

fin tip). It appears that both SIF values and crack geometry during growth are quite variable due to shear modes for the off-axis inclined cracks. On the other hand, the symmetric cracks situated on the fin axis are quite predictable in their growth, as they tended to grow much more readily than the off-axis crack, always in the plane of the fin axis. It was found that the substantial delay in crack growth for the inclined cracks is also due to some initial misalignment of the blade with respect to the normal to the fin surface that is corrected by the turning of the crack as it grows and eliminates the shear modes.

NUMERICAL 2-D SIMULATIONS AND COMPARISON WITH EXPERIMENTAL RESULTS

A FRANC2D/L plane-strain finite element analysis was performed on half model using triangular 6-node elements. The mesh has 988 elements with 2153 nodes. A refined mesh was used around the notches. The material constants used in the analysis were the same as of the photoelastic material.

The initial numerical study was to find the SIFs versus crack length for three different configurations: symmetric crack, off-axis straight-in crack and off-axis inclined crack. The remeshing by delete and fill algorithm was used, which requires: to delete a group of elements in a region around the crack tip, then the crack is extended into this region, singular elements are placed around the crack tip, [4]. The stress intensity factors were obtained using the Modified Crack Closure Integral method. A study of crack propagation of off-axis cracks was carried on. The numerical prediction of the direction of crack trajectory was based on the maximum principal stress theory.

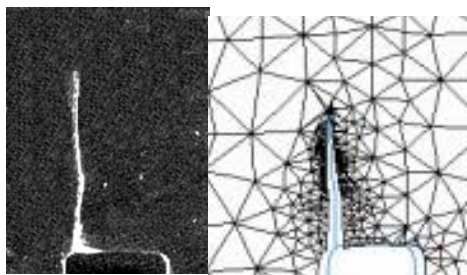


Fig. 2. Experimental off-axis straight-in crack and numerically simulated crack growth.

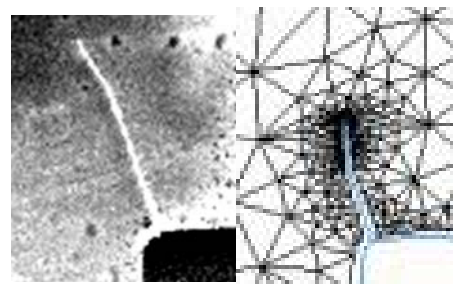


Fig. 3. Experimental off-axis inclined crack and numerically simulated crack growth in early stages.

The crack in Fig. 2 remains straight after some minor rearrangements, and Mode I is present. For the off-axis inclined crack, this one turns on a curved path (note path of mid-point at left of Fig. 3 in the experimental test), and after this limited amount of growth some Mode II as well as Mode I remained. Presumably, with further extension, the crack will straighten out and eliminate Mode II. The numerical simulation shows a rapid change of direction and presence of Mode I. At maximum depth all the experimental 3-D SIFs were smaller than the numerical 2-D corresponding values.

CONCLUSIONS

Off-axis cracks are retarded in growth by shear modes (II or II and III) and eventually gain their local and global symmetry. For three-dimensional numerical simulations mode III has to be considered. For two-dimensional simulations, one should remember that any local imperfections of crack location and loading will change at the beginning the crack trajectory, but later Mode I will be dominant.

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References

- [1] Leblond J.B.: Crack paths in three-dimensional elastic solids. I: two-term expansion of the stress intensity factors – application to crack path stability in hydraulic fracturing. *International Journal of Solids and Structures* **36**: 79-103, 1999.
- [2] Leblond J.B., Lazarus V. and S. Mouchrif S.: Crack paths in three-dimensional elastic solids. I: three-term expansion of the stress intensity factors – applications and perspectives. *International Journal of Solids and Structures* **36**: 105-142, 1999.
- [3] Goldstein R.V. and Salganik R.L.: Brittle fracture of solids with arbitrary cracks. *International Journal of Fracture* **10**: 507-523, 1974.
- [4] Cotterell B. and Rice J.R.: Slightly curved or kinked cracks. *International Journal of Fracture* **16**: 155-169, 1980.
- [5] Rubenstein A.: Mechanics of crack path formation. *International Journal of Fracture* **47**: 291-305, 1991.
- [6] Carter B.J., P.A. Wawrzynek P.A. and Ingraffea A.R.: Automated 3-D crack growth simulation. *International Journal for Numerical Methods in Engineering* **47**: 229-253, 2000.
- [7] Swenson D.V. and James M.A.: FRANC2D/L: A Crack Propagation Simulator for Plane Layered Structures, Version 1.4 User's Guide, Kansas State University, Manhattan, Kansas, 1996.
- [8] Smith C.W., Constantinescu D.M. and Liu C.T.: Stress intensities and crack growth in photoelastic motor grain models. *Proceedings of the 2002 SEM Annual Conference & Exposition on Experimental and Applied Mechanics, Session 36, Experiments in Fatigue & Fracture*, Paper 3, June 10-13, Milwaukee, Wisconsin, 2002.
- [9] Smith C.W., Constantinescu D.M. and Liu C.T.: Crack shapes and stress intensities in a motor grain geometry. *Proceedings of the 2002 International Conference on Computational Engineering & Sciences*, Chapter 7, Paper No. 5, Technical Science Press, Irvine, Ca., 2002.