Crack Propagation Analysis of Near-Surface Defects with Radial Basis Functions Mesh Morphing

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Introduction

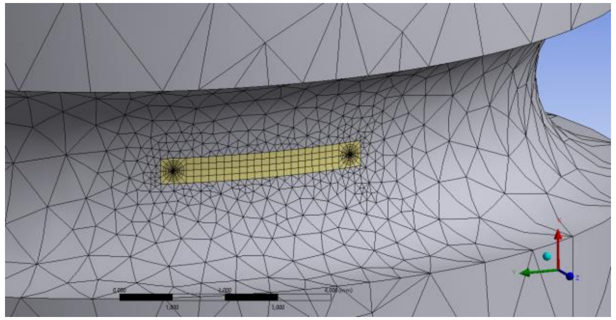
- The fatigue life of a structural component copes with the initiation and propagation of a **crack**.
- The Stress-Intensity Factors (**SIFs**), which can be deducted via Finite Element Method (**FEM**) analyses, together with the Paris-Erdogan Law can be used to investigate the crack stability and growth.
- The update of the **FEM** mesh onto new crack shape can be performed as follow:
  - by **re-meshing** (classic approach).
  - by applying the **mesh morphing** to a baseline FEM model of the flawed part.
- The second approach brings an important reduction of the time needed to generate the new FEM model.

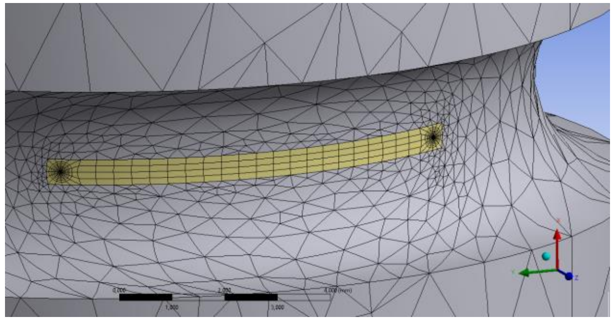
Introduction

- An important research path concerns the propagation of internal defects located near the free surface. Due to the interaction of the flaw with the free surface, the crack front tends to assume complex shapes. These fashions can be reproduced with **mesh morphing** technique.
- In the present work the tool adopted for morphing the FEM mesh is **RBF Morph™**, which is based on Radial Basis Functions (**RBFs**).

Research Path

- RBF Morph was introduced in ANSYS Mechanical in 2014.
- RBF4CRACKS project (2016 ends March 2018) was funded by the University of Rome Tor Vergata within the programme “**Consolidate the Foundations**”.
- Collaborations with F4E and SACMI.
- Latest work* performed by Tor Vergata crew relies on a two degree of freedom model for the simulation of crack propagation.





SACMI

ANSYS (rbf-morph)™

Università di Roma Tor Vergata

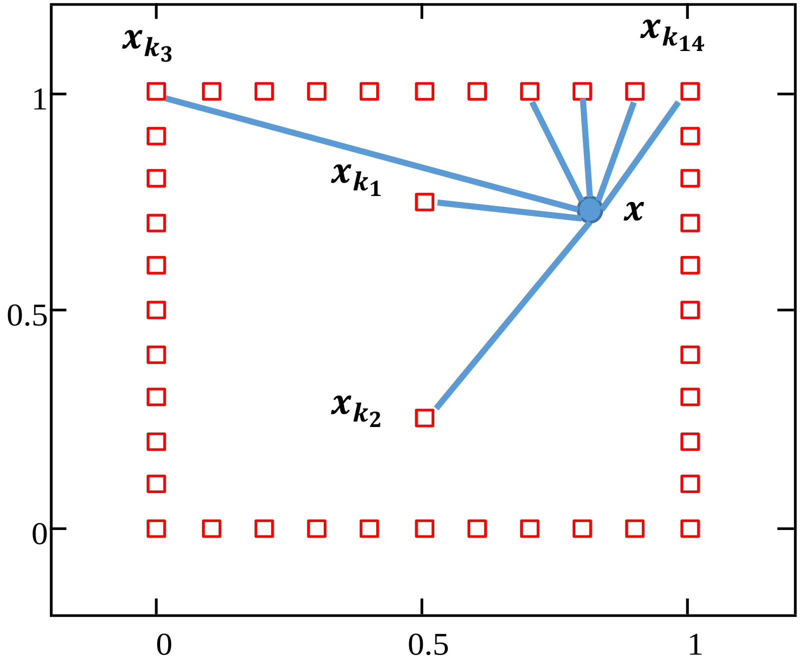
FUSION FOR ENERGY

*Biancolini, M. E., Chiappa, A., Giorgetti, F., Porziani, S., Rochette, M., 2018. Radial basis functions mesh morphing for the analysis of cracks propagation. Procedia Structural Integrity, 8, 433–443.

Mathematical Background: RBFs

- RBFs are a mathematical tool capable to **interpolate** in a generic point in the space a function **known** in at a set of given points (**source points**).
- The interpolating function is composed by a **radial basis** and by a **polynomial**:

$$s(\boldsymbol{x}) = \overbrace{\sum_{i=1}^{N} \gamma_i \varphi\left(\underbrace{\left\| \boldsymbol{x} - \boldsymbol{x}_{k_i} \right\|}_{\text{Euclidean distance from the i-th source point}}\right)}^{\text{radial basis}} + \overbrace{h(\boldsymbol{x})}^{\text{polynomial}}$$



Mathematical Background: RBFs

- If evaluated on the source points, the interpolating function gives exactly the input values:

$$s(\mathbf{x}_{k_i}) = g_i \qquad h(\mathbf{x}_{k_i}) = 0 \qquad 1 \le i \le N$$

- Given the scalar nature of the interpolation procedure, a vector field can be handled component-wise.
- Several different radial function (kernel) can be employed:

$$\begin{cases} s_x(\mathbf{x}) = \sum_{i=1}^{N} \gamma_i^x \varphi(\mathbf{x} - \mathbf{x}_{k_i}) + \beta_1^x + \beta_2^x x + \beta_3^x y + \beta_4^x z \\ s_y(\mathbf{x}) = \sum_{i=1}^{N} \gamma_i^y \varphi(\mathbf{x} - \mathbf{x}_{k_i}) + \beta_1^y + \beta_2^y x + \beta_3^y y + \beta_4^y z \\ s_z(\mathbf{x}) = \sum_{i=1}^{N} \gamma_i^z \varphi(\mathbf{x} - \mathbf{x}_{k_i}) + \beta_1^z + \beta_2^z x + \beta_3^z y + \beta_4^z z \end{cases}$$

RBF	φ(r)
Spline type (Rn)	r^n, *n odd*

Mathematical Background: Crack Propagation

- The **Multi Degree Of Freedom (MDOF)** model allows to simulate the actual growth of the defect, evaluating the displacement (both modulus and direction) to be assigned to each node of the front.
- **Displacement modulus**: for each node is directly correlated to its SIF through the Paris Erdogan Law.

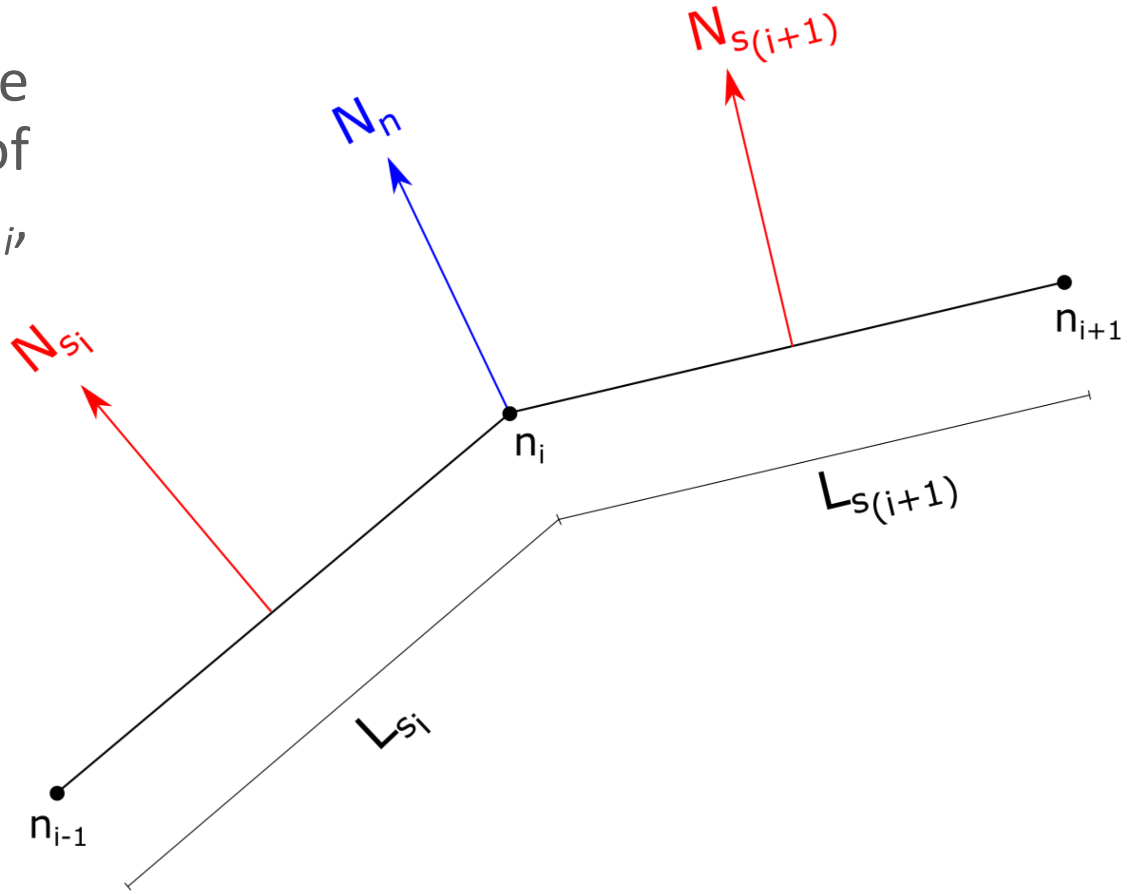
$$\Delta a_i^{(j)} = \left(\frac{\Delta K_i^{(j)}}{\Delta K_{max}^{(j)}}\right)^m \Delta a_{max}^{(j)} \qquad \Delta N^j = \frac{\Delta a_{max}^{(j)}}{C(\Delta K_{max}^{(j)})^m}$$

- In addition, the maximum crack growth increment $\Delta a_{max}^{(j)}$, with the corresponding maximum SIFs ($\Delta K_{max}^{(j)}$) are used for the evaluation of the loading cycles.

Mathematical Background: Crack Propagation

- **Displacement direction**: each node on the crack front moves orthogonally to the front itself.
- The propagation direction is calculated as the weighted average of the normal vectors of each segment connecting to the node n_i, being the weights the segments lengths.

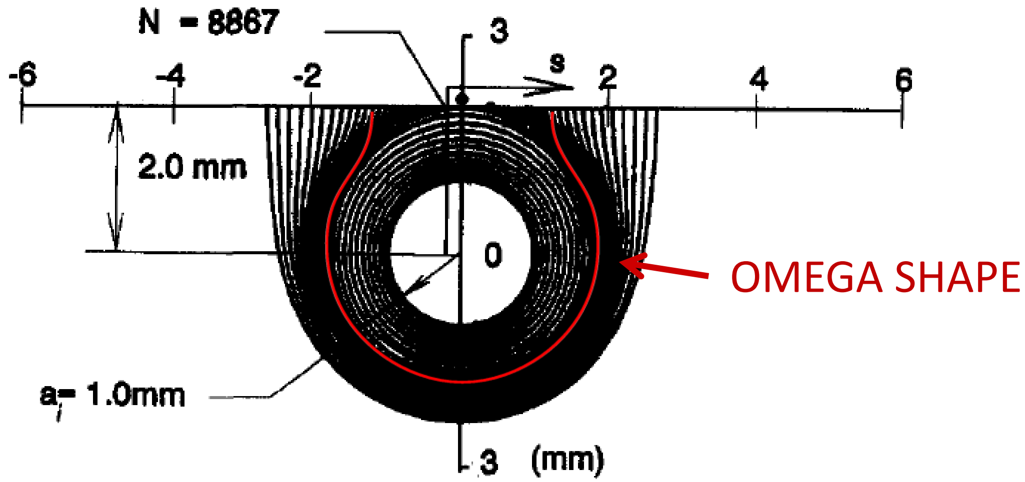
$$\overrightarrow{Nn} = \frac{\overrightarrow{Ns_i} \cdot Ls_i + \overrightarrow{Ns_{(i+1)}} \cdot Ls_{(i+1)}}{Ls_i + Ls_{(i+1)}}$$



Problem Description

- As described in literature* an initially circular (or elliptical) near surface crack, tends to assume complex shapes (omega aspect) after the breakout.

- After a certain number of cycles the crack front becomes circa semi-elliptical.
- It is intended to demonstrate that:
  - Mesh morphing allows to reproduce the omega shape.
  - starting from this aspect of the crack it is possible to obtain almost the semi-elliptical one by means of MDOF model coupled with mesh morphing.



(a). Initially circular crack, radius 1.0 mm, at a depth of 2.0 mm. Early stages of growth.

*Dai, D. N., Hills, D. A., Hrkegard, G., Pross, J., 1998. Simulation of the growth of near-surface defects. Engineering fracture mechanics, 59.4, 415–424.

Problem Description: workflow

ANSYS

Semi-elliptical crack generation with ANSYS FT

Omega shaped crack generation with Mesh Morphing

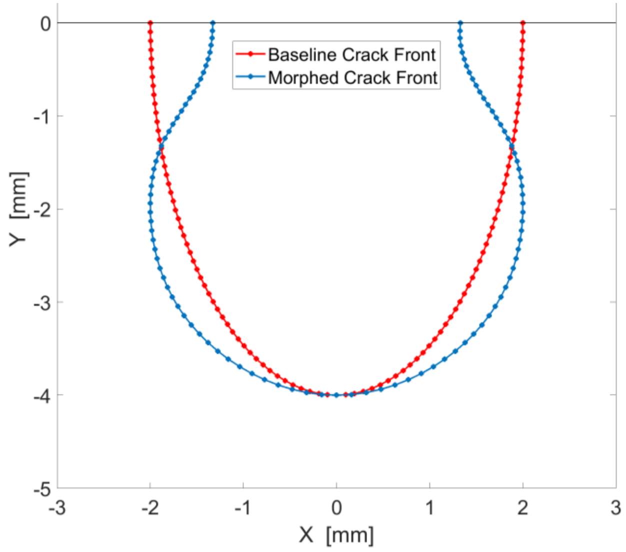
CRACK GROWTH

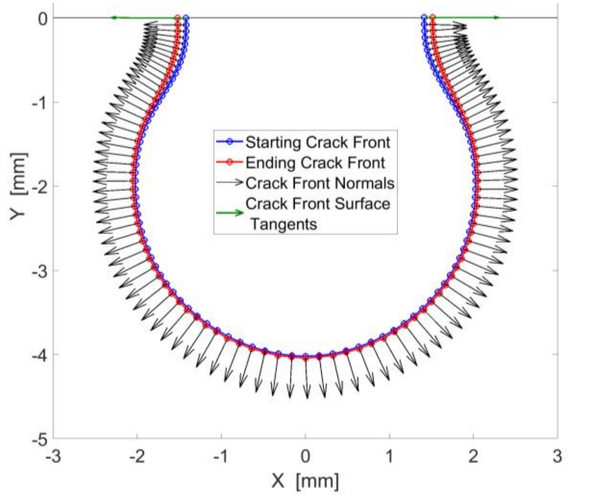
New FEA?

NO → Final Crack Front

YES → SIFs Extraction → Nodal Displacements evaluation with Paris Erdogan Law → Crack Front adjustment with Mesh Morphing → New FEA?

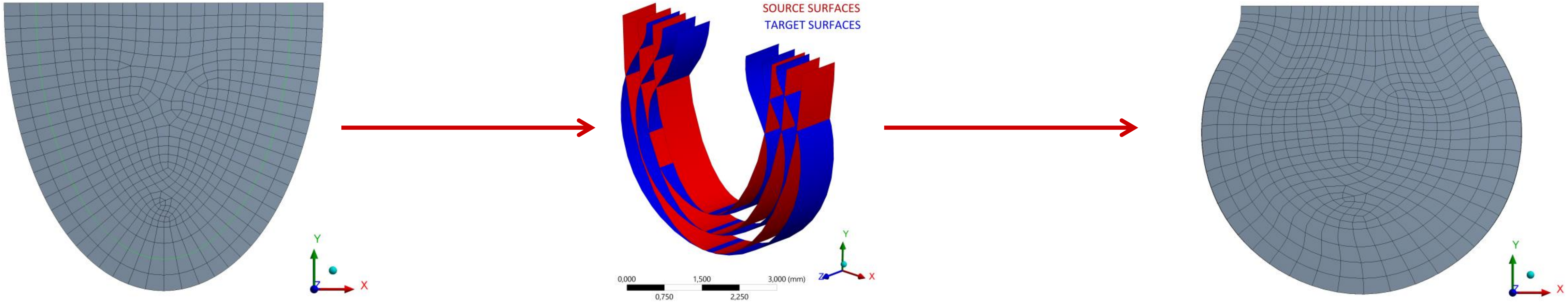
(rbf-morph)™





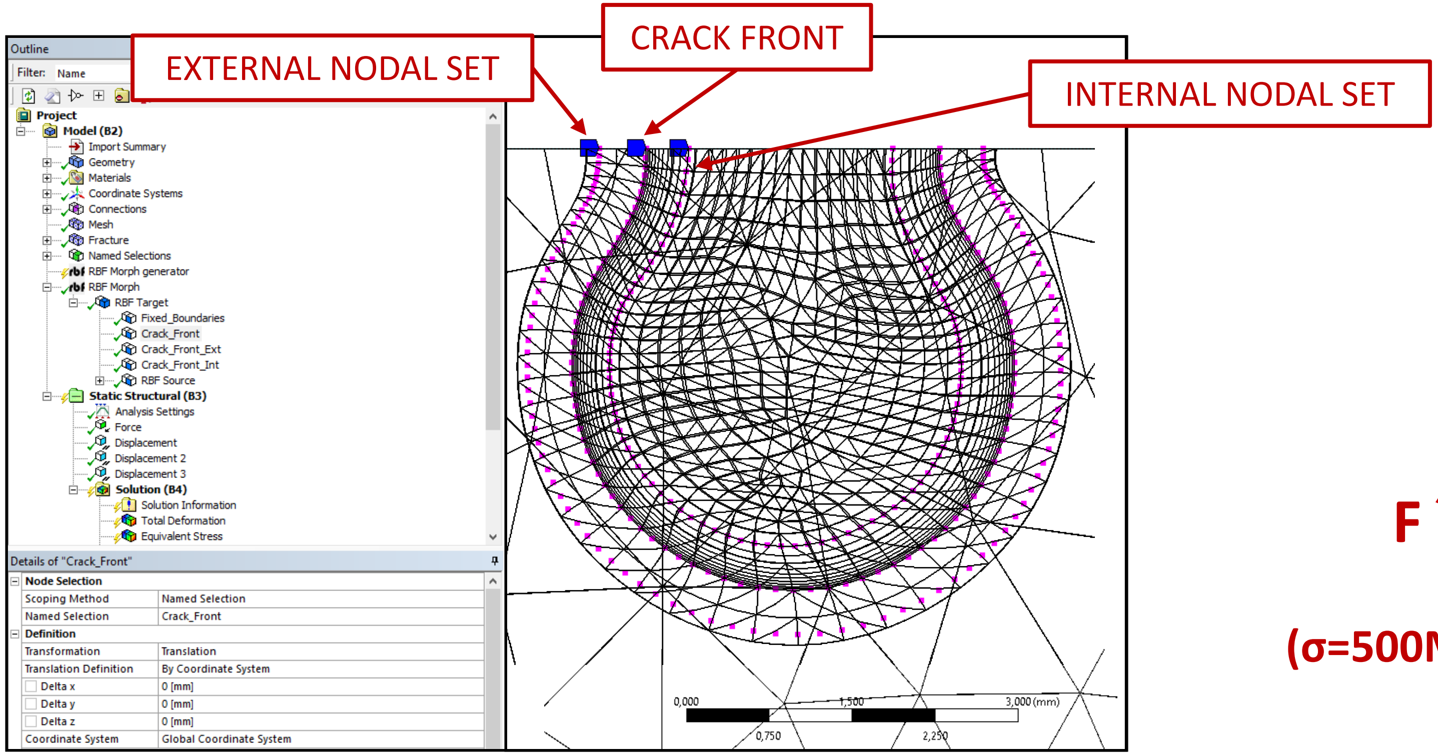
Preliminary Mesh Morphing

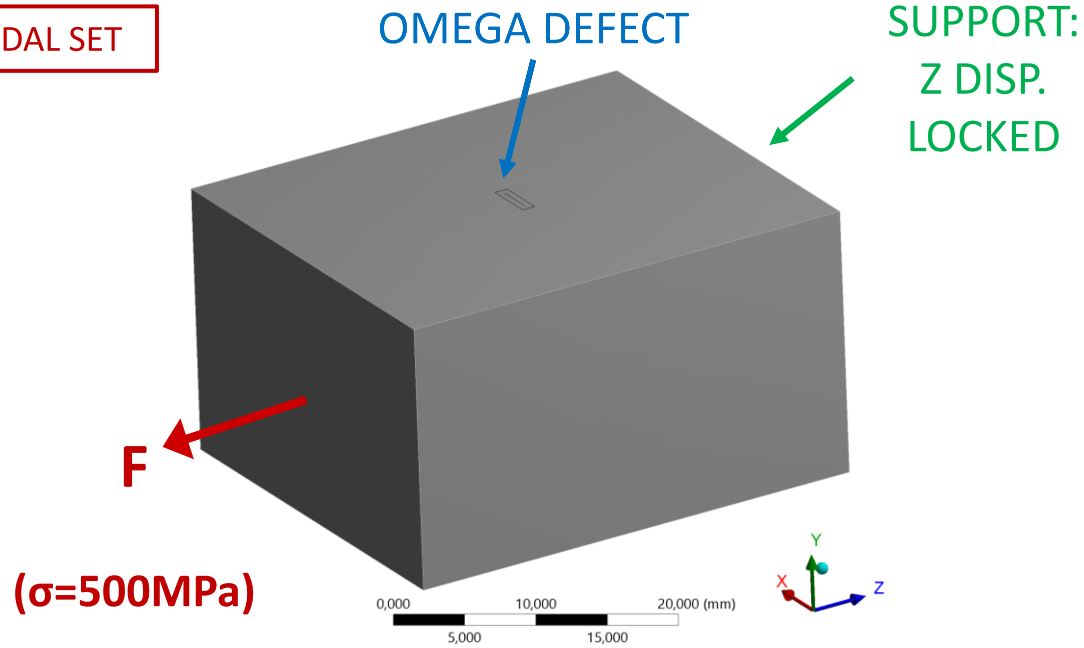
- The ANSYS **Fracture Tool** (FT), embedded in ANSYS Mechanical, allows to generate semi-elliptical or semi-circular cracks.
- In order to obtain the omega shape a morphing action (making use of RBF Morph ACT extension) is required.
- A set of auxiliary surfaces used to prevent excessive deformations during morphing procedure.



Crack Growth Simulation

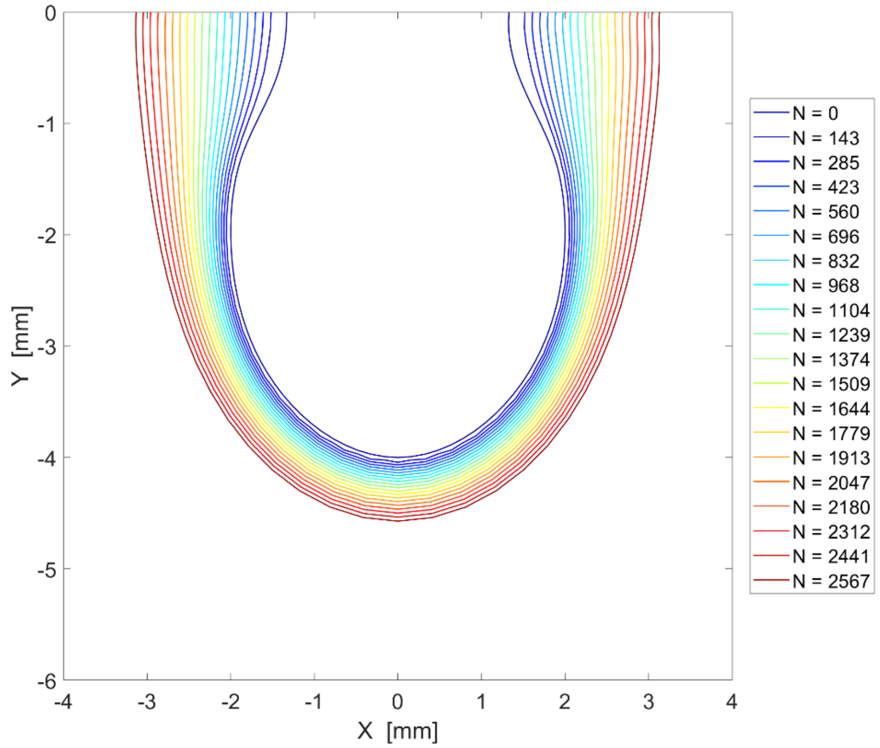
- The morphing action is related to the nodes of the crack front.
- In addition, to prevent deformation of the crack, the same displacement are applied to the following two set of nodes.



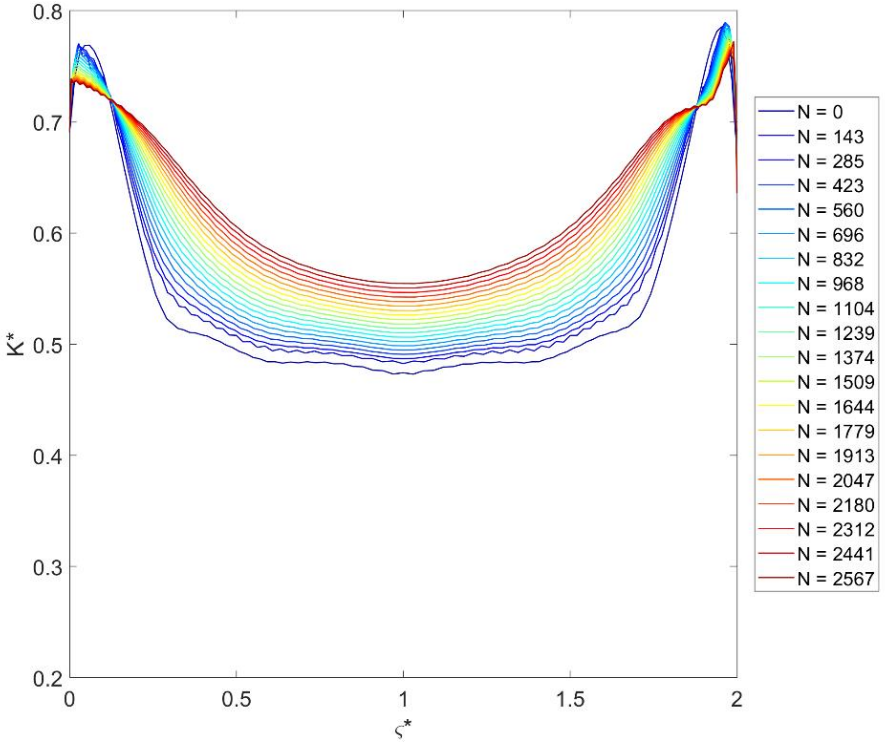


Results

Crack Front Positions



Crack Front SIFs



(Dimensionless curvilinear abscissa)

$$\zeta^* = \frac{\zeta}{h}$$

(Dimensionless SIF)

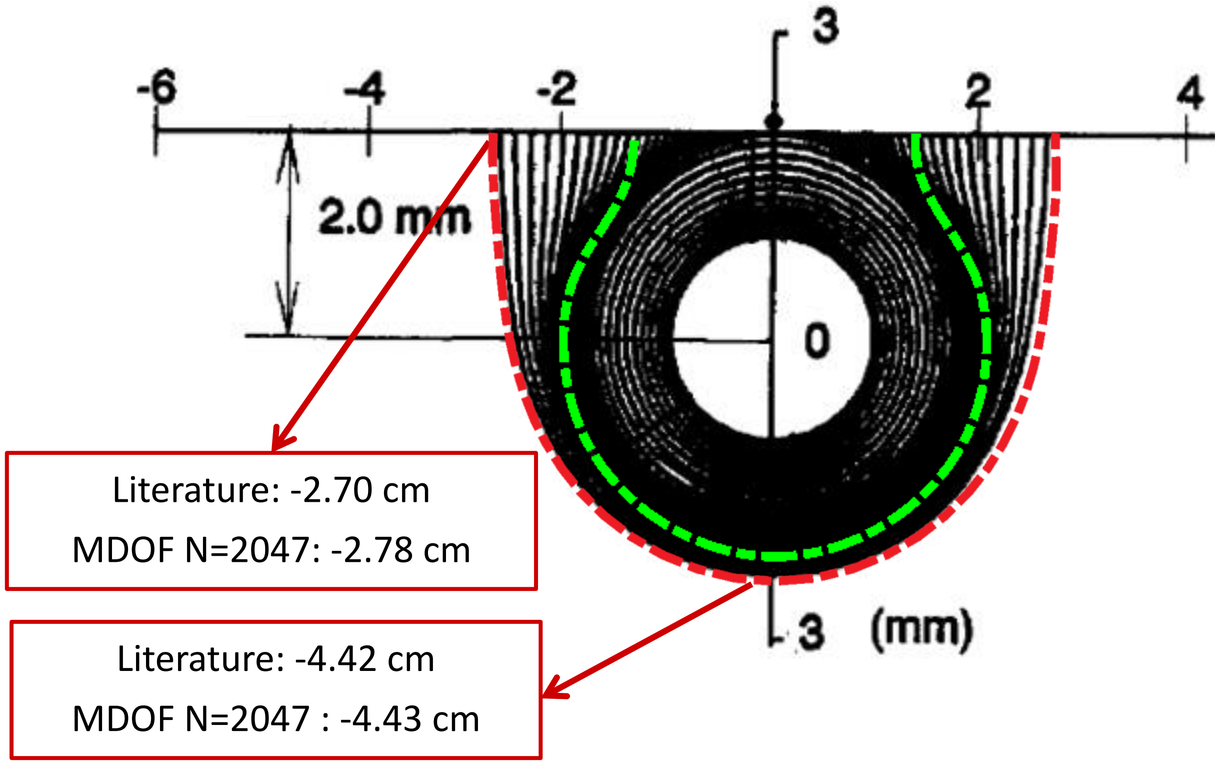
$$K_I^* = \frac{K_I}{\sigma_F \sqrt{\pi a}}$$

(Nominal stress)

$$\sigma_F = \frac{2F}{\pi D_0^2}$$

- The proposed approach for the simulation of the generic crack growth leads to results consistent with literature ones, with a very good superposition.

- The percentage difference measured after 2047 cycles (16 FEM analysis) at the free surface is 3% and at the crack tip is 0.2%.

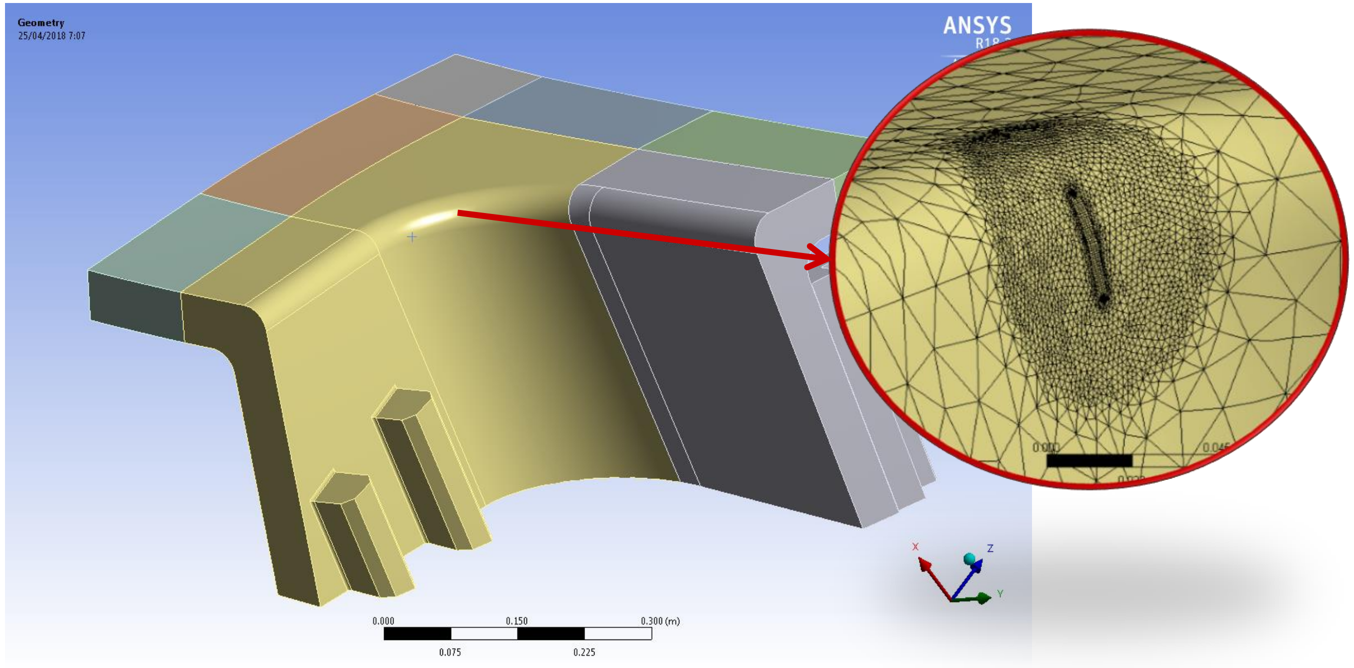


Conclusions

- The crack growth of near surface defects after breakout generates a series of omega shaped fronts, due to the interaction of the flaw with the free surface. After a certain number of cycles the crack becomes almost semi-elliptical.
- To obtain the omega aspect of the crack after breakout a preliminary mesh morphing was adopted, making use of RBFMorph ACT Extension inside ANSYS Workbench environment.
- Once that the crack was morphed to the desired aspect, it was possible to automatically predict the growth of the flaw, using the MDOF model.

Conclusions

- The shape of the crack front after 2047 cycles (corresponding to 16 analyses) is almost semi-elliptical and in accordance with literature results. A very good agreement between the literature and the obtained results was found.
- This methodology can be also used with complex shapes.



Thank you for your kind attention!

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