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FATIGUE LIFE ANALYSIS OF THE INTEGRAL SKIN-STRINGER PANEL USING XFEM

ANALIZA ZAMORNOG VEKA INTEGRALNOG PANELA SA OJAČANJEM PRIMENOM XFEM

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Keywords
- integral skin-stringer structures
- XFEM
- stress intensity factor (SIF)
- crack propagation modelling

Abstract

Fatigue life of integral skin-stringer panels produced by laser beam welding (LBW) is analysed. This type of panel is used in airframe construction where fatigue and damage tolerance are of paramount importance, since aircrafts must be designed to tolerate relatively large fatigue cracks. The analysed integral skin-stringer panel is made of AL-AA 6156T6/2.8 mm, where stringers are laser beam welded to the airframe skin. By using the extended finite element method (XFEM), fatigue life of simple flat plate, as well of the skin-stringer panel, are numerically simulated in order to investigate the effect of stringers.

Ključne reči
- integralna konstrukcija sa ojačanjima
- XFEM
- faktor intenziteta napona
- modeliranje rasta prsline

Izvod

Zamorni vek integralnog panela sa ojačanjima, proizveden zavarivanjem laserom (LBW), je analiziran u ovom radu. Ovakva vrsta panela se koristi u konstrukcijama letelica kod kojih su otpornost na oštećenja i zamor od ključne važnosti, budući da letelice moraju biti u stanju da izdrže pojavu velikih zamornih prslina. Integralni panel sa ojačanjima je izrađen od AL-AA 6156T6/2.8 mm, pri čemu su ojačanja laserski zavarena za ram. Primenom proširene metode konačnih elemenata (XFEM) numerički je simuliran zamorni vek jednostavne ravne ploče, kao i ojačanog panela, kako bi se ispitao uticaj ojačanja.

INTRODUCTION

Fatigue crack initiation and growth as well as fracture resistance and corrosion issues associated with riveted structures are well understood and it seems difficult to get significant improvements in riveting technology regarding the extension of the fuselage fatigue life. However, the development of welding technology and the integral skin-stringer structures have reduced riveted joint applications, /1/. Integral skin-stringer structures (Fig. 1), which make skin and stringers as a continuum, are more suitable for improvements even though they might be poor at damage tolerance performance. Compared to conventional riveted structures, integral skin-stringer structures have many advantages, such as lower weight and lower cost to manufacture. It is worthy of note that fewer components mean they are easier to inspect and, at the same time, integral structures have less holes with high stresses suitable for crack initiation. Aluminium alloys are major materials for light-weight constructions due to their good mechanical properties and low density, and their recent developments have led to the use of advanced welding technologies to reduce weight and fabrication costs, /2-5/. Laser beam welding (LBW) has been successfully applied for manufacturing skin-stringer curved panels for various civilian aircraft in Europe. Friction stir welding (FSW) is also considered as a prospective welding process for butt-joint applications in fuselage and wing structures, /6-7/. Optimisation of welding processes and joint design are prerequisite to achieve damage tolerance properties equal to- or even better than riveted structures.

Figure 1. Integral skin-stringer structure of the fuselage.

Despite manufacturing precautions, cracks may appear in the integral skin-stringer structure and reduce its stiffness, load-carrying capacity and fatigue life. Two types of damages most frequently associated with the structural integrity of a fuselage are the longitudinal cracks under hoop stresses (induced by cabin pressurization) and circumferential cracks under stresses from vertical bending of the fuselage, /8/. A critical element of damage tolerant design in pressurized fuselage is the ability to predict the growth rate of fatigue cracks under applied loading.

The crack growth stage is studied by using the stress intensity factor (SIF). SIF is a fundamental quantity that governs the stress field near the crack tip. It depends on the geometrical configuration, crack size, and loading conditions of the body. There are many methods used in numerical fracture mechanics for SIF calculation. FEM has been used for decades for calculating SIFs, but it has some restrictions in crack propagation simulations, mainly because the finite element mesh needs to be updated after each propagation step in order to track the crack path. Extended finite element method (XFEM) suppresses the need to mesh and remesh the crack surfaces and is used for modelling different discontinuities in 1D, 2D and 3D domains. XFEM allows for discontinuities to be represented independently of the FE mesh by exploiting the Partition of Unity Finite Element Method (PUFEM), /9/. In this method, additional functions (commonly referred to as enrichment functions) can be added to the displacement approximation as long as the partition of unity is satisfied. XFEM uses these enrichment functions as a tool to represent a non-smooth behaviour of field variables. There are many enrichment functions for a variety of problems in areas including cracks, dislocations, grain boundaries and phase interfaces. Recently, XFEM and its coupling with level set method are intensively studied. The level set method allows for treatment of internal boundaries and interfaces without any explicit treatment of interface geometry.

NUMERICAL SIMULATIONS USING XFEM

The main idea of numerical modelling was, firstly, to test XFEM by making FE model of base metal plate with initial crack, as shown in Fig. 2a, simulating the real loads from experiment, and consequently comparing the number of cycles obtained numerically to the number of cycles obtained experimentally. Base metal plate is chosen as it had simple geometry, and because the calculated values of SIF could be verified using other methods, or can be even found in the literature. The second step was FE modelling of 4-stringer panel (Fig. 2b) and determination of the number of load cycles that would grow crack to critical length that will then be compared to number of cycles obtained in experiment with real 4-stringer structure. In both simulations the aluminium alloy AA6156 T6 is used (Young's modulus $E = 71000$ MPa, Poisson's ratio $\nu = 0.33$), and the FE models of base plate and 4-stringer plate are shown in Fig. 2. The loads used in simulations equal to the average values of maximum tensile forces over time measured in experiments, /6/. For base metal plate, the average maximum force is $F_{max} = 112.954$ kN, while the load ratio $R = 0.146$ is determined on the basis of average minimum tensile force measured. Coefficients for Paris equations are adopted on the basis of the values obtained in tests with base metal plates: $m = 3.174$ and $C = 1.77195^{-12}$ MPa·mm$^{1/2}$.

a)

b)

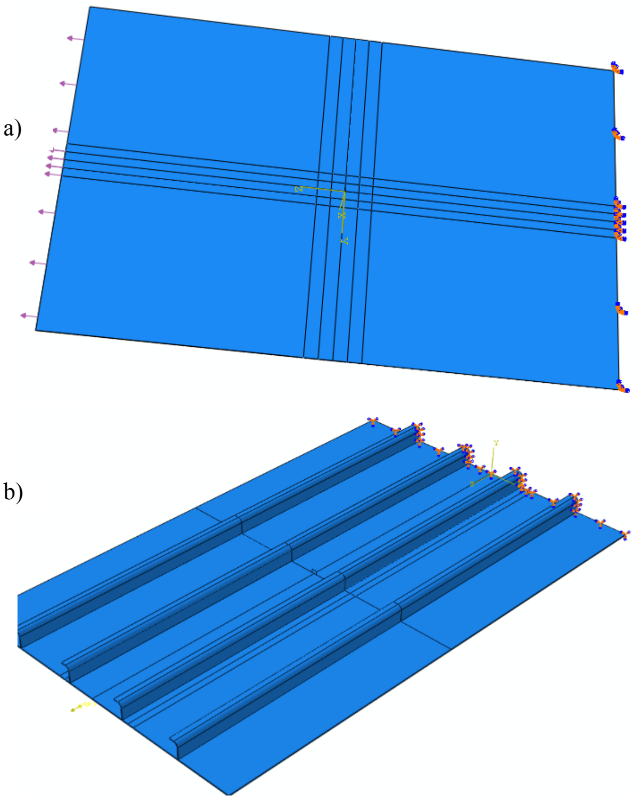

Figure 2. FE model of base metal plate with initial crack, a) simple panel, base metal, b) integral 4-stringer panel.

Initial crack in the first simulation propagated to length $2a = 275$ mm, and Fig. 3 shows its shape after the last growth step. As it can be seen in Fig. 4, the number of cycles predicted by Paris equation incorporated into Morfeo/Crack for Abaqus software is comparable to the number of cycles obtained in one of the experiments with base metal plate (different values of number of cycles are obtained in series of experiments; however, the deviation is not above 15%).

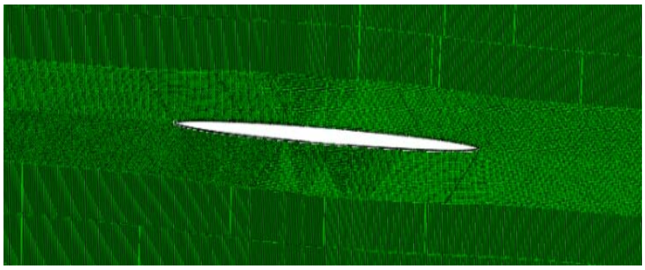

Figure 3. Crack in base metal plate after 260 steps of propagation ($2a = 275$ mm).

Figure 4 shows that in the XFEM simulation, the number of cycles to critical crack length is less than that obtained in experiment (169 076 cycles versus 189 514 cycles, which is a difference of about 10%); however, under crack length $2a = 60$ mm (almost linear growth) the numbers of cycles differ insignificantly. This confirms the previously drawn conclusion, /10/, that in case of simple geometry, XFEM is a fairly reliable method for crack growth rate determination, as it provides more conservative values compared to the experimental ones.

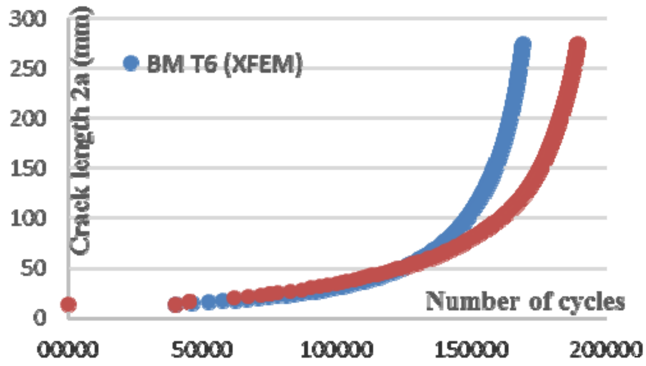

Figure 4. Numbers of cycles obtained in experiment and XFEM simulation (base metal T6).

After successful numerical simulation of crack growth on base metal plate, a more complex geometry of the 4-stringer plate is analysed (Fig. 2a). The central crack of length a_0 = 14 mm is initiated and the load identical to that used for the base metal plate is applied. The crack propagated for a total of 173 steps (in each step the crack length increased by 2 mm). During the 160-th step, complete failure of the left stringer occurred (Fig. 5), after which the crack continued to spread along the right stringer and through the base metal plate. Simulation of crack growth stopped after 173 steps because the number of load cycles necessary to propagate the crack by one millimetre dropped under 100, which is a sign that the crack started to propagate rapidly and that the 4-stringer plate is under complete failure.

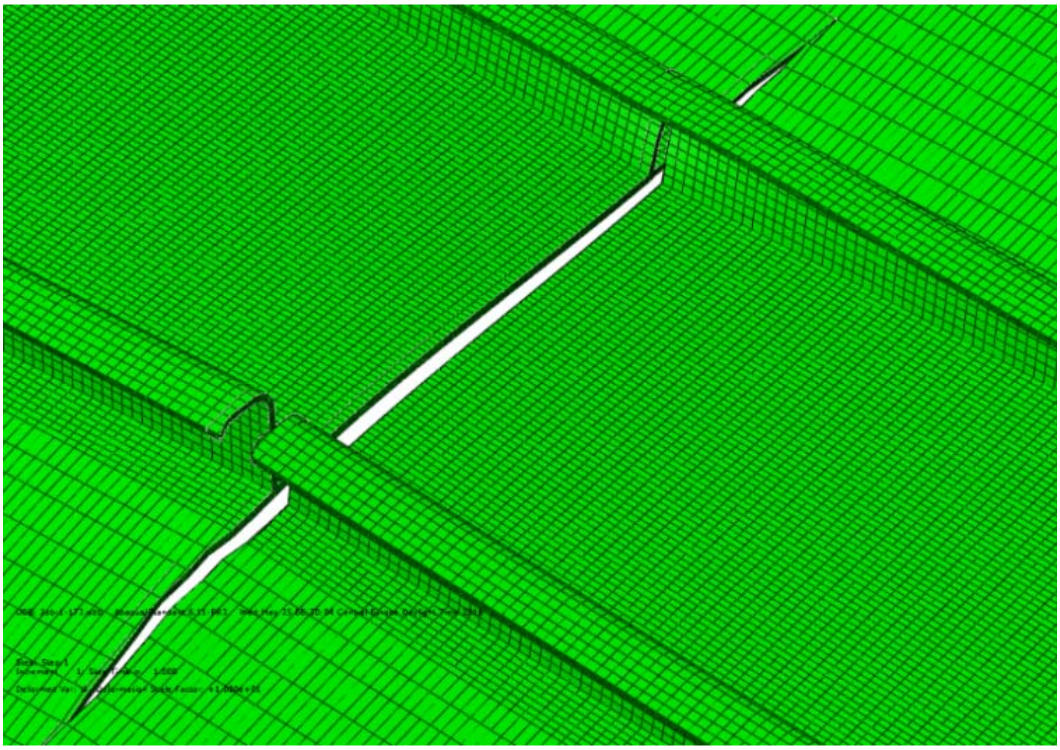

Figure 5. Crack after 160 steps of propagation.

Finally, the crack length vs. number of cycles is shown in Fig. 6, as obtained in simulation with 4-stringer plate and compared to experimental results, in the same way as in the case of the base metal panel, Fig. 4.

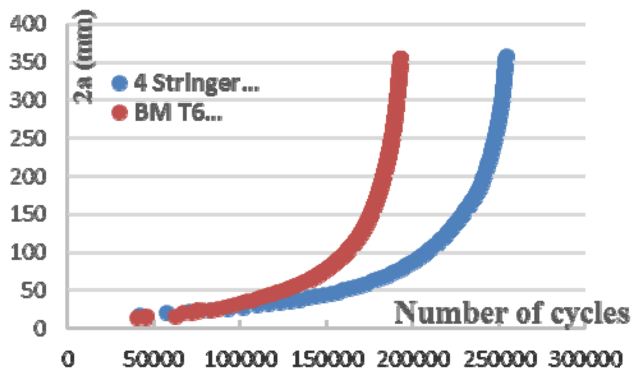

Figure 6. Number of cycles for base metal plate obtained in the experiment and 4-stringer plate obtained in simulation by XFEM.

DISCUSSION AND CONCLUSIONS

The estimation of fatigue life of integral aircraft structures, being the subject of this paper, is also very important although the possibility of crack occurrence in the integral structure is lower than in the case of a differential structure. XFEM can play a significant role in this subject and may reduce to a minimum the number of experimental verifications and so fulfil one of the requirements mentioned at the beginning of this paper: cost-efficient design. The results of numerical simulations based on XFEM presented in this paper are quite well correlated with experimental values, which is particularly true for the simulation of crack propagation in a 4-stringer plate.

There are, of course, some differences due to the fact that the initial length of the crack in experiment is $2a_0 =$ 75 mm whereas in simulation $2a_0 =$ 14 mm, because the intention was to compare the 4-stringer plate with the base metal plate whose initial crack length was $2a_0 =$ 14 mm; as a result, the graph presented in Fig. 6 is created. Figure 6 shows that the 4-stringer plate with given stringer dimensions and for given tension force has a fatigue life approximately 30% longer than the base metal plate (254 274 cycles vs. 194 453 cycles), estimated on the basis of the Paris law (unfortunately, the information on the number of cycles obtained in experiment with the 4-stringer plate is not available). There are other equations that can be used to estimate fatigue life under given conditions (NASGRO equation, for instance) and they might give another number of cycles, but not so different from the one presented here. If aircraft designers consider the improvement by 30% as not satisfactory, the redesign of a 4-stringer panel and consequent tests on new panels would take much time and money. However, using XFEM estimation of the total fatigue life of a new structure is relatively easier to obtain and inexpensive, not only for loads used in experiments but for the whole spectrum of loads that might appear during the intended life of the structure. So, this is the major competitive advantage of XFEM.

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