Advances in Computational & Experimental Engineering & Science

Experimental and Numerical Analysis of Delamination Growth in a Graphite/Epoxy Specimen Caused by a Ply Cut

M. König[1], R. Krüger[1], E. Kohler[1], M. Kurz[1] and T. Ruckstuhl [1]

Summary

In this paper a specimen is considered that was employed in [1] to study delamination growth under fatigue loading, starting from a ply cut of the outermost plies that extends over the entire width of the specimen (see Figure 1). The specimen was considered as a model system for delamination growth that could start from a ply drop in graphite/epoxy laminates. Numerical methods have been developed for the determination of energy release rates at the delamination front. Based on this, tools have been developed for prediction of delamination growth in graphite/epoxy laminates under quasi-static and fatigue loading.

Extended Abstract

As a first step, a one-dimensional (1D) model of the specimen was established, from which an analytical formula can be derived for the total energy release rate at the delamination front. This formula can then be applied for the limiting cases of plane stress and plane strain (with respect to the specimen's width direction) and to the more realistic case of generalized plane stress (also called generalized plane strain), the latter coinciding with the basic assumptions of the Classical Laminated Plate Theory.

The 1D model has the advantage of yielding a simple analytical formula, however, it has two severe disadvantages. It is not valid for very small crack lengths and it can not distinguish between the individual mode contributions (Mode I, II and III) to the total energy release rate. However, as found e.g. in [2], the delamination growth in graphite/epoxy laminates is considerably dependent on the mixed mode ratio of the normal opening mode (Mode I) and the shear mode. Therefore, a 2D Finite Element model of the longitudinal section of the specimen has been built, employing 2D Finite Elements, and again the conditions of plane stress and plane strain. The results of this model show, that the analytical 1D solution for the total energy release rate is valid for crack lengths larger than 1 *mm*, but that, in fact, there exist mixed mode conditions at the delamination front. The case of generalized plane stress could not be realized by the authors employing 2D Finite Elements. Instead, one layer of 3D brick elements has been used. The results for

---

[1] Institute of Statics and Dynamics of Aerospace Structures, University of Stuttgart, Pfaffenwaldring 27, D-70550 Stuttgart, Germany, Fax ++49-711-685-3706, email: koenig@isd.uni-stuttgart.de

the total energy release rate compare again very well with the analytical 1D solution (Figure 2), which, however, as already mentioned, does not render the mixed mode ratio for Mode I and Mode II.

For investigating the 3D effects, finally, a full 3D Finite Element model has been built (Figure 3). A continuum based 3D shell element and a 3D non-linear contact processor, to avoid interpenetration of the delaminated surfaces, have been employed for this 3D model. The results obtained by this model (Figure 4) show, that the Mode III contribution to the total energy release rate is negligible for the considered specimen and the chosen stacking sequence of the plies. The total energy release rate compares well with that from the 2D and the 1D models, supposed the generalized plane stress condition is assumed for these models.

The following conclusions can be drawn from the study presented:

- Due to the simple geometry of the specimen with respect to the ply cut and the delamination, which extend through the entire width of the specimen, it is possible to derive an analytical expression for the total energy release rate. When the generalized plane stress assumption is used, the result obtained by this expression is a very good approximation for the 3D situation, whereas the plane stress assumption yields a value that is 71 *percent* too large and the plane strain assumption a value that is 22 *percent* too small, which both would not be usable for delamination growth prediction (see Figure 5, which shows the experimentally determined delamination growth rates as a function of the computed total energy release rates, and which provides a comparison with Paris law lines from material characterization from [2]).
- All 2D Finite Element solutions yield a rough approximation of the mixed mode ratio, which may actually be required to predict delamination growth adequately. This can be seen from Figure 5, which shows that the delamination growth rate differs by a factor larger than 10, when the mixed mode ratio changes between pure Mode I and pure Mode II for the values of the total energy release rates obtained for the present example. This means, that the knowledge of the total energy release rate from the 1D solution is not sufficient in our case for an adequate prediction of the delamination growth rate.
- A better result than from 2D is obtained for the mixed mode ratio by the presented 3D analysis. Such an analysis will, in fact, be required in all cases in which the 3D effects are more dominant than in the present example. The

3D analysis renders the distribution of the total energy release rate, as well as, the distribution of the individual mode contributions along arbitrarily shaped delamination fronts.

Reference

1. Project Consortium, Brite-Euram Project BE-3444: ”Analytical and Experimental Approach to Cumulative Damage and Residual Strength Prediction for CFRE Composites”, CEC, Sept. 1990 - Aug. 1994.
2. Koenig, M., Krueger, R., Kussmaul, K., von Alberti, M., Gaedke, M.: ”Characterizing Static and Fatigue Interlaminar Fracture Behavior of a First Generation Graphite/Epoxy Composite”, 13th Composite Materials: Testing and Design, Thirteenth Volume, ASTM STP 1242, S.J. Hooper, Ed., American Society for Testing and Materials, 1997, pp. 60-81.

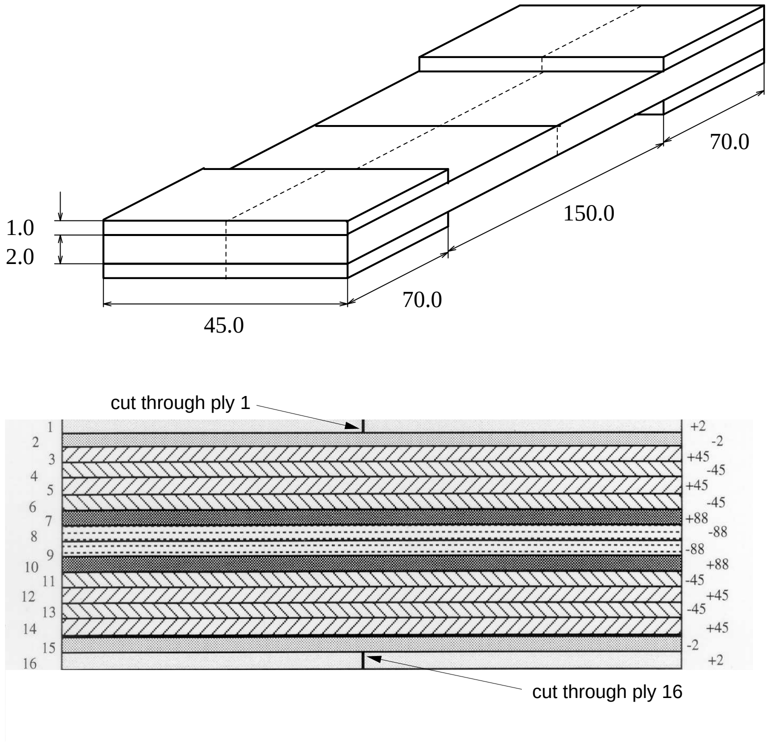

Figure 1: Graphite/epoxy specimen with stacking sequence $[\pm 2/\pm 45/\pm 45/\pm 88]_S$, containing ply cuts through layers 1 and 16, for studying delamination growth under tension-tension (R = 0.1) fatigue loading

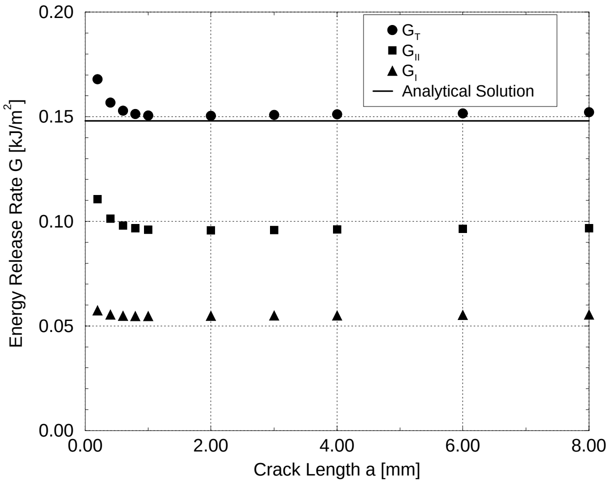

Figure 2: Computed energy release rates from 1D analysis and 2D analysis (generalized plane stress case)

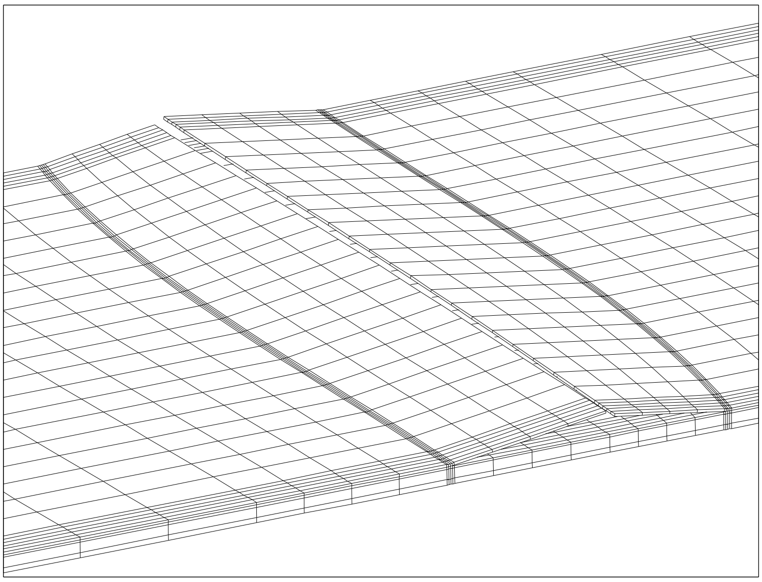

Figure 3: Detail of deformed geometry of the 3D model for front s_3

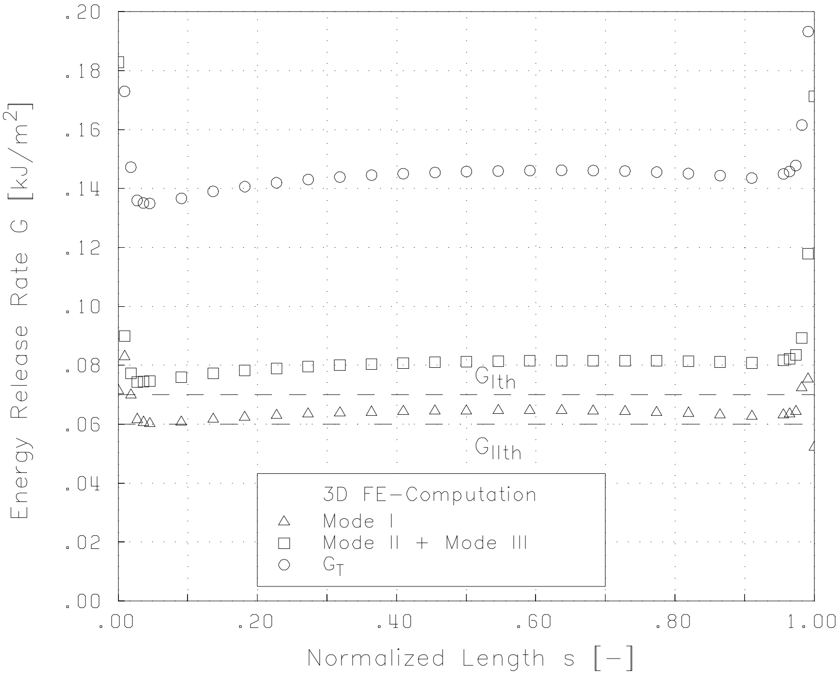

Figure 4: Distribution of energy release rate along front s_3 (after 40,000 load cycles)

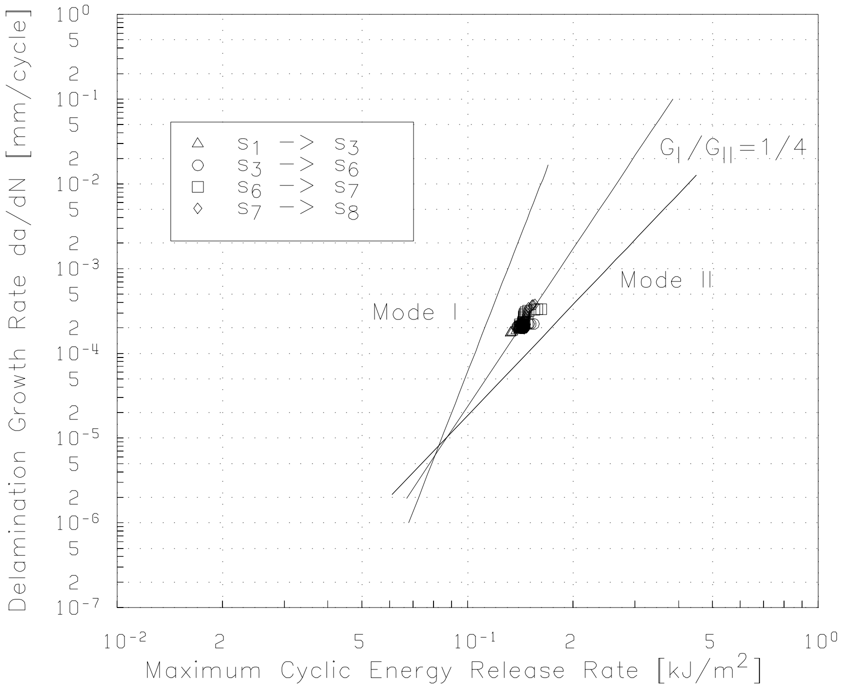

Figure 5: Experimentally observed delamination growth in comparison to Paris law from material characterization