Crack Propagation Calculations in Aircraft Engines by Coupled FEM-DBEM Approach

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ABSTRACT. *New generation jet engines are subject to severe reduced fuel consumption requirements. This usually leads to thin components in which damage issues such as thermomechanical fatigue, creep and crack propagation can be quite important. The combination of stresses due to centrifugal loads and thermal stresses usually leads to mixed-mode loading. Consequently, a suitable crack propagation tool must be able to predict mixed-mode crack propagation of arbitrarily curved cracks in three-dimensional space. To tackle this problem a procedure has been developed based on a combined FEM (Finite Element Method) - DBEM (Dual Boundary Element Method) approach. Starting from a three-dimensional FEM mesh for the uncracked structure a subdomain is identified, in which crack initiation and propagation are simulated by DBEM. Such subdomain is extracted from the FEM domain and imported, together with its boundary conditions (calculated by a previous thermal-stress FEM analysis), in a DBEM environment, where a linear elastic crack growth calculation is performed. Once the crack propagation direction is determined a new crack increment can be calculated and for the new crack front the procedure can be repeated until failure. The proposed procedure allows to also consider the spectrum effects and the creep effects: both conditions relieve residual stresses that the crack encounters during its propagation. The procedure has been tested on a gas turbine vane, getting sound results, and can be made fully automatic, thanks to in house made routines needed to facilitate the data exchange between the two adopted codes.*

INTRODUCTION

Turbine blades and vanes used in aircraft engines are typically the most demanding structural applications for high temperature materials due to combination of high operating temperature, corrosive environment, high monotonic and cyclic stresses, long expected component lifetimes, and the enormous consequence of a structural failure. The material of jet engine turbine blades used in today’s airplane applications is subjected to very high temperatures and mechanical loads. The loading conditions vary drastically during starting and landing cycles of the airplane, with operational temperatures reaching up to 1400 K and imposing a thermo-mechanical loading on the material. Extreme temperature gradients and transients thermally induce the most severe cyclic stresses encountered by turbine airfoils. These thermal stresses combine with mechanically induced centrifugal and bending loads to produce thermo mechanical fatigue (TMF) of the airfoil. It is therefore of interest to develop a robust design approach, so that the effects of defects and damages can be evaluated with great accuracy. TMF cracking occurs at many locations on turbine airfoils, including pressure and suction sides and both leading and trailing edges [1].

Commonly large structures are modeled with finite element methods (FEM) because of the many varied types of structural elements. Modeling crack growth with FEM results in a particularly complex remeshing process as the crack propagates. Hence, self-adaptive remeshing is one of the major features that must be incorporated in the construction of a computational tool to properly perform crack propagation analysis with the FE method [2].

The dual boundary element method (DBEM) simplifies the meshing process and correctly characterize the singular stress fields near the crack front [2-3].

One challenge is how the two methods can work together for a large structure.

In this paper a sub-model methodology for TMF crack propagation simulation is presented. This method enables prediction of a crack growth rate and trajectory.

It is important to emphasize the sub-modeling approach that greatly reduces the amount of processed data. This procedure is implemented into FE and BE software through development of user subroutines. The developed crack propagation framework and model predictions can lead to the formulation of damage tolerant failure criteria and possible design optimization. The life prediction and damage tolerant failure criteria of engine components require the consideration of TMF cycles.

The problem of thermal mechanically driven crack growth in the presence of non negligible inelastic strains is a challenging problem.

In order for a sub-model methodology to be useful for predicting thermal-mechanical crack growth in components, it should satisfy the following conditions: 1) predict crack growth rate of a single or multiple cracks, 2) predict fatigue crack growth rates independently of part geometry and 3) be calculable for complex real part geometry. To fulfil such tasks, specific attention is given to sub-modeling of TMF crack propagation in turbine blades to achieve both computational efficiency and accuracy.

The methodology combines CAD modelling, FE and BE analysis, fracture mechanics, creep, meshing, sub-modeling and accurate prediction of crack growth.

A three-dimensional elastic-plastic FE model is developed and a 3D mixed-mode fatigue crack propagation is simulated by DBEM. The effects of temperature gradients distribution, complex model geometry, material properties, initial crack size, location and orientation can be investigated using the proposed procedure.

The value of ΔK, Range of Stress Intensity Factor, is used as the crack driving force to obtain the corresponding da/dN from the basic material fatigue crack growth data of the material, even if the plastic field ahead of the crack tip can significantly limit the applicability of the linear elastic fracture mechanics, especially for small cracks and high temperatures applications.

PROBLEM DESCRIPTION

Introduction

A first stage high pressure Nozzle Guide Vane (NGV) made of a nickel based superalloy (Renè 41), with isotropic mechanical behaviour, is considered. Even if the procedure under development is aimed at aircraft turbine analysis, the CAD model adopted is related to a land based power generation plant NGV [4], but such approximation is not deemed critical because the main objective here is to set up a numerical simulation procedure rather than solving a real case.

Due to a combination of mechanical and thermal cyclic stresses and strains, fatigue cracks can nucleate at the blade leading or trailing edge (Figure 1) and specifically at cooling hole locations, but in this methodological study such holes (Figure 2) are not modelled for sake of simplicity. Such cracks usually show sub-critical growth behavior.

In this study, the critical stress state variables such as temperatures, stress and strain components are obtained by FEM, with allowance for elastic-plastic material behaviour, resulting in an accurate prediction of the stress state due to the thermal and mechanical loadings at the mission point being analyzed. The thermal-mechanical results are then used as input for the following DBEM life analysis.

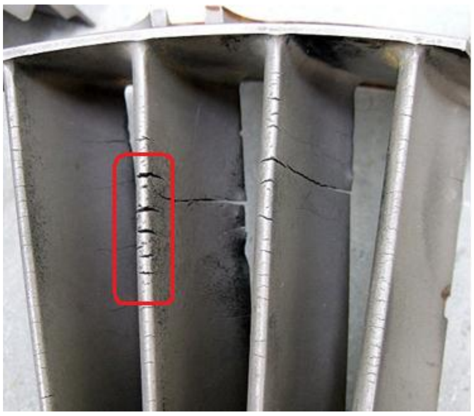


Figure 1. NGV stress rupture cracking. Figure 2. NGV with highlight of cooling holes.

Thermal-stress analysis

The thermal portion of the analysis consist of two steps: the first step is a steady-state analysis in which the blade is brought from an initial ambient temperature to a steady operating temperature distribution (corresponding to the aircraft cruise phase) and than a second step that simulates the cool down (corresponding to an aircraft on the ground). Temperatures from thermal analysis are interpolated through ANSYS onto structural finite element mesh. A nonlinear FEM analysis is performed using temperature-dependent material properties (elastic modulii and coefficients of thermal expansion) as reported in Tables 1-4.

In this study the thermal analysis is based on the direct knowledge of the high pressure NGV surface temperatures (normally the external heat transfer coefficients and film temperatures are provided). When the temperature distribution has been found, the determination of the resulting stress distribution comes from the non linear uncoupled quasi-static theory of thermoelasticity. Temperature-dependent stress/strain curves are used in nonlinear solutions to allow for yielding (Figure 3).

Table 1. Young modulus (MPa) and Poisson ratio against temperature (°K)

	T1	T2	T3	T4	T5	T6	T7
Temperatures	298	366	589	811	922	1033	1144
EX	2.1801E+005	2.14E+005	2.02E+005	1.88E+005	1.79E+005	1.71E+005	1.6E+005
PRXY	0.31	0.31	0.31	0.31	0.31	0.31	0.31

Table 2. Yield stress (MPa) and plastic modulus (MPa) against temperature (K)

	T1	T2	T3	T4	T5	T6
Temperature	294	866	922	1033	1144	1200
Yield Stss	1062	1007	1000	938	552	345
Tang Mod	2594.2	2695.7	2449.3	1527.8	367	213.2

Table 3. Thermal expansion coefficient (K^{-1}) against temperature (K)

	T1	T2	T3	T4	T5	T6	T7	T8
Temperatures	366	589	811	922	1033	1255	1366	2273
ALPX	1.21E-005	1.26E-005	1.35E-005	1.4E-005	1.48E-005	1.58E-005	1.67E-005	1.78E-005

Table 4. Thermal conductivity (W/(mK)) against temperature (K)

	T1	T2	T3	T4	T5	T6
Temperatures	422	589	811	922	1033	1144
KXX	11.5	14.7	18.9	21.1	23.2	25.2

The 3D-20 node tetrahedral thermal solid element Quadratic Solid90 is used for the thermal analysis, with a transition to the Solid186 element type for the subsequent structural analysis, where mechanical boundary conditions are added in terms of elastic reaction pressures p_1, p_2, p_3 (corresponding to resultant forces F_1=410 N, F_2=1205 N and F_3=540 N) and a fluid pressure (Δp=0.26 MPa) is applied on the pressure side, as shown in Fig. 4. The NGV FEM mesh adopted is based on 83000 elements with a localised refinement in the area of crack insertion (Fig. 5).

Numerical fracture mechanics analysis

The DBEM submodel, extracted form the blade trailing edge, after crack insertion, has a mesh with 2192 reduced quadratic elements (the central node is missing). The DBEM submodel is cut from the FEM subvolume with an ideal sphere of radius r=15 mm and a semielliptical crack is introduced, with semiaxis a=0.5 mm and c=0.3 mm (Fig. 6).

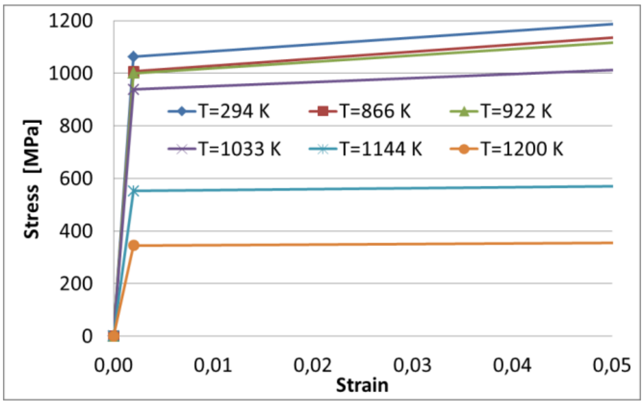


Figure 3. Stress-strain curves vs. temperatures.

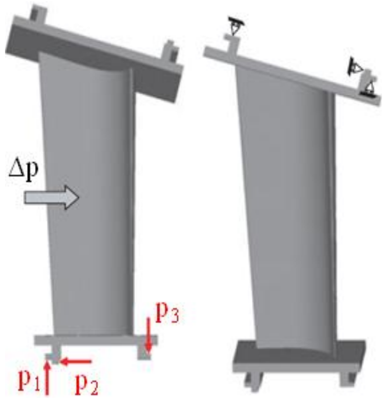


Figure 4. Boundary conditions.

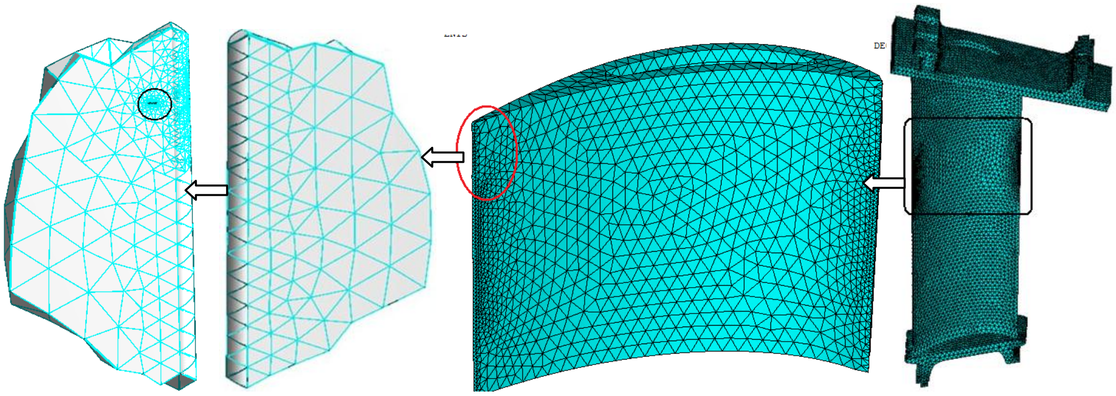


Figure 5. From right to left: overall FEM mesh, FEM sub-volume with refined mesh, DBEM extracted submodel, DBEM mesh refinement after crack insertion.

ANSYS is selected based on availability and compatibility with the crack propagation software BEASY, that in turn was used to investigate airfoil damage using linear elastic fracture mechanics. The J-integral approach is adopted for SIFs assessment [3] and the crack growth rates are calculated with the NASGRO 4 law (Eq. 1), calibrated with reference to Renè41 at a temperature of 649 C (the code to retrieve the values from NASGRO database is Q7AD26AA20). The Minimum Strain Energy Density criterion provide the crack path definition.

Confining the remeshing for crack growth to the sub-model greatly reduces the amount of data that needs to be transferred and processed, thus speeding the crack growth process. Using ANSYS we create a mesh, and then use BEASY to incorporate this mesh and insert a crack, identifying its size, shape, and orientation. BEASY computes the location of the new crack front, extends the crack, and updates the model geometry. Finally, remeshing is done and the process is continued until a through the thickness crack is obtained. This approach allows evaluating a non standard geometry of both structure and cracks by updating the mesh to conform to the crack shape.

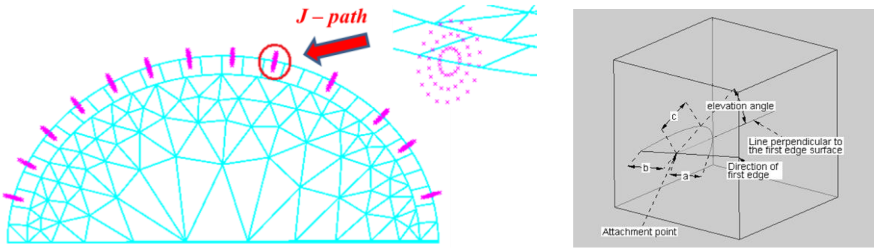


Figure 6. Initial crack mesh with highlight of the j-path along the crack front, needed for the j-integral evaluation (left); scheme showing the crack introduction procedure (right).

$$\frac{da}{dN} = \frac{C*(1-f)^n*\Delta K^n*\left(1-\frac{\Delta K_{th}}{\Delta K}\right)^p}{(1-R)^n*\left(1-\frac{\Delta K}{(1-R)*K_c}\right)^q} \qquad (1)$$

The sub modeling method, in this initial development, does not take into account the redistribution of the loads in the structure caused by the growing crack, thus requiring a large part of the structure to be included in the crack growth model. As a matter of fact, to improve the accuracy, BEASY should send the updated crack data back to the FEM-based software for analysis (this part is under development).

After reading the results, BEASY “grows” the crack based on the analyzed data, creates a corresponding mesh, and repeats this process accordingly.

The BEASY/ANSYS interface has been enriched with in house made routines to reduce the manual intervention during the crack growth iterations.

The thermomechanical load spectrum considered is simplified to a sequence of GAG (ground/air/ground) cycles with the blade temperatures varying from ambient values (ground) to those related to the cruise flight phase (Fig. 7).

RESULTS

Thermomechanical FEM and DBEM analyses

The steady state thermal analysis on a first stage pressure gas turbine blade proceeds with imposed temperatures on the internal cooled blade surface (T=913 K), on the suction side (T=1113 K) and on the pressure side (T=1138 K), with adiabatic conditions on the remaining surfaces (*hub* and *casing*), and provides the temperature distribution in the domain (Fig. 8). Such distribution, together with the mechanical boundary conditions, represent the input for the thermal-stress analysis that provides e.g. the Von Mises stress distribution (MPa) as shown in Fig. 8.

BEASY code can automatically extract that portion of the domain where to grow the crack and read from the ANSYS result file (.rst) temperatures and displacements to apply on the subdomain boundaries (Fig. 9).

The DBEM mesh is obtained from the FEM mesh by a *skinning* process (Fig. 9).

A new thermo-mechanical analysis is needed in the DBEM environment in order to recreate the volume thermal-stress scenario (these data cannot be transferred from FEM due to the peculiarity of the DBEM approach that lack a domain mesh to associate those results). In such analysis the thermal and mechanical material properties can only be assumed uniform throughout the subdomain volume (alternatively a further zoning is needed in the DBEM subdomain) and are calculated at the average temperature in the subdomain T=1126 K (available by the previous FEM thermal analysis). Such approximation is acceptable because the sudomain is sufficiently small and without appreciable temperature gradients. Moreover, differently from the FEM analysis, the DBEM simulation assume a material linear elastic behaviour. This approximation is also judged acceptable because the stress level in the subdomain is not sufficiently high to produce appreciable plastic effects (Fig. 8).

The correctness of the aforementioned approximations comes from the consistency between the results of FEM and DBEM analyses in the uncracked subdomain (Fig. 9).

DBEM crack propagation under TMF

The contour plots with Von Mises stresses related to the initial and final (after thirteen increments) crack scenario are showed in Fig. 10, showing a mode I crack propagation evolving in the initial crak plane. The SIFs along the evolving crack fronts and the crack sizes against increasing number of cycles, are showed in Figs. 11-12 respectively. The average crack advance considered is equal to Δa=0.15 mm.

CONCLUSIONS

The proposed procedure has been tested on a gas turbine vane, getting sound results, and can be made fully automatic, thanks to in house made routines needed to facilitate the data exchange between the two adopted codes: ANSYS and BEASY.

Such procedure also allow to consider the spectrum and the creep effects: both conditions relieve residual stresses that can be calculated by an elastic plastic sequential FEM analysis and transferred to the DBEM environment where they are automatically applied on the crack faces during its propagation [5].

The procedure is currently under improvement, in such a way to include an automatic update of the FEM overall model during crack propagation, in order to periodically update the boundary conditions on the submodel (the case study presented used the same submodel boundary conditions along the whole crack propagation). To this aim, in order to allow for the crack precense in the overall FEM model, it is sufficient the inclusion of a notch (e.g. an elliptical disk), with dimensions provided by the DBEM current crack advance: this avoid all the FEM meshing difficulties related to a real crack introduction [2].

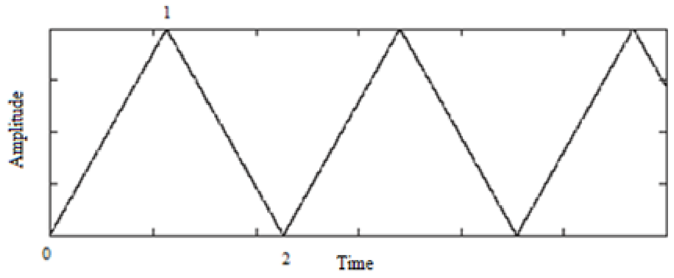


Figure 7. Load spectrum considered for crack propagation assessment.

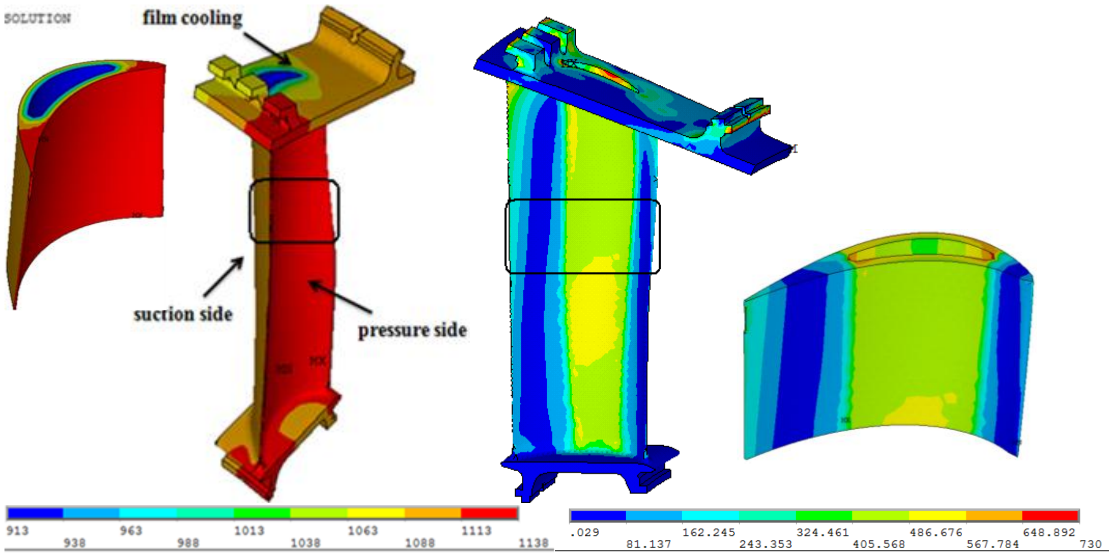


Figure 8. Distribution of temperatures (K) (left) and Von Mises stresses (right) with close-up of the FEM volume where to extract the cracked subdomain.

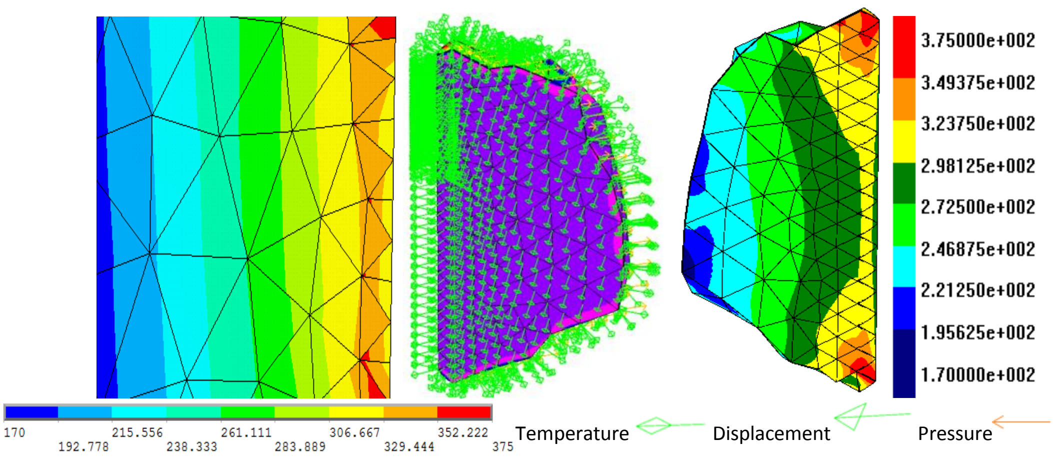


Figure 9. FEM (left) and DBEM (right) maximum principal stress in the subdomain, with highlight of boundary conditions on the DBEM subdomain boundaries (centre).

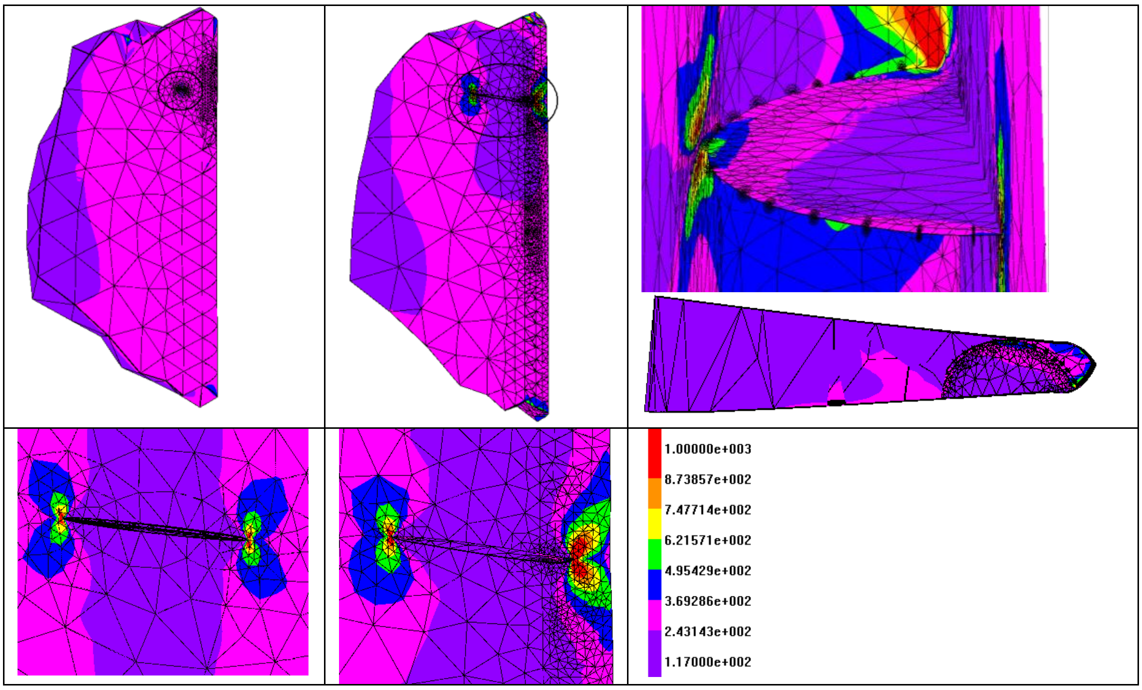
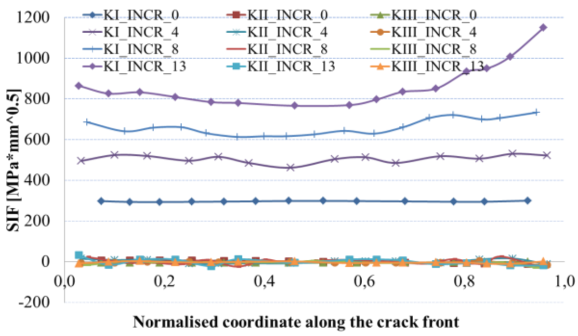


Figure 10. Von Mises stresses (MPa) on the initial (left) and final cracked configuration (middle), with an internal view of the crack that is becoming through the thickness.



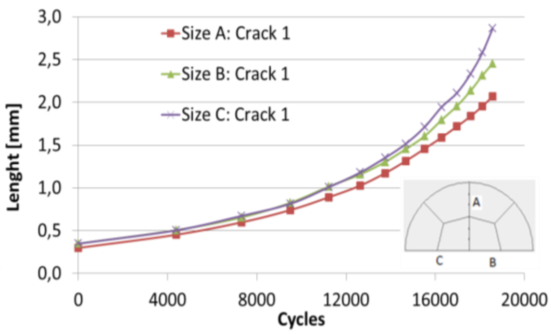


Figure 11. SIFs along the crack front.

Figure 12. Crack sizes vs. number of cycles.

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