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SOLID MECHANICS

FRACTURE IN COMPOSITES – AN OVERVIEW (PART II)

Continuation from Volume 42 No 2.

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Abstract. An overview of the literature for the last twenty years on the fracture mechanics of unidirectional fibre reinforced polymer composites is presented. Pure mode (I, II, and III) as well as mixed mode longitudinal cracks (i.e., cracks that propagate along the fibres) are considered mainly. It is shown that the strain energy released rate is the most widely used parameter for fracture toughness characterization. Various solutions for determination of the strain energy release rate in composites using linear-elastic fracture mechanics are presented. Studies on fracture in composite sandwich structures are reviewed, too. Some analyses of damages and their influence on fracture behaviour also are considered. Topical problems of composite fracture mechanics are formulated.

Key words: Crack, fibre reinforced composite, beam, fracture mechanics.

Another widely used test method for characterization of mode III interlaminar fracture toughness is the Edge Crack Torsion (ECT) specimen [129]. The geometry and loading of the ECT are illustrated in Fig. 22.

The ECT test configuration is simpler compared with the SCB and the CRS tests. A thin film is placed at the mid-plane of the ECT specimen to give an initial delamination crack of length a. It has been shown that the ECT test is very effective because almost pure mode III delamination crack loading conditions can be achieved. Three-dimensional finite element simulations were performed of the ECT specimen in Ref. [117]. The delamination behaviour was analyzed using linear-elastic fracture mechanics. The strain energy release rate mode components along the crack front were calculated by the virtual crack closure technique using the results obtained from the finite element modelling. It was found that the mode III component of the strain energy release rate

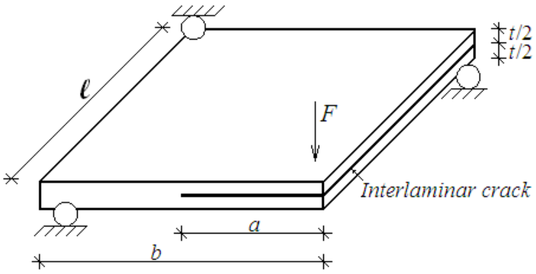

Fig. 22. Edge crack torsion specimen

was distributed almost uniformly in the central region of the crack front. The mode III component decreased to zero at the free edges of the specimen. Mode II components were found near the loading point and close to the ends of the specimen. In these regions, the maximum value of the mode II component was about 30 % of the mode III component value. However, the average mode II component value over the crack front was negligibly small compared with the mode III. The effects of various configuration parameters such as loading conditions, crack length, and specimen geometry on the interlaminar fracture behaviour were investigated. The mode III component of the critical strain energy release rate averaged over the crack front was comparable with the fracture toughness determined by the compliance method using the ECT test data.

Prediction of the interlaminar crack growth onset under mixed-mode loading conditions is one of the important problems in fracture mechanics of composites. For this purpose, various interactive fracture criteria have been developed. One of the most widely used of these criteria is given by the following equation [130]:

$$\left(\frac{G_I}{G_{IIC}}\right)^m + \left(\frac{G_{II}}{G_{IIC}}\right)^n = 1, \tag{52}$$

where G_I and G_{II} are the strain energy release rates in modes I and II, respectively; G_{IC} and G_{IIC} are the critical values of the G_I and G_{II}; and m and n are empirically determined exponents.

The mixed-mode interactive fracture criterion, developed in Refs. [131, 132], possesses the form:

$$\left(\frac{G_I}{G_{IC}}\right)^m + \left(\frac{G_{II}}{G_{IIC}}\right)^n + k\left(\frac{G_I}{G_{IC}}\right)^2 = 1, \tag{53}$$

where the parameter k is determined by correlating the experimental data.

Ref. [133] reports the following mixed-mode interactive fracture criterion:

$$\frac{G_I}{2} + \frac{1}{2}\sqrt{G_I^2 + 4\left(\alpha_1 G_{II}\right)^2} = G_{IC}, \tag{54}$$

where the material constant $\alpha_1$denotes the mode I to mode II fracture toughness ratio, i.e.:

$$\alpha_1 = \frac{G_{IC}}{G_{IIC}}. \tag{55}$$

A mixed-mode delamination fracture criterion of exponential form was developed in Ref. [130] for graphite/epoxy composites, i.e.

$$G_I + G_{II} + e^{-C_1 M + C_2} - C_3 = 0, \tag{56}$$

with

$$M = \sqrt{1 + \frac{G_{II}}{G_I}\sqrt{\frac{E_1}{E_2}}}, \tag{57}$$

where E_1 and E_2 are Young's modules of the composite and C_1, C_2 , and C_3 are empirical parameters.

The mixed-mode fracture criterion proposed by Gong and Benzeggagh includes the total strain energy release rate G_T and its critical value G_{TC} [132]:

$$G_{TC} = G_{IC} + \left(G_{IIC} - G_{IC}\right)\left(\frac{G_{II}}{G_T}\right)^m, \tag{58}$$

where m is a material parameter.

The total strain energy release rate is included also in the mixed-mode delamination criterion introduced by Yan et al. [134]:

$$G_{TC} = g_1 + g_2\left(\frac{G_{II}}{G_T}\right) + g_3\left(\frac{G_{II}}{G_T}\right)^2, \tag{59}$$

where g_1, g_2, and g_3 are empirical parameters.

Kaczmarek et al. [135] used the following criterion to predict delamination growth onset under general mixed-mode I/II/III crack loading conditions:

$$\frac{G_I}{G_{IC}} + \frac{G_{II}}{G_{IIC}} + \frac{G_{III}}{G_{IIIC}} = 1, \tag{60}$$

where G_{III} is the strain energy release rate in mode III, G_{IIIC} is the experimentally measured critical value ofG_{III} for the composite considered.

One of the perspective applications of the continuously fibre reinforced composites are the sandwich structures. These structures typically consist of two stiff composite face sheets adhesively bonded to a light-weight core (Fig. 23).

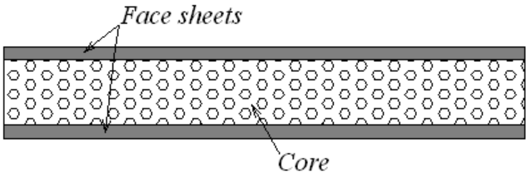

Fig. 23. Sandwich structure

The face sheets carry the bending moments and the axial loads while the function of the core is to carry the transverse forces and to connect the faces. In this way, every component of the sandwich is stressed to its limit, which is a precondition for weight savings. The use of sandwich structures in various branches of engineering is constantly increasing [136, 137, 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 148] due to a superior stiffness and strength per weight in comparison with conventional structural materials.

However, the sandwich structures may contain various defects induced during manufacturing process, inherent imperfections in the core, and damages inflicted during lifetime of the structures. The presence of such damages and imperfections is a premise for crack initiation and propagation. It should also be noted that cracks in the core are especially insidious, because they can be very difficult to detect by visual inspection of the sandwich structure. Therefore, it is important to perform both experimental and analytical investigations of the fracture behaviour of sandwich structures.

Mode I fracture behaviour of syntactic foam used as light core material for composite sandwich panels was studied in Ref. [149]. For this purpose Three Point Bending (TPB) fracture tests were performed. The geometry and loading of the TPB are shown in Fig. 24.

The specimens were manufactured by the Tencare 2000 syntactic foam. A very sharp-edged notch with length of 7 mm was introduced in the mid-span section of the specimen to act as an initial crack. The tests were carried-out under displacement control at a constant rate of 0,2 μm/min. The experimentally obtained load-displacement diagram was linear up to the crack growth initiation. After that there was a sudden vertical drop, i.e. the fracture re-

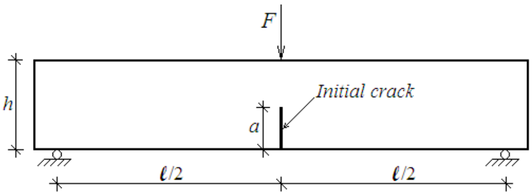

Fig. 24. Three point bending specimen

sponse was quasi-brittle. It was observed that the crack growth initiated in the vicinity of the sharp-edged notch and propagated vertically. Two-dimensional finite element simulations of the TPB specimen were performed. The results of the simulations were in good agreement with the test data.

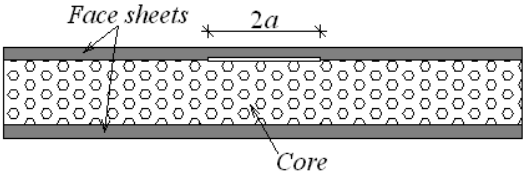

Fig. 25. Face sheet/core debonding problem

Face sheet/core delamination cracks in sandwich structures were analyzed in Ref. [148]. The research was motivated by the fact that the ultimate load carrying capacity of a sandwich structure may be significantly reduced by the presence of a face sheet/core debonding or delamination. The fracture problem under consideration is illustrated in Fig. 25. A delamination crack of length $2a$ is located along the face sheet/core interface. It was assumed that the face sheets are manufactured of graphite/epoxy composite. The sandwich core itself was assumed to be a rigid foam material. A two-dimensional finite element model of the sandwich structure was developed. The delamination crack was analyzed according to linear-elastic fracture mechanics. The tendency of the delamination to grow was assessed by the virtual crack closure technique. The total strain energy release rate was partitioned into mode I and mode II components. It was found that the mode II component was predominant compared with the mode I in the considered situation. The effects of various structural and material parameters on the delamination fracture behaviour were investigated. The calculations revealed that the strain energy release rate mode components increase with increasing the crack length. The influence of the core stiffness on the strain energy release rate was also studied. The analysis indicated a significant decrease of delaminaton tendency with increasing the core Young's modulus. The effect of a variation of the face-sheet thickness was also examined. It was found, that the mode I component of the strain energy release rate is monotonically decreasing with the increasing bottom face sheet thickness. The variation of the mode II component exhibited a non-monotonic nature. The calculations showed that the mode II is maximum when the top and bottom face sheet thicknesses become equal.

Fracture behaviour of closed cell rigid polymeric foam frequently used as core material in sandwich structures was investigated by Bazhant et al. [150]. Mode I fracture toughness was characterized using the tensile fracture test (Fig. 26).

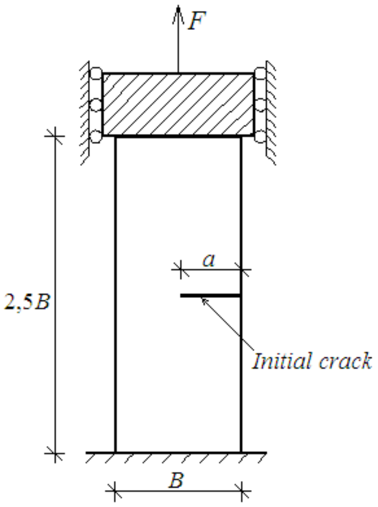

Fig. 26. Single edge-notched prismatic specimen

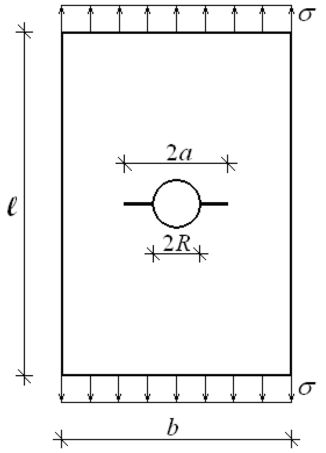

Fig. 27. Rigid foam panel specimen with a centric horizontal crack of length $2a$

Single edge-notched prismatic specimens were cut from foam panels and tested under tension in an Instron-8500 testing machine. It was found, that linear-elastic fracture mechanics can be applied to analyze the test data. The obtained fracture toughness values were compared with values determined using the three-pint bending test. An analysis of the tensile fracture test data for holed rigid foam panels was also performed. The geometry and the loading of the panels are depicted in Fig. 27.

It was concluded, that a tensioned prism with one edge notch at mid-length is a suitable fracture test specimen for light foams, because this specimen fails in purely mode I fracture.

The fracture behaviour of linear-elastic cellular foams was analyzed by

Ashby et al. [151]. They developed a model based on the assumption that the crack extension occurs when the stress is sufficient to fracture of the cell wall closest to the crack tip. For this purpose, the forces and the bending moments in the cell walls were calculated considering the equivalent continuum problem. Expressions were derived for the fracture toughness as a function of the foam density.

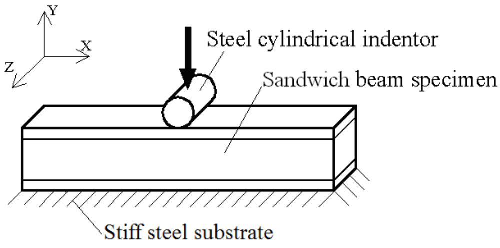

Fig. 28. Schematic of the composite sandwich beam indentation test

The compliance method was applied to calculate the fracture toughness of cellular foam using test data from specimens of four different geometries in Ref. [152]. The fracture toughness was analyzed in terms of the critical strain energy release rate applying linear-elastic fracture mechanics. Good agreement was found between results generated by different specimens. It was concluded that the mode I critical strain energy release rate is a fundamental property that characterizes the tensile behaviour of the foam under consideration. Other authors found a dependence between the mode I fracture toughness and the cell structure [153].

It was mentioned above that cracks in composite sandwich structures usually initiate from damages inflicted during the manufacturing or lifetime of the structures. Foam core sandwich structures are highly susceptible to local damages induced by external lateral load due to their low transverse stiffness. Therefore, it is important to investigate the nonlinear mechanical behaviour of sandwich structures subjected to localized loading (indentation). Elastic-plastic indentation behaviour of foam core composite sandwich beams is studied in Ref. [154, 155, 156]. Static indentation tests were carried-out using a steel cylindrical indentor (Fig. 28). The load-indentation curve was recorded automatically for both loading and unloading steps during the testing. A typical load-indentation curve is depicted in Fig. 29. The curve has a generally nonlinear shape due to the elastic-plastic behaviour of the foam core. The load-indentation response is linear at the beginning of the testing (i.e., at

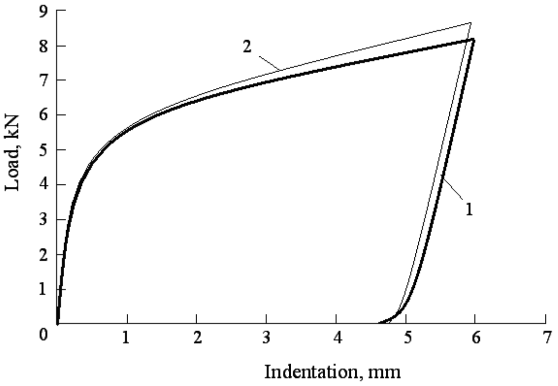

Fig. 29. Load-indentation diagram of a foam core composite sandwich beam: experimental data (curve 1) and finite element modelling (curve 2)

low indentation magnitudes). The end of the linear response is associated with onset of plastic deformation in the core in the area under the indentor. After that the curve becomes nonlinear with a rather fast progressive degradation of the sandwich beam stiffness. A residual dent was clearly observed in the upper face sheet after the unloading. This finding was associated with the extensive plastic deformation of the foam. Finite element simulations of the indentation behaviour of composite sandwich beams were conducted. The foam core was modelled as an elastic-plastic material. Good agreement was found between the calculated load-indentation response and the experimental one (Fig. 29). The nonlinear indentation behaviour of foam core composite sandwich panels is investigated in Refs. [157, 158, 159]. Indentation tests were performed using steel spherical indentor. Finite element analysis was carried-out using elastic-plastic model. Good match between the numerical results and the experiential findings was achieved.

Finally, a few words about the through-thickness fracture behaviour of composites. One of the frequently used test methods for experimental characterization of through-thickness cracks is the Compact Tension (CT) specimen [160]. The loading and geometry of the CT specimen are depicted in Fig. 30. A notch was introduced in the specimen to act as an initial crack of length a. The fracture toughness was characterized in terms of the critical value of the mode I stress intensity factor. Linear-elastic fracture mechanics was applied to calculate the stress intensity factor on the basis of the experimental data. However, when characterizing through-thickness cracks in some cases linear-elastic fracture mechanics is not applicable, because the longitudinal strength

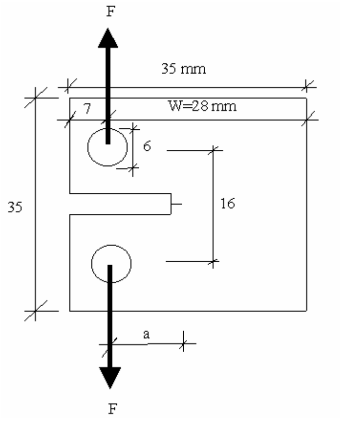

Fig. 30. Compact tension test specimen

(which is fibre dominated) tends to be much higher in comparison with the strength in transverse direction. Typically, in such cases damage zone develops in the crack tip area prior to crack growth onset. This type of fracture has to be analyzed using non-linear fracture mechanics. The effect of damage induced non-linear deformation on the through-thickness fracture behaviour is studied in Refs. [161, 162, 163]. Non-linear finite element simulations were carried-out using different failure criteria. Very good agreement was obtained between the simulated and the measured load-displacement response up to the crack growth onset. The damage distribution was analyzed. It was found that the damage is located in the vicinity of the crack tip.

4. Conclusions

The following conclusions can be drawn from the overview of the literature on the fracture in composites.

1. Interlaminar fracture in continuously fibre reinforced composite materials is one of the commonly observed failure modes.
2. The interlaminar crack path is parallel to the reinforcing fibres. This is due to the fact that the crack initiates and propagates in the matrix along the fibres.
3. The strain energy release rate is the most widely used approach in both theoretical and experimental studies of fracture. Obtaining of closed form analytical solutions for determination of the strain energy release rate is an important problem of fracture mechanics. The closed form solutions can be very useful in parametric analyses of interlaminar cracks in beam type composite structures.

4. The closed form analytical solutions published in the specialized literature are concerned with determination of the strain energy release rate in composite beams containing an initial crack at the mid-thickness. However, cracks in real composite structures may have an arbitrary position in the thickness. Therefore, it is important to obtain closed form solutions for composite beam specimens with asymmetrical location of the initial crack.

5. Usually, two-dimensional finite element models are used for analyses of cracks in the foam core of sandwich structures. However, these models can not be applied to investigate the distribution of the strain energy release rate along the crack front.

6. Fracture is closely related to the damages in the material (cracks usually initiate from damages which act as stress concentrators). Therefore, the problem of damage behaviour needs more investigations.

5. Topical problems

1. Obtaining of closed form analytical solutions for determination of the strain energy release rate in composite beam configurations which contain an initial interlaminar crack with arbitrary position in the thickness. These solutions can be used for parametric analyses of the interlaminar fracture behaviour. The results obtained can be applied for optimisation of the composite structures with respect to the fracture resistance. The solutions can also be used to evaluate the interlaminar fracture toughness under various mixed-mode I/II loading conditions on the basis of the test data.

2. Obtaining of closed form analytical solutions of J-integral for interlaminar cracks in composite beams.

3. Performing three-dimensional finite element analyses of cracks in rigid foams (widely used as core material in sandwich structures). Investigation of the strain energy release rate distribution along the crack front.

4. Studying of mode III interlaminar fracture behaviour of composite materials.

5. Analyses of indentation damage behaviour of composite sandwich structures.

6. Investigations of the influence of damages on through-thickness fracture behaviour of composites.

REFERENCES

The references are cited in PART I, published in vol. 42, No. 2, pp. 3–42.