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# Fatigue life assessment of the structure with widespread damage exposed to high temperature

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## Abstract

The exhaust nozzle represents a part of a jet engine which is crucial to its overall performance, since it accelerates the flow of hot gases out of the engine and creates a thrust. During its long service, it is exposed to elevated temperatures and high compressive and hoop stresses, which makes the cracks' occurrence in the exhaust nozzle's inner sleeve almost unavoidable. The aim of this paper is to analyze and numerically estimate the fatigue life of inner sleeve in the presence of widespread damage. When damage is detected, two repair methods are employed: welding of single cracks (manual TIG welding) and the use of welded patches. Using numerical simulations based on extended finite element method (XFEM) and finite element method (FEM), fatigue life of repaired inner sleeves were estimated. Based on the comparison of the results obtained in simulations, it was shown that the repair method with welded patches provides longer fatigue life of widespread damaged nozzle than the other with welding of cracks.

*Keywords:* Crack propagation; Thermal loading; XFEM, FEM

## 1. Introduction

It is well known that widespread fatigue cracks represent one of the greatest threats to the structural integrity of the aging aircraft. This type of damage occurs due to the long term cyclic loadings. These cyclic loadings are in the most cases the mechanical ones. However, there are some parts of the aircraft, like jet engine parts, that are exposed to high

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operating temperatures. Those parts are subjected to thermal cyclic loading as well, due to the extreme temperature changes over the cycle which produce thermal stresses. Fatigue cracks propagation under this type of loading is obviously very complex which makes the assessment of fatigue life much more difficult.

It has to be mentioned that fatigue cracks propagation under combined thermo-mechanical cyclic loading is not exclusive to aircraft industry. It causes severe degradation of parts in automotive industry, (Ktari et al. (2011)), turbine blades, (Abdul-Aziz (2002)), and railway disc brakes, (Kim et al. (2008)). It is also listed as one of the major degradation mechanisms in the nuclear industry (Wang et al. (2019)).

It is obvious that this phenomenon has been under intensive investigations over many years.

The researchers were mostly focused on experimental analyses. As technology and computer sciences became more available, numerical analyses, like finite element analysis (FEA) started to be used for the fatigue life estimations of the structures exposed to high temperatures. Still, there is a lack of available literature of this kind. FEA was firstly applied on the two-dimensional models, (Kaguchi et al. (1998)) and (Abdul-Aziz (2002)), and later on, on the three-dimensional models, (Ktari et al. (2011) and (Le and Gardin (2011)). It has to be noted that in all mentioned studies experiments were carried out as well, and analysed finite element models had simple geometry with only one crack. However, even the most recent studies use only experimental analysis, like Lansinger et al. (2007) or Gourdin et al. (2018). Previously mentioned Wang et al. (2019) used FEA just for determining more realistic loading conditions to be applied in the experiments.

Although FEA has been used in fracture mechanics for decades, 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, proposed by Babuska and Melenk (1998) and improved by Jovicic et al (2010). So, because of its advantages researchers tried to apply XFEM for modelling thermo-mechanical problems involving cracks. One of the first attempts was made by Pathak et al. (2015), who developed its own XFEM code to simulate fatigue crack growth of three-dimensional linear elastic single crack under cyclic thermal load. Habib et al. (2018) also used XFEM to develop a custom made code for modelling two-dimensional thermo-mechanical problem involving multiple cracks.

However, when in-service parts are concerned, fast and reliable fatigue life assessment is need. This represents challenging task, since these parts are usually of complex geometry. In this paper numerical study of fatigue life assessment of the complex structure with widespread damage exposed to high temperatures has been conducted. To investigate and improve fatigue life of analyzed component in the presence of widespread damage, two repair methods were employed: welding of single cracks (manual TIG welding) and the use of welded patches.

The computations for crack propagation simulations and fatigue life estimations were carried out by XFEM, using Morfeo/Crack for Abaqus code and by FEM using ANSYS WORKBENCH software.

## 2. Problem definition

Complex structure that has been analyzed in this paper is the exhaust nozzle's inner sleeve. As pointed out in the abstract, the exhaust nozzle represents a part of a jet engine which is crucial to its overall performance, since it accelerates the flow of hot gases out of the engine and creates a thrust. During its long service, it is exposed to elevated temperatures and high compressive and hoop stresses, which make the cracks' occurrence in the exhaust nozzle's inner sleeve almost unavoidable (Fig. 1). The enhanced detail in Fig. 1. represents modelled part of the inner sleeve with the damage. In Fig.2. it can be seen that the analysed model consists of inner skin, outer skin, honeycomb (which is of no interest, from the structural point of view) and inner sleeve plate.

The solid skin is made of β-phase titanium alloy Beta21S (improved oxidation resistance, elevated temperature strength). β-phase is metastable, stabilized by V and Mo. Properties of this material can be seen in Table 1. Since operating temperatures are relatively high, oxidation (alpha case) occurs.

The loads were provided from the third party who commissioned the fatigue estimation of analysed component. Due to high operating temperatures thermal transients induce hoop stresses in outer skin of the inner sleeve. Base on this and input data taken from original equipment manufacturer's (OEM's) documentation (approved data) stresses in solid skin were computed (Fig. 3).

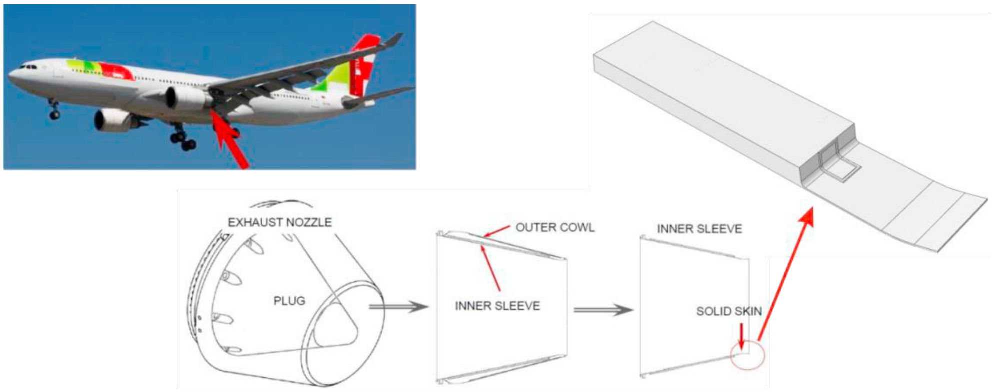
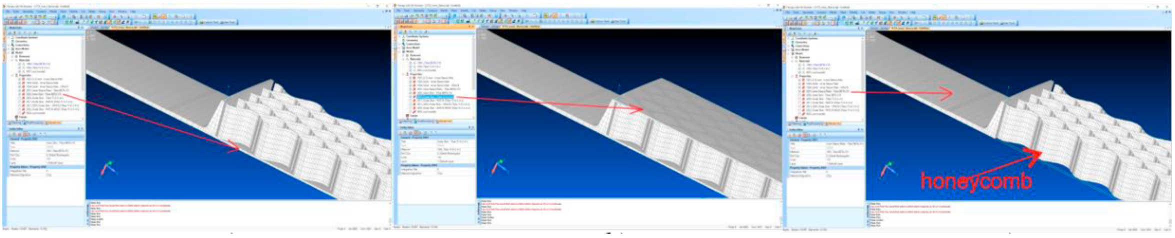
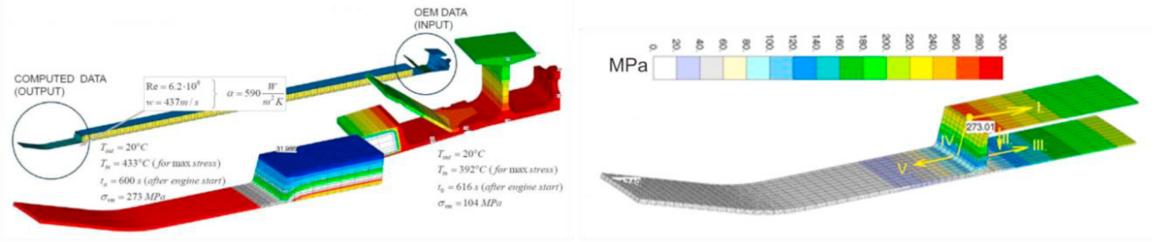


Fig. 1. The exhaust nozzle’s inner sleeve.



a) b) c)

Fig. 2. Inner sleeve subpart: (a) Inner skin; (b) Outer skin; (c) Inner sleeve plate.



a) b)

Fig. 3. (a) Temperature distribution; (b) stress distribution

Table 1. Titanium alloy Beta21S properties.

| Heat treatment | Tensile yield Strength [MPa] | Ultimate tensile Strength [MPa] | Elongation [%] | Test medium | Fracture toughness [MPa√m] |
|---|---|---|---|---|---|
| Beta annealed | 865 | 879 | 15 | Air | 107.5 |
| | | | | | 107.5 |
| | | | | Salt water | 107.5 |
| | | | | | 106.7 |
| Beta annealed +540˚C, 8h | 1220 | 1320 | 6 | Air | 75.4 |
| | | | | | 72.6 |
| | | | | Salt water | 68.5 |
| | | | | | 67.8 |
| Beta annealed +595˚C, 8h | 1040 | 1130 | 7.5 | Air | 100.8 |
| | | | | | 100.8 |

The cracking mechanism is complex, as it can be seen in Fig. 3 (b): the cracks initiates from the edge of the outer skin (point of maximum stress) in flight direction (I). This is due to the tensile stress while the inner skin is under compressive load. When the crack reaches approximately 200 mm, the crack propagates through the honeycomb (II) into the inner perforated skin (III). The cracks up to 400 mm in length were found in outer skin (TSV - Time between Shop Visit, 20,000 eng. hrs, 2,000 cycles) and 50 mm in inner skin. Fourth stage is the crack propagation through the end wall (IV). Finally, the crack reaches the sold skin (V).

## 3. Repairs

When damage was detected, two repair methods were employed. First was welding of single cracks per OEM repair-09, Fig. 4 (b). This implied cleaning and routing out cracks, manual TIG welding, stress relief and fluorescent penetrant inspection (FPI). It has to be mentioned that drilling holes at crack tips did not work in this case, Fig. 4 (a).


a) b)

Fig. 4. (a) Crack propagation; (b) First repair: welding of single cracks

As it can be seen in Fig. 4 (b), this type of repair was not proving to be very efficient, since cracks reappear rather quickly. Hence, new type of repair was proposed: a welded patch. This implied cutting out the whole damaged area and welding patches donated from another but undamaged inner sleeve (Fig. 5). Here also particular care was given to removal of oxides and other contaminants and stress relief.


a) b) c)

Fig. 5. (a) Damaged area; (b) Damaged section cut off; (c) Patch from donation nozzle inserted (before welding).

After a certain time, the damage appeared in this type of repair as well. The cracks initiated from weld (Fig. 6).

a) b)

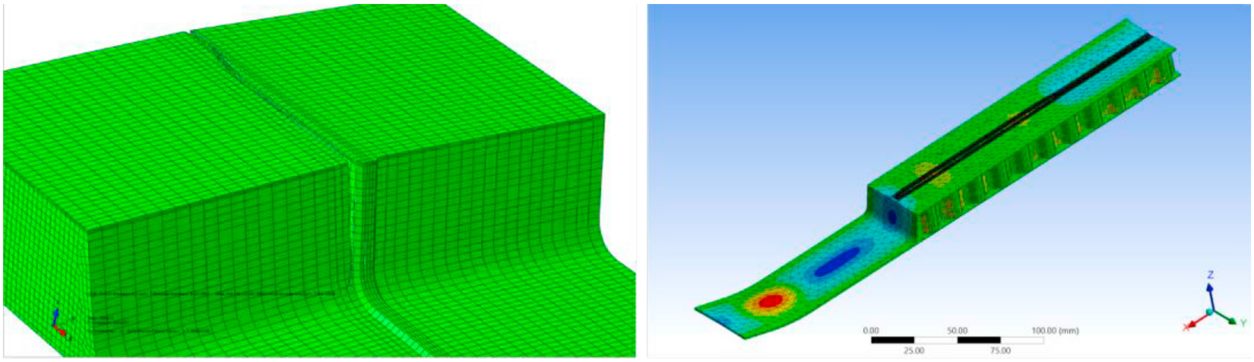
Fig. 6. (a) Crack initiation; (b) Crack propagation from weld into a base material.

## 4. Numerical analysis

In order to determine which type of repair should be conducted, fatigue life estimations for both repairs were needed. In this paper they were obtained by XFEM, using Morfeo/Crack for Abaqus code and by FEM using ANSYS

WORKBENCH software. The XFEM has successfully being used for problems involving multiple, interacting cracks, resulting from multiple site damage (Aldarwish et al. (2017) and (2018)), as well as for simulating crack paths development in more complex models (Sedmak (2018)). The FE model of investigated component made of β-phase titanium alloy Beta21S was created. For mesh generation linear hexahedral element of type C3D8R was used. This is a linear brick 8-node element, with three degrees of freedom at each node. Since Morfeo/Crack for Abaqus code can't simulate crack propagation under thermal loading, corresponding mechanical loading was applied based on the loading data.

The most popular numerical method nowadays is finite element method (FEM). This method has being used for decades for crack involving analyses and it is still being used very successfully (Djurdjevic et al (2015), Grbovic et al, (2019), and (2017) and Kraedegh et al (2017)). But, since this kind of analysis demands models with cracks, crack growth simulation is very demanding since new mesh of whole model is required after every step of crack propagation. Here FEM was implemented thru ANSYS WORKBENCH software, within which simulating fatigue crack growth was carried out by recently introduced **S**eparating **M**orphing and **A**daptive **R**e-meshing **T**echnology (SMART). Although quite new, this improved FEM has been successfully applied in several studies: Aleksić et al. (2019), Kastratović et al. (2020), and Đukić et al. (2020). This feature automatically updates the mesh but only near the crack at each solution step. Since SMART allows crack growth simulation in the presence of thermal loading, input data taken from OEM's documentation was used for loading condition. For mesh generation SOLID 187 finite element was used. This is a high-order 3-D, 10-node tetrahedral element, with three degrees of freedom at each node, i.e. translations in the nodal x, y, and z directions. The same material properties were used as for XFEM analysis. First analyzed model concerns the first repair, i.e. single crack welding, Fig. 7, whereas the second model deals with inserted welded patch, Fig 8.



a) b)

Fig. 7. (a) XFEM analysis; (b) FEM analysis.

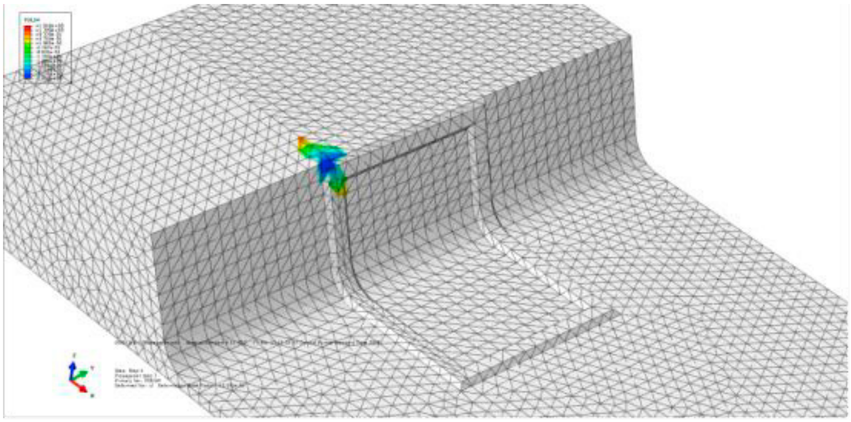


Fig. 8. XFEM analysis

## 5. Discussion and conclusions

The cracking mechanism is very complex since the crack (or multiple cracks) might propagate in 4 directions at the same time, as shown in Fig. 3b. The main goal of this research, simulation of fatigue crack growing through the solid skin with a patch for the purpose of remaining life estimation, was achieved by relatively simple FEM model and by applying XFEM afterwards. Comparison of load cycles to complete failure in the case when crack was welded (standard procedure) with the case when welded patch is applied (proposed alternative procedure) showed that cracks propagate at lower rate when patch is used. For evaluation of residual fatigue life in both cases Paris equation with arbitrary coefficients was used since actual values $C$ and $m$ for used material were not available.

The material of the solid skin (Beta21S) is slightly different from the outer skin, so one material can be used in simulations. Numerical model could be also simplified if the honeycomb part is removed, which looks like acceptable option since cracks' growth in skins is critical. Anyhow, since the component analyzed here comes from long operation (thousands of engine hours), for evaluation of the life to failure of the skin (with or without patch) virgin material properties cannot be used and this must be clearly emphasized. This implies that sample material taken from "donor" engine (with approximately same engine hours) should be examined and Paris coefficients must be determined if fairly accurate prediction is needed. On the other hand, the crack in outer skin can be fixed using other approaches (by making double weld repair, for example): thus, complete model with all parts may be needed, after all.

Finally, one should know that the structural-thermal coupling in ANSYS WORKBENCH is now possible, which enables more precise modelling.

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