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Fracture analysis in the modified split-cantilever beam using the classical theories of strength of materials

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Abstract. The modified split-cantilever beam is a specimen type applied in fracture mechanics to measure the mode-III fracture properties of composites. In this paper an improved beam model is developed, which is based on the superposition of four different effects. The analytical model is validated by numerical calculations using the finite element software ANSYS and it is demonstrated that the agreement is very good between the analytical and the numerical models. Experimental measurements are also performed on unidirectional glass/polyester composite specimens, and a very good agreement is obtained between the results of the analytical model and the experiments. Apart from the excellent accuracy of the beam model it is shown that the modified split-cantilever beam has an important role in fracture mechanics, because it applies the same specimen geometry as the standard mode-I and mode-II tests and it is suitable to investigate the mode-III fracture properties in a quite extended crack length range.

1. Introduction

In the last decade more and more attention was focused on the investigation of the mode-III interlaminar fracture mechanisms of laminated composite materials [1,2]. This indicates that – apart from the mode-I and mode-II fractures - the mode-III is also important for the complete fracture characterization of the material. However, the mode-III fracture involves several difficulties, which do not take place under mode-I, mode-II and mixed-mode I/II tests. One of them is that – to the best of the author's knowledge – a pure mode-III fracture can not be produced. One of the mode-III specimen types is the modified split-cantilever beam (MSCB).

The aim of the present work is to improve the efficiency of the MSCB specimen [3,4], to provide an accurate closed-form solution for the compliance and the energy release rate and to demonstrate its applicability for the reduction of the experimental data. The MSCB specimen maintains the traditional beam-like geometry. Another reason for developing closed-form solution and performing experiments is that it is possible to combine it with mode-I double cantilever-beam (DCB) [5] and mode-II end-notched flexure test (ENF) [6,7]. Although these tests have several drawbacks, their simplicity is a great advantage.

2. Analysis – beam theories

The MSCB specimen is demonstrated in Fig. 1, where it is shown that the rigs subject the specimen by four grub screws inducing a scissor-like load of the sample [5,6]. The specimen is treated as a slender beam and the bending, shear, the so-called Siant-Venant effect and the free torsion of the specimen are equally accounted for [8]. The compliance (defined as $C=\delta/P$, δ is the displacement at roller C, P is the applied load at roller C in Fig. 1) of the MSCB specimen is [8]:

$$C = \frac{8a^3}{b^3 h E_{11}} [f_{EB1} + f_{TIM1} + f_{FT1} + f_{S-V1}], \tag{1}$$

where:

$$f_{EB1} = 1 - 3\left(\frac{s_1 + s_2}{a}\right) + 3\left(\frac{s_1 + s_2}{a}\right)^2 - \frac{s_1(s_1 + s_2)(s_1 + 2s_2)}{a^3}, \tag{2}$$

$$f_{TIM1} = 0.3(1 - \frac{s_2^2 - s_1^2}{as_1})\left(\frac{b}{a}\right)^2\left(\frac{E_{11}}{G_{13}}\right), \; f_{FT1} = 0.19\frac{1}{\varsigma}(1 - \frac{s_1}{a})\left(\frac{b}{a}\right)^2\left(\frac{E_{11}}{G_{12}}\right), \tag{3}$$

$$f_{S-V1} = 0.48\left(\frac{a - (s_1 + s_2)}{a}\right)^2\left(\frac{b}{a}\right)\left(\frac{E_{11}}{G_{13}}\right)^{\frac{1}{2}}, \; \varsigma = 1 - 0.63\mu\frac{h}{b}, \; \mu = \left(\frac{G_{13}}{G_{12}}\right)^{\frac{1}{2}}. \tag{4}$$

where a is the crack length, b is the specimen width, h is the half thickness, s_1 and s_2 are the distances between the grub screws (see Fig. 1), E_{11} is the flexural modulus of the specimen, G_{12} and G_{13} are the shear moduli of the specimen, furthermore, f_{W1} is from the Winkler-Pasternak foundation, f_T is from transverse shear and f_{S-V1} accounts for the Saint-Venant effect [8].

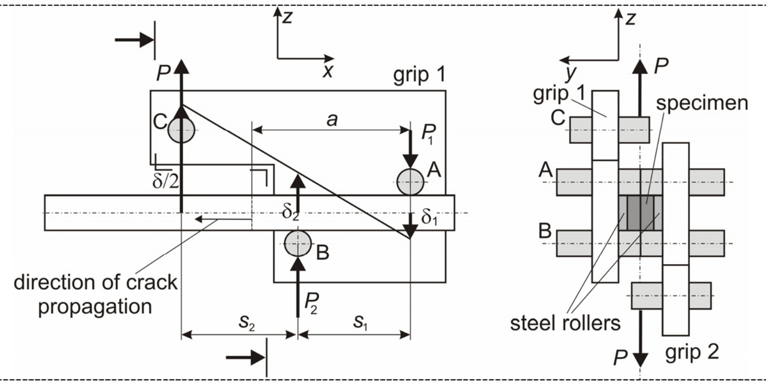

Figure 1. 2D illustration of the MSCB specimen.

The energy release rate of the MSCB specimen is [8]:

$$G_{MSCB} = \frac{12P^2a^2}{b^4 h E_{11}}[f_{EB2} + f_{TIM2} + f_{FT2} + f_{S-V2}], \tag{5}$$

where:

$$f_{EB2} = 1 - 2\left(\frac{s_1 + s_2}{a}\right) + \left(\frac{s_1 + s_2}{a}\right)^2, \; f_{TIM2} = 0.1\left(\frac{b}{a}\right)^2\left(\frac{E_{11}}{G_{13}}\right), \tag{6}$$

$$f_{FT2} = 0.06\frac{1}{\varsigma}\left(\frac{b}{a}\right)^2\left(\frac{E_{11}}{G_{12}}\right), \; f_{S-V2} = 0.32\left(1 - \frac{s_1 + s_2}{a}\right)]\left(\frac{b}{a}\right)\left(\frac{E_{11}}{G_{13}}\right)^{\frac{1}{2}}. \tag{7}$$

3. Comparison with numerical and experimental results

The analytical model (Eqs. (1)-(7)) is compared to finite element results to prove the accuracy of the model. The details of the FE models and the calculations are given in [8]. Fig. 2 shows the compliances at rollers A, B and C (Fig. 1) calculated from analysis and numerical models. The agreement is excellent and proves that the beam models captures very well the deformation of the specimen.

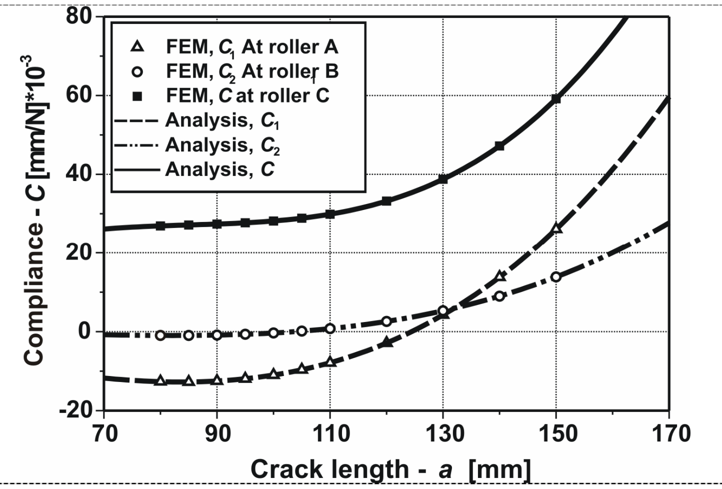

Figure 2. Comparison of the compliances by analysis and FE computations

The next step was to apply the model to data reduction in experimental tests. For this reason glass/polyester specimen were manufactured and tested using two rigs like the one, shown in Fig. 1. During testing the displacement of the specimen at roller C was measured by using a mechanical dial gauge, the load was recorded by using the scale of the testing machine. The measurements were performed by varying the crack length in the range of a=80 to 150 mm. The compliance versus crack length data was fitted by a third order polynomial and was plotted in Fig. 3 as well as the analytical model (Eq. (1)). The agreement is excellent, indicating the accuracy of the measurements and the analytical model. Table 1 shows the energy release rates calculated by two methods: the analytical model and the compliance calibration (CC) method [1, 2]. In this case the largest difference is 18.9 % between the results by beam model and CC, which can be explained by the sensitivity of the experimental compliance curve to the curve fit process. Overall the analytical model is assessed to be more accurate than the CC method.

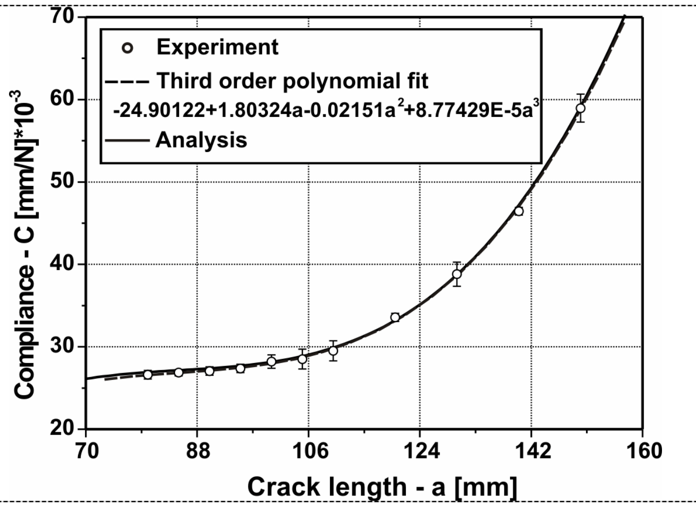

Figure 3. Experimentally measured and calculated compliances.

Table 1. Energy release rates calculated by the analytical model and the compliance calibration.

a [mm]	80	85	90	95	100	105	110	120	130	140	150
$G_C{}^a$	120.9	110.5	130.2	156.6	199.7	244.3	269.1	381.1	488.0	576.2	659.0
Scatter	±8.31	±2.7	±9.2	±3.01	±3.51	±4.91	±3.04	±6.86	±2.56	±8.44	±0.34
$G_{Beam}{}^b$	138.8	101.3	105.6	127.5	171.0	220.4	253.7	382.6	509.9	618.7	721.5
scatter	±6.91	±7.6	±8.2	±4.8	±5.01	±8.61	±8.83	±5.68	±2.86	±6.33	±8.34
diff^{ab}[%]	-14.8	8.4	18.9	18.6	14.4	9.8	5.7	-0.4	-4.5	-7.4	-9.5

$G_C{}^a$ – ERR by compliance calibration method [J/m^2]
$G_{Beam}{}^b$ – ERR by beam theory (Eq. (5)) [J/m^2]

4. Conclusions

In this paper the modified-split cantilever beam was revisited and an accurate analytical solution was developed. The compliance and the energy release rate of the specimen were calculated and were compared to results by numerical analysis and experiments. In both cases the agreement was excellent with the analytical model confirming the applicability and accuracy of the analytical model. The possibility to develop closed-form solution for fracture mechanical specimens is important, since this can make the data evaluation very fast. On the other hand the modified-split cantilever beam specimen is the only mode-III configuration, which is suitable to investigate the effect of crack length on the critical energy release rate at crack initiation in an extended crack length range.

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