključne reči
- uška
- proširena metoda konačnih elemenata (XFEM)
- ramenjača
- zamorni vek

Abstract

Geometry of the wing-fuselage attachment lug was optimised using the fatigue life as the criterion geometry (thickness, hole radius, crack location). Numerical simulation of fatigue crack growth by XFEM was used to obtain fatigue life for different geometry parameters. The wing structure of the light aircraft was analysed first, and it was shown that it satisfies strength requirements according to standard CS23. Experimental verification of analytical/numerical results was carried out on the full-scale wing, and it was shown that differences between deformations are at a satisfactory low level.

Izvod

Geometrija uške za vezu krilo-trup aviona je optimizovana primenom zamornog loma kao kriterijuma, u pogledu debljine, prečnika otvora i lokacije prsline. Numerička simulacija primenom XFEM je upotrebljena kako bi se odredio zamorni vek za različite geometrijske parametre. Prvo je analizirana konstrukcija krila lake letelice, kako bi se pokazalo da zadovoljava zahteve otpornosti prema standardu CS23. Eksperimentalna verifikacija analitičkih/numeričkih rezultata je urađena na modelu krila u prirodnoj veličini, i potvrdila je da su razlike u deformacijama na prihvatljivo malom nivou.

INTRODUCTION

The wing spar is connected to the supporting elements of the aircraft fuselage through specially designed elements-aircraft fittings. All loads from the wing are transmitted to the main frame and through the wing-fuselage fitting. Design of this fitting is of utmost importance: its fatigue damage could lead to a separation of wing from fuselage with catastrophic consequences. In a few recent cases, as in November 2019, fatigue cracks were discovered on the wing-fuselage fitting for two Boeing 737NG aircraft accidentally discovered before their regular inspection, /1/. After that, over 50 aircraft of this type were landed around the world to determine the condition of their wing-fuselage fitting (Ryanair discovered 3 cracked wing-fuselage fittings in its fleet), /2/. The institutions of international aviation authorities in charge of aircraft safety are now widely considering the introduction of mandatory fatigue tests for damaged fittings to estimate their remaining fatigue life.

By redesigning the wing-fuselage attachment, it is possible to extend the life even in the event of damage, but this will not change the long-adopted approach (safe-life) in their design /3, 4/. The intention is to increase the aircraft's safety and guarantee it even in the event of unforeseen damage (fail-safe approach), leading to the question about the crack size that will not lead to its failure.

The answer to this question can be given most precisely by experiments that are often time-consuming and expensive. As a suitable alternative to the experimental verification of a newly designed (or modified) fitting, numerical modelling is imposed. Over the years, many numerical techniques, such as finite element method (FEM) /5, 6/, boundary element method (BEM), meshless process, and extended finite element method (XFEM), have been used to simulate fracture mechanics problems, including fatigue crack growth /7-15/.

By using XFEM, a conformal mesh is not required, which makes modelling of variable discontinuities or crack growth significantly simplified. On the other hand, by applying the Unstructured Mesh Method (UMM), FEM has been improved by enabling alteration of the finite element mesh only in the immediate vicinity of the crack which considerably simplifies the modelling of crack propagation with this method as well.

FEM OPTIMISATION

In this section we focus on the optimisation of the attachment lug's geometry. To be more specific, the effect of crucial geometrical parameters on crack growth rate is analysed /16-18/. Also, an improved geometry that is more fatigue resistant will be suggested. It has to be noted that one of the easiest ways to extend the fatigue life is the selection of the material, in this case steel that is more fatigue resistant /19/. But the wing-fuselage attachment assembly made of this kind of steel would significantly increase the costs of the design and production of the aircraft. So, it was decided that the material of the attachment lug should remain the same, while its geometry will be redesigned.

The initial geometry dimensions of the attachment lug, needed for the optimisation are given in /11/. The new finite element mesh was generated (Fig. 1), with average element mesh size of 1.7 mm. This average element mesh size will be used throughout the optimisation to avoid the influence of the mesh density on the optimisation results (number of cycles to catastrophic failure). All other input parameters (boundary conditions, load value, and material) are identical to those used in /10/. The SIF values after the first crack propagation step are shown in Fig. 2, where it can be seen that K_{Imax} = 1880.0 MPa√mm, and also that most of the K_{I} values along the crack front are between 1850 and 1880.0 MPa√mm. However, mentioned maximal value of K_{Imax} will be used afterwards as the main optimisation criterion, i.e., the goal is to achieve that the K_{Imax} after the first propagation step shall be reduced under the prescribed value (K_{Imax} < 1400 MPa√mm), if possible.

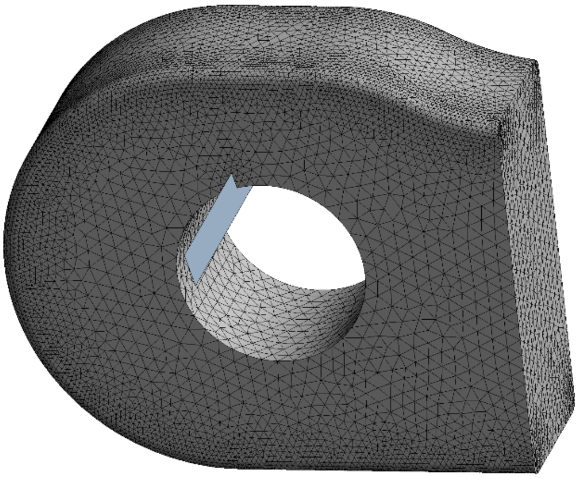

Figure 1. Finite element mesh used in the optimisation.

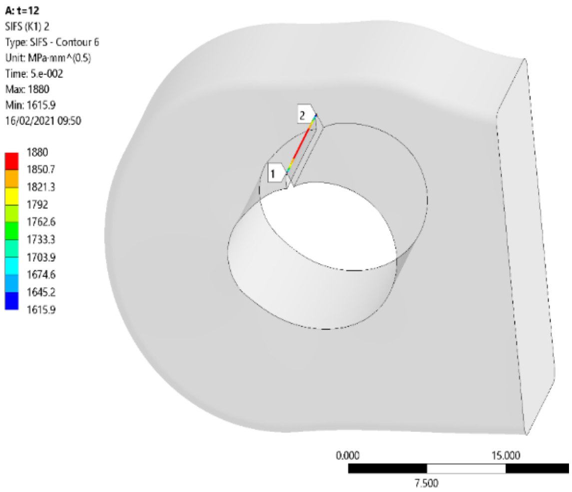

Figure 2. SIF values along crack front after 1st step of propagation (original lug).

The SIF values just before the fracture of the attachment lug are shown in Fig. 3, where it can be seen that the crack has grown for an additional 7.37 mm, regarding its initial size (1 mm). In Fig. 4, the diagram of crack growth as a function of the number of cycles is presented. The maximum number of cycles $N_{\max}$ = 515 (calculated for R = -1, as before) is slightly higher than obtained in /10/. The reason for this is that with every new calculation, the software generates a new finite element mesh around the crack front, so some result discrepancies will always be present. In any case, the results obtained here will be used for comparison with values to be obtained after the geometry optimisation of the attachment lug. The initial mass of the attachment lug is 87 grams.

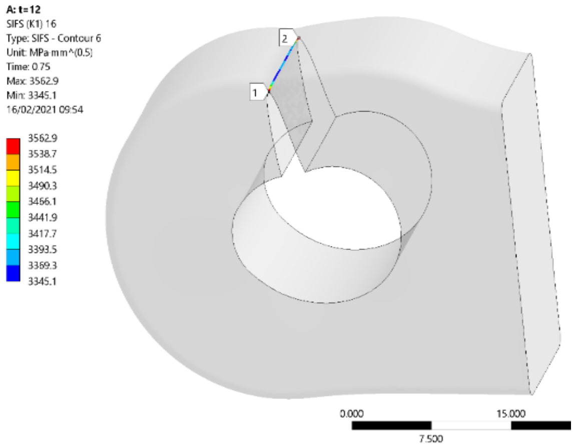

Figure 3. SIF values after the 15th step of propagation (total crack extension 7.37 mm).

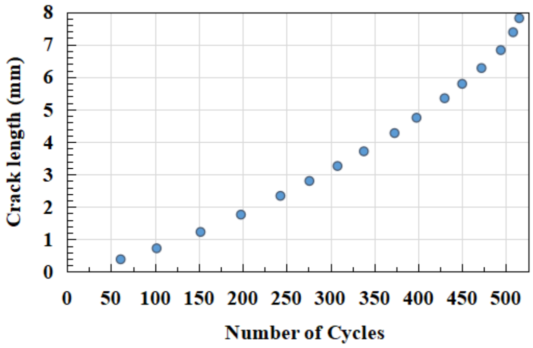

Figure 4. Crack length vs. number of cycles for original lug ($N_{\max}$ = 515).

Increased thickness was modelled as the first step in optimisation. The number of cycles for lug of thickness 17 mm was increased to $N_{\max}$ = 1085, i.e., almost double in respect to the original thickness (12 mm). This model and results are shown in Figs. 5-9, including values of maximal SIFs after crack opening for different thicknesses.

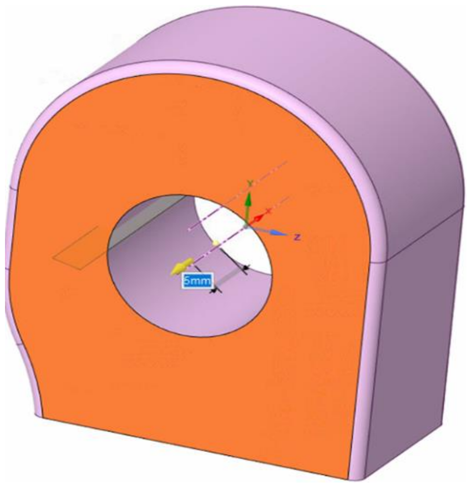

Figure 5. Model number 1: original lug with increased thickness.

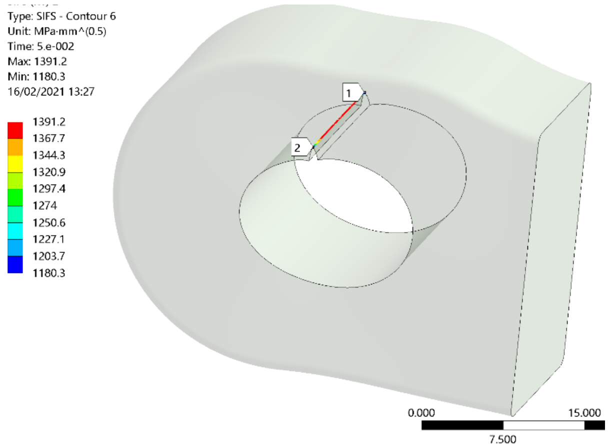

Fig. 6. (SIF) values along crack front after 1st step

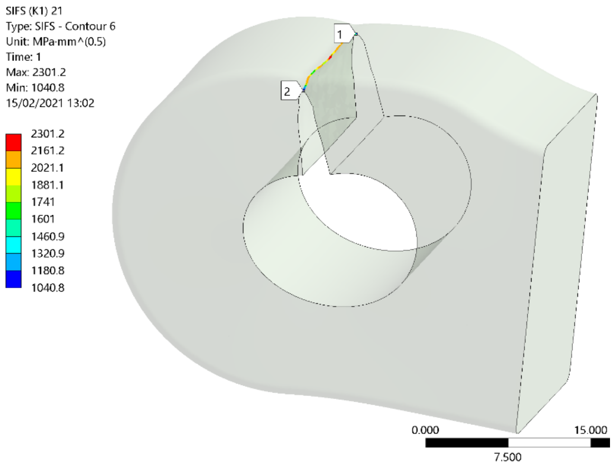

Figure 7. SIF values after 20th step of propagation (total crack extension 6.84 mm).

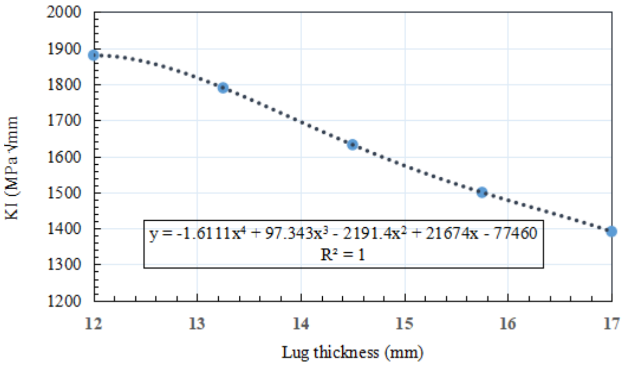

Figure 8. Maximal K_I after crack opening vs. lug thickness.

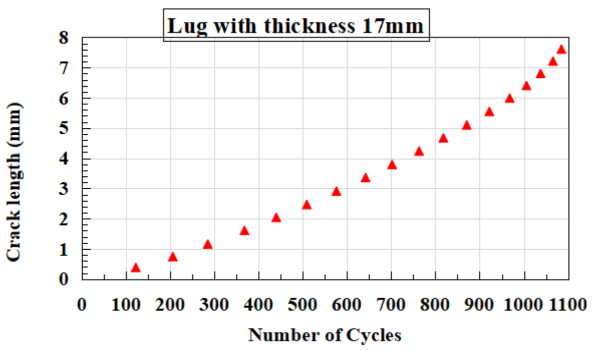

Figure 9. Crack length vs. number of cycles for lug with thickness 17 mm (N_{max} = 1085).

As expected, increasing the thickness of the lug lead to a decrease in stress intensity factors, from 1880 MPa√mm (original 12 mm thickness) to 1390 MPa√m for 17 mm thickness. In addition to a 26 % decrease in SIFs, the total number of cycles more than doubled, going from 515 to 1085. Thus, it can be seen that the first step in the model optimisation was confirmed as successful. The next step involved the optimisation of additional parameters, as will be further shown.

Model number 2: in two-parameter optimisation of lug, the thickness and radius are varied, Figs. 10-16. The most favourable crack length vs number of cycles result is obtained for a lug of thickness t = 17 mm and radius r = 19 mm (N_{max} = 1933). Although the SIFs were higher in this case compared to the one-parameter optimisation model, total crack length also increased noticeably, to 10.89 mm, and the aforementioned number of cycles was almost two times greater than the one obtained in the previous case. This parameter combination also had the best compromise between mass and SIFs, as can be seen in Fig. 11.

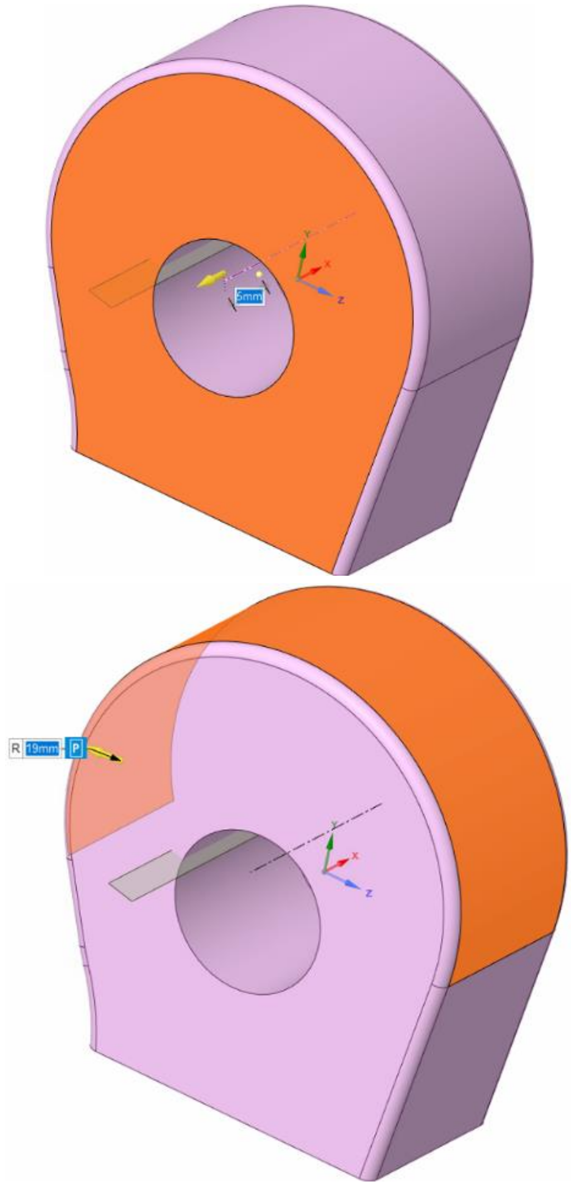

Figure 10. Two-parameter optimisation of the lug model (thickness and radius).

Table of Outline A2: Design Points of Design of Experiments

	A	B	C	D	E
1	Name	P3 - radius (mm)	P5 - thickness (mm)	P4 - SIFS (K1) Maximum (MPa mm^0.5)	P6 - SYS-3\PartBody Mass (kg)
2	1	14.5	0	2119.8	0.078385
3	2	10	0	2844.3	0.058793
4	3	19	0	1785.7	0.10789
5	4	14.5	-5	3648.5	0.045599
6	5	14.5	5	1479.5	0.11117
7	6	10	-5	4947.2	0.034186
8	7	19	-5	3059.4	0.06279
9	8	10	5	1989.4	0.083401
10	9 DP 2	19	5	1250	0.15299

Figure 11. Maximal K_I (column D) and lug mass (column E) after crack opening.

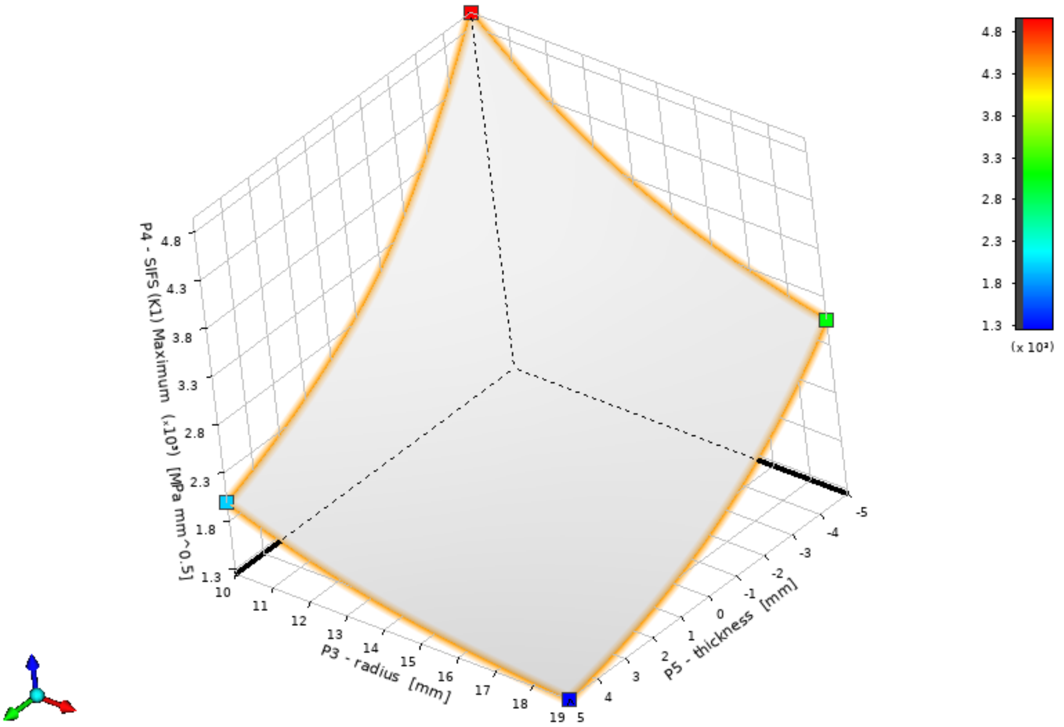

Figure 12. Response surface for different thickness and radii of lug.

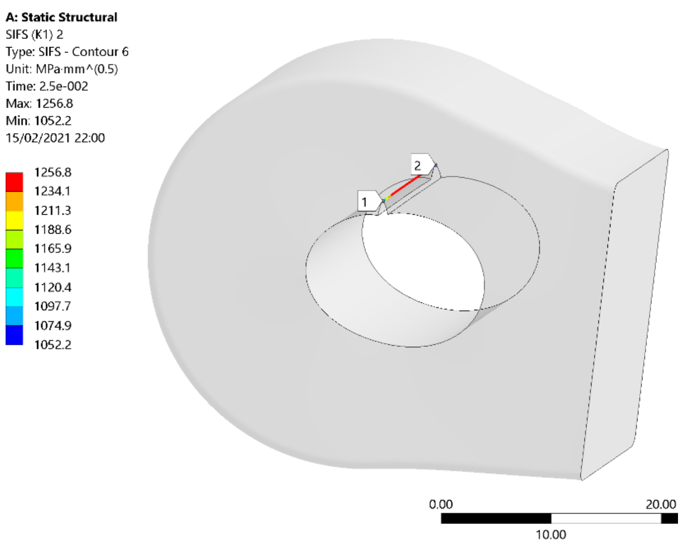

Figure 13. SIF values along crack front after 1st step.

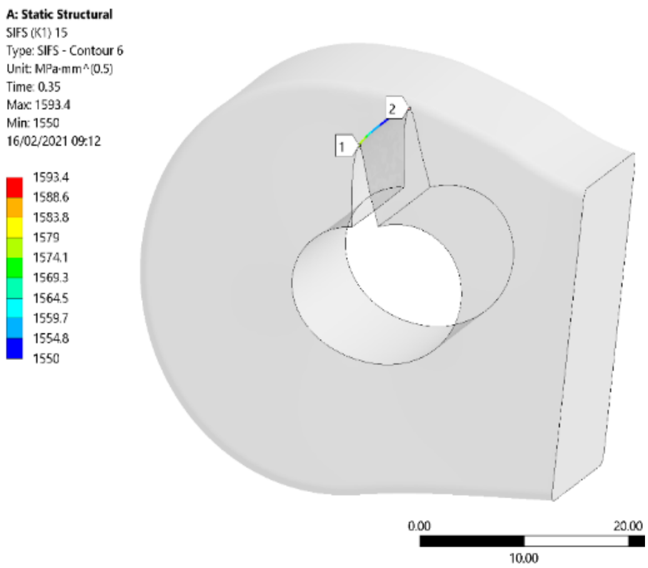

Figure 14. SIF values after 14th step (total crack ext. 6.75 mm).

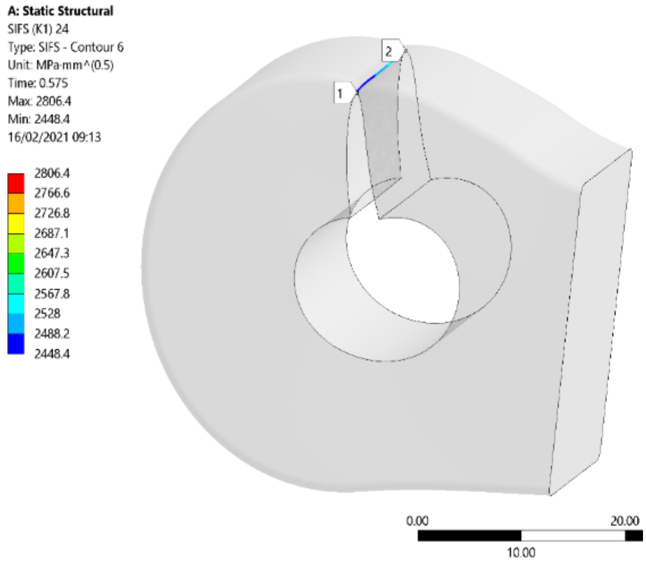

Figure 15. SIF values after 23rd step (total crack 10.89 mm).

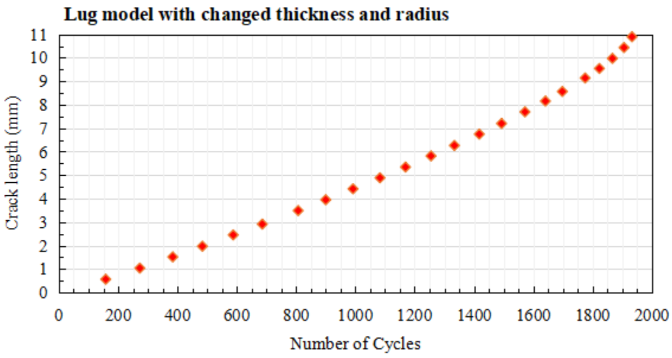

Figure 16. Crack length vs. number of cycles for lug with t = 17 mm and r = 19 mm (N_{max} = 1933).

CONCLUSIONS

Based on SIF values obtained in simulations of the penny shaped corner crack growth it can be concluded that damage propagates rapidly and that it takes a small number of cycles to reach critical depth. The SIFs calculated can provide a wider picture of possible crack paths once damage is initiated and that finite element mesh type might influence results, but not dramatically.

It was shown that XFEM based analyses could be very useful, not only for SIF calculation, but also for three-dimensional crack path predictions in complex geometries.

The last phase of research focused on the optimisation of the attachment lug's geometry with some assumptions that were taken into account. The longest fatigue life was obtained for model 2, where the number of cycles was increased 3.75 times with respect to the initial lug, but with the cost of 75.9 % of mass increase.

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Plenary speaker
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Important dates
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Notification to authors: 30 November 2023
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