Mode-II and Mode-III Effects of Cyclic Crack Propagation in Specimens

G. Dhondt[1] and M. Schrade[2]

[1] MTU Aero Engines GmbH, Dachauer Str. 665, 80995 Munich, Germany. E-mail: guido.dhondt@mtu.de
[2]Institute of Aircraft Propulsion Systems, University of Stuttgart, Pfaffenwaldring 6, 70569 Stuttgart, Germany. E-mail: marcus.schrade@ila.uni-stuttgart.de

ABSTRACT. *Crack propagation in real aircraft engine components calculated by the in-house software CRACKTRACER3D frequently exhibits Mode-II and Mode-III effects, i.e. the cracks do not stay in-plane. Validation, however, is quite difficult since few experimental results are available. The present contribution uses mixed-mode experimental evidence from MTU and the literature in order to verify the predictions of CRACKTRACER3D. The tests include the propagation of a slanted crack in a 4-point bending specimen, a Compact Tension Shear Rotation Specimen under mode-III loading and a biaxial test of a square specimen with holes. It is shown that the results are on the conservative side due to the neglection of friction between the crack faces.*

INTRODUCTION

Generally, crack propagation in real components does not stay in-plane due to the complicated geometry and complex loading. Therefore, a good crack propagation program has to be able to predict out-of-plane growth. At MTU, an automatic cyclic crack propagation tool has been developed based on the finite element method. It consists of a pre-processor, which inserts the actual arbitrary crack shape into a given structure, a call to the finite element software CalculiX and a post-processor, which calculates the new crack propagation increment based on the actual stress intensity factor distribution along the crack front [1],[2]. In order to validate the program, well-documented mixed-mode crack propagation experiments are needed, which are rare. At MTU a total of 15 four-point bending (4PB) specimens with slanted cracks were tested and described in [3]. At the university of Paderborn a Compact Tension Shear Rotation (CTSR) Specimen was tested under mode-III [4]. Finally, biaxial tests on a plate with holes were reported in [5] and [6].

THE CRACK INSERTION PROCEDURE

In the pre-processor of CRACKTRACER3D the actual crack shape is inserted into the uncracked structure. To this end a set of elements in the uncracked structure has to be identified by the user (also called the domain), in which the crack will grow. The original mesh in this domain is replaced by a concentric hexahedral mesh at the crack front (the tube), which is attached to an automatically generated tetrahedral mesh filling the remaining part of the domain. This is illustrated in Fig. 1 for a quarter circular crack inserted into a Corner Crack Specimen. Since the domain is completely remeshed, the only requirement for the corresponding original mesh is that it constitutes an accurate description of the geometry of the component.

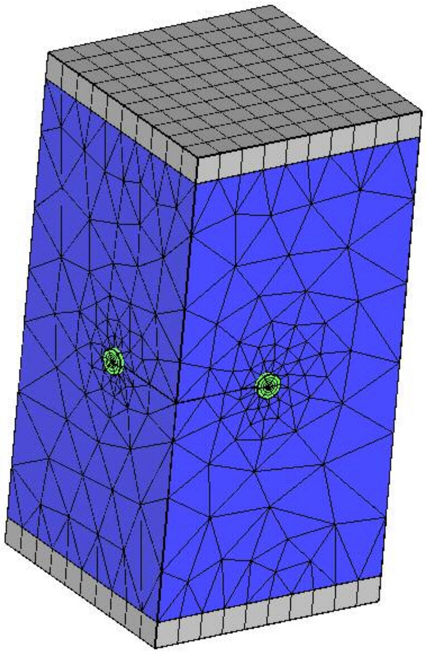

Figure 1. Tube (green), domain (blue) and original mesh (gray) for the CC-Specimen.

The tetrahedral mesh in between the tube and the original mesh outside the domain is generated using the free software tool NETGEN [7]. The input for NETGEN is a triangulation of the surface of the domain minus the tube. This triangulation serves as a geometrical description only. Internally, NETGEN generates a new triangulation of the surface, on which the subsequent tetrahedral meshing is based. The density of this latter triangulation is based on the smoothness of the surface. In the past, test cases were discovered with a too coarse NETGEN triangulation leading to an intersection of the triangles of adjacent crack faces. This resulted in a tetrahedral mesh with occasional stitching of the crack. This is illustrated for a Center Crack Tension Specimen (CCT) in Fig. 2. This phenomenon leads to smaller stress intensity factors at the crack front and consequently to a smaller crack propagation rate [8].

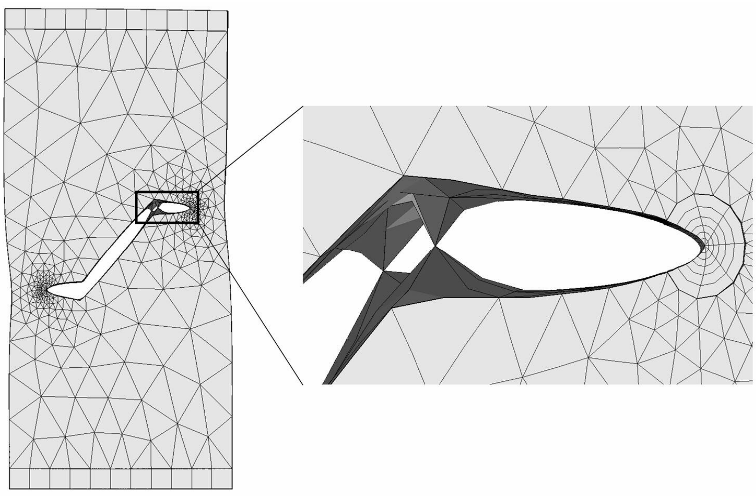

Figure 2. Stitching in the CCT-Specimen.

This problem was solved by augmenting the triangulation given to NETGEN by information on edges in the mesh which have to be kept in the new triangulation. At the location of the edges the NETGEN triangulation is finer and does not lead to overlapping crack faces.

FOUR-POINT BENDING SPECIMEN

At MTU and at the KTH Stockholm about 15 Titanium-Alloy 4-point bending specimens with initial slanted crack were tested under cyclic loading. The experimental set-up is shown in Fig. 3. Due to the slant angle of 45° the bending moment leads to a mixed-mode loading of the initial crack [2] (initial crack length is 5 mm). The original mesh, the domain and a triangulation of the initial crack is illustrated in Fig. 4.

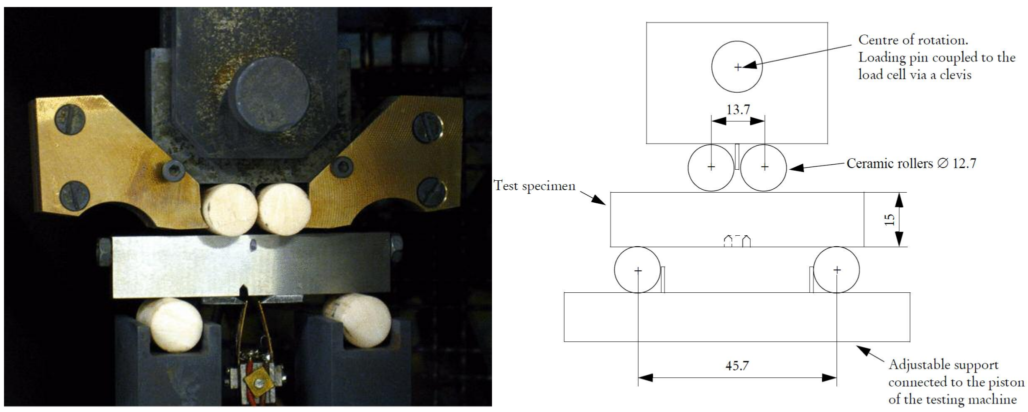

Figure 3. Experimental set-up of the 4PB tests.

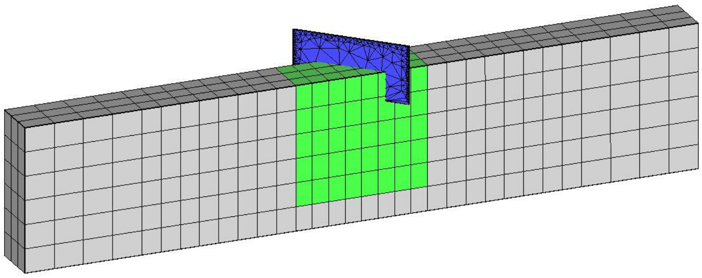

Figure 4. Initial crack (blue), domain (green) and rest (gray) for the 4PB-specimen.

During crack propagation the crack twists and grows into the symmetry plane, thus effectively switching into Mode-I. Figure 5 shows the final crack shape before rupture after about 60 iterations. One clearly notices the initial crack, the twisting of the crack faces during propagation, the concentrated hexahedral mesh at the crack front and the tetrahedral mesh generated by NETGEN. In CRACKTRACER3D the mixed-mode crack propagation increments are calculated based on an equivalent K-factor and a bending angle, both of which are determined in a unique way from the local Mode-I, Mode-II and Mode-III K-factors [9]. The size of the propagation increment is obtained by substituting the equivalent K-factor into a Mode-I Paris-type crack propagation law. Figure 6 compares the experimental crack shape with the numerical prediction. One notices that the overall shape is similar. However, there is one major difference: the numerical crack shape is smooth, whereas the experimental shape is, especially at the start of the propagation, discontinuous. This is the so-called factory-roof effect. It results from the simultaneous growth of several cracks along the initial crack front growing together after a while and is believed to be a consequence of Mode-III. Numerically, Mode-III leads to a twist angle, simulating precisely this effect. However, taking this twist angle into account would require the treatment of discontinuous crack faces, which is not possible right now.

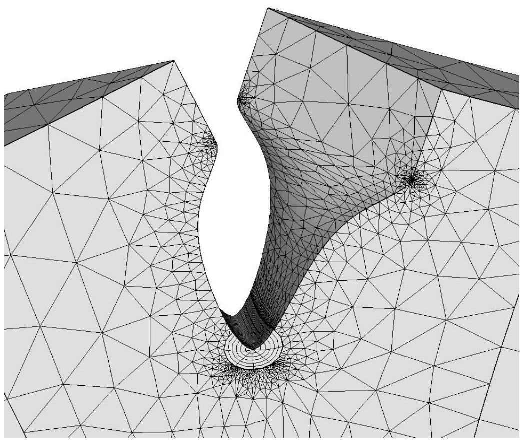

Figure 5. Crack propagation in the 4PB-Specimen.

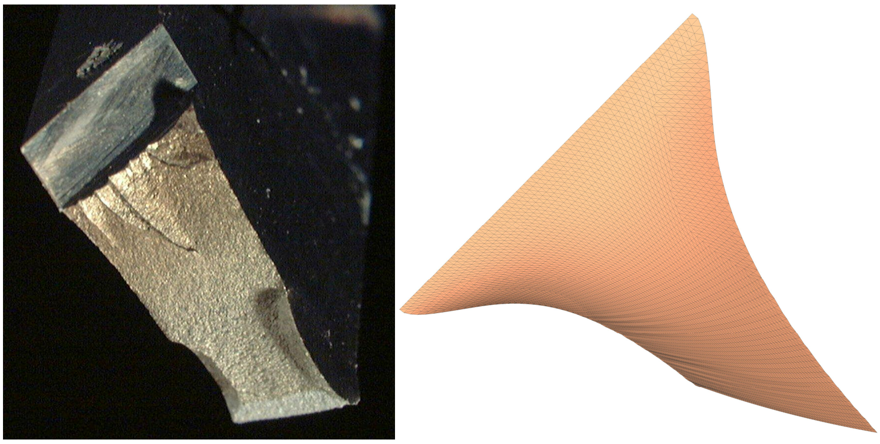

Figure 6. Crack shape (left: experimental; right: numerical) in the 4PB-Specimen.

The factory-roof effect does not influence the overall shape of the crack propagation, however, it does have an effect on the life cycles. This is shown in Fig. 7, where the crack length versus the number of cycles is plotted for 4 specimens and 3 data sets: the experimental data, the numerical data with stitching and the numerical data without stitching. One clearly notices that the numerical crack growth is faster than in the experiments and that the removal of the stitching error increases the discrepancy. This can be explained by the absence of friction in the numerical simulations. Indeed, in the experiments the factory roofing leads to substantial friction, which slows down the propagation. Exactly the same effect is created by the stitching of the crack faces: the K-factors are reduced leading to less propagation. Overall, the numerical curves are similar in shape, collapse occurs at the same crack lengths and they are on the conservative side.

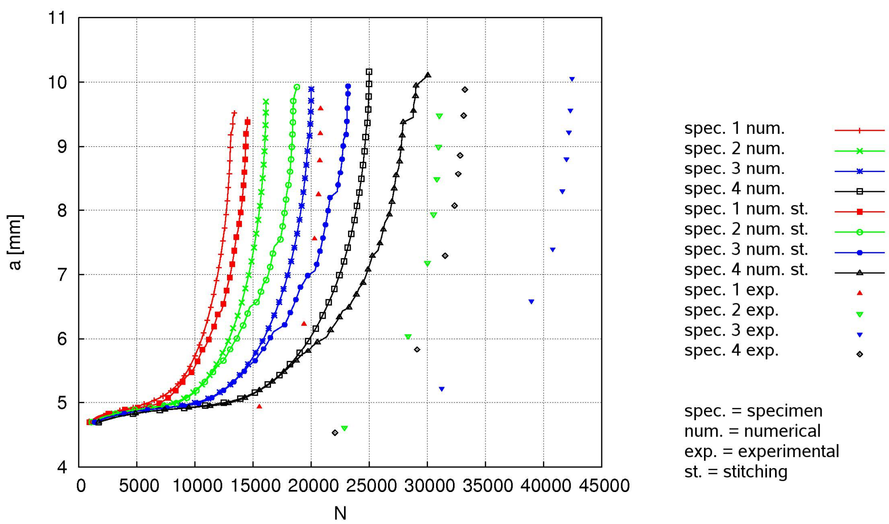

Figure 7. Crack propagation for the 4PB-Specimen.

COMPACT TENSION SHEAR ROTATION SPECIMEN

The Compact Tension Shear Rotation Specimen has been designed at the University of Paderborn and is described in [4]. Together with an appropriate fixation it allows for an arbitrary selection of the mode-I/mode-II/mode-III ratio. In the present context, a test under pure Mode-III is analyzed. The geometry of the specimen, together with the crack at an early propagation stage is presented in Fig. 8. Unter Mode-III loading the right part of the specimen is moved forward, while the left part is moved backward.

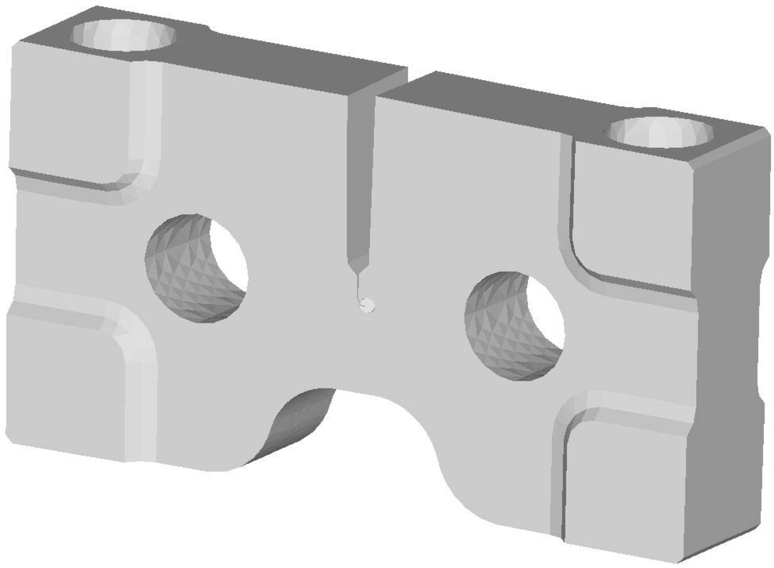

Figure 8. Compact Tension Shear Rotation Specimen.

Figure 10 shows a comparison of the experimental crack shape with the numerical prediction. In agreement with the expectation the crack propagation in the calculation is smooth and rotates such that Mode-I loading ensues. The experimental result is not so easy to interpret. While the back part of the crack front in Fig. 9 immediately rotates, the front part is retardated and grows at first in-plane. Only after a substantial in-plane crack propagation this part also rotates in the expected way. Qualitatively, the crack faces of the numerical simulation are nearly parallel to the experimental ones. Here too, the retardation effect is assumed to be caused by friction. The different crack face orientation near collapse is probably due to large plastic deformation. This effect is not taken into account in the numerical simulation.

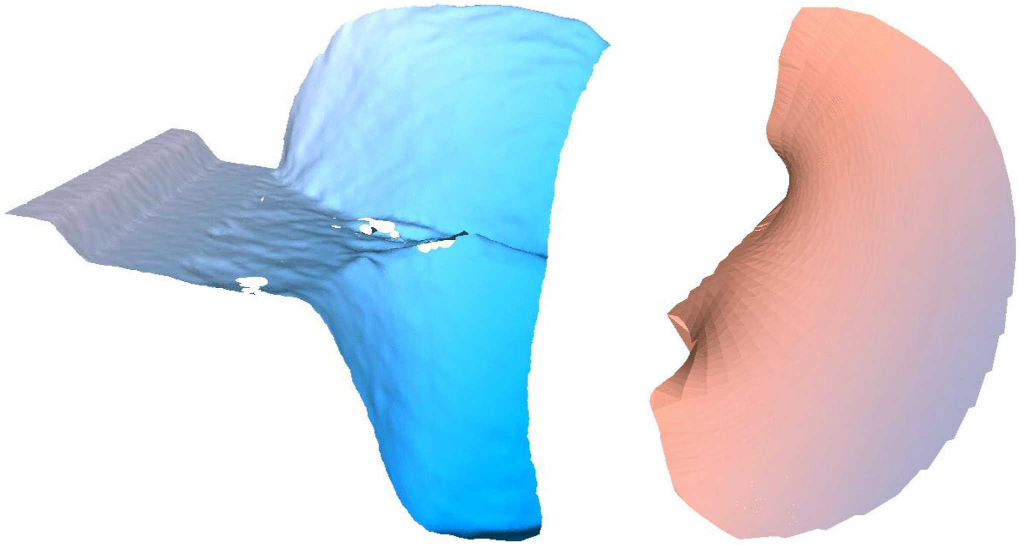

Figure 9. Experimental (left) and numerical (right) crack shape for the CTSR-Specimen.

BIAXIALLY LOADED SPECIMEN

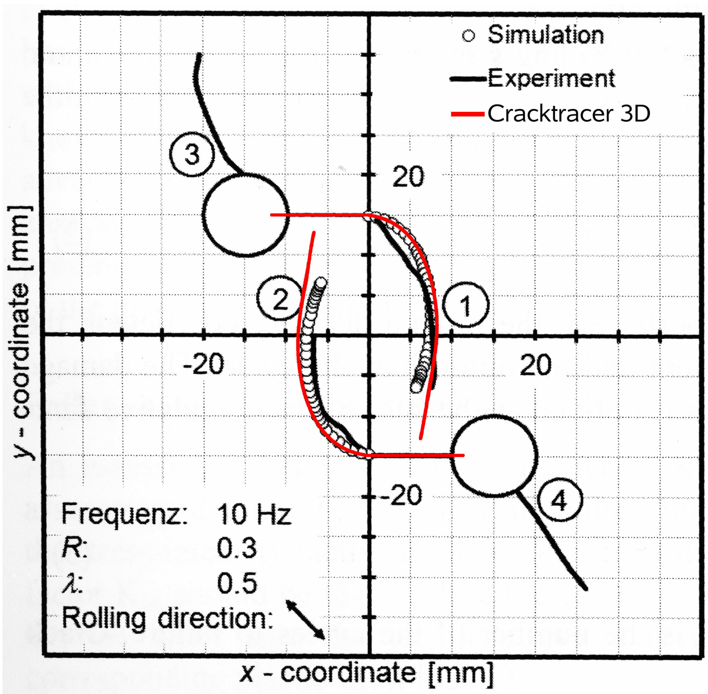

Figure 10. Crack propagation in a biaxial plate.

The last validation example is a square plate with a side length 120 mm and a thickness of 5 mm under biaxial loading. The plate contains two holes, the centers of which are at (15,-15) and (-15,15), respectively. The radius of the holes is 5 mm. Details of the material constants can be found in [5] and [6]. The plate is loaded by a force of 81 kN in x-direction, the simultaneous force in y-direction is half as large. The initial cracks start at the holes and have a length of 10 mm. After 20,000 cycles the cracks in the test had a total length of 19.5 mm (including the initial crack) and two additional, 0.2 mm long cracks were observed (crack 3 and 4). Using CRACKTRACER3D with 2 initial cracks, 24993 cycles were needed to reach a total crack length of 19.5 mm. Taking into account that the actual crack propagation is faster due to the existence of two more cracks this is quite close to the experimental evidence. Figure 10 shows that the predicted crack shape is also very well modelled. The circular symbols correspond to the numerical prediction in [6].

CONCLUSIONS

The crack propagation software CRACKTRACER3D was validated using several test examples. A comparison has shown that the qualitative agreement is very good. Differences especially arise in cases with significant Mode-III participation, leading to factory-roofing and large friction. Neglecting the friction yields life predictions on the safe side.

REFERENCES

1. Bremberg, D., Dhondt, G. (2008) *Eng. Fract. Mech.* **75**, 404-416.
2. Bremberg, D., Dhondt, G. (2009) *Int. J. Fract.* **157**, 109-118.
3. Dhondt, G. (2004). In: DVM-Bericht 236, pp. 163-170, DVM, Berlin.
4. Schirmeisen, N.-H., Richard, H.A. (2011). In: DVM-Bericht 243, pp. 214-223, DVM, Berlin.
5. Holländer, D., Henkel, S., Wünsche, M., Theilig, H., Biermann, H., Hübner, P. (2011). In: DVM-Bericht 243, pp. 105-112, DVM, Berlin.
6. Holländer, D., Wünsche, M., Henkel, S., Theilig, H. (2012) *Key Eng. Mat.* **488-489**, 444-447.
7. Schöberl, J. (2003) *NETGEN-4.3*, http://www.hpfem.jku.at/netgen.
8. Schrade, M. (2011) *Automatic Mixed-Mode Crack Propagation Calculations with the Finite Element Method*, Master Thesis, Institute of Aircraft Propulsion Systems, University of Stuttgart.
9. Dhondt, G. (2003) *Key Eng. Mat.* **251-252**, 209-214.