DEVELOPMENT OF TEST METHODS FOR ADHESION MEASUREMENTS OF FLEXIBLE ELASTIC MATERIALS

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ABSTRACT

In this paper a new test method for the fracture toughness measurements is presented. This method is best suited for delamination testing of long flexible elastic specimens. The method is based on a *J*-integral calculation for a well-known Double Cantilever Beam (DCB) specimen and doesn't require any knowledge about elastic properties of the tested material or crack length measurements. The comparison with method based on beam theory and finite element simulations was made and sufficiently good agreement was obtained.

1. INTRODUCTION

In the last years the composite materials become material of choice for many advanced aircraft structural applications. Superior weight/performance properties of carbon fiber composites take advantage over the metals. However, the cost of the manufacturing process still is a critical issue for composites. In the PreCarBi project new materials [1] (carbon fibers and liquid resins) will be developed, that have advantages of both prepreg and liquid resin moulding technologies. Pre-impregnated carbon fibers with a polymer binder can be repeatedly activated (by using heat, microwave, ultrasound) and shaped prior to resin infusion. The ability of activated binder yarns to adhere to different materials is very important property and should be tested at the development stage to optimise the binder content.

The objective of this work is to develop a new test method for fast and reliable fracture toughness measurements of new material activated at different conditions. The method should simplify the preparation of the specimens and experimental set-up, allowing to perform many experiments in short time.

2. DCB TEST METHOD

The DCB test method is one of the most used experimental techniques for fracture toughness measurements. Comprehensive reviews on the DCB tests method was published by Davies *et al*. [2] and Blackman *et al*. [3]. The energy release rate G in a DCB specimen is defined in the usual way:

$$G = \frac{P^2}{2b}\frac{\partial c}{\partial a} \quad . \tag{1}$$

The deflection of an ideal cantilever beam of length a, width b, and bending stiffness $EI = \frac{Ebh^3}{12}$ under a load P is equal to $\frac{a^3 P}{3EI}$. The full opening of the DCB specimen equals the doubled deflection

$$d = \frac{2a^3 P}{3EI} \ , \qquad (2)$$

and the compliance is

$$c = \frac{2a^3}{3EI} \ . \qquad (3)$$

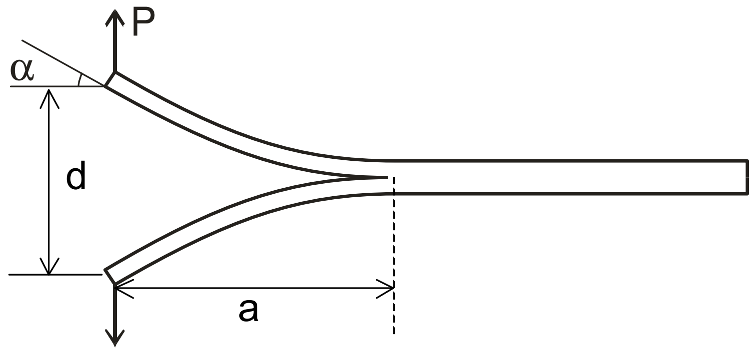

Figure 1: Geometry of the DCB specimen.

Several expressions for the energy release rate can be obtained by combining Eqs. (1-3), as described in [4]. They all give different results, because real DCB specimen is not perfectly clamped at the end of the delamination, as it was assumed in the beam analysis above. One of the most popular formulas for energy release rate calculation is

$$G(P,a,d) = \frac{3Pd}{2ba} \ . \qquad (4)$$

Another formula for the energy release rate calculation also can be derived as follows

$$G(P,d) = \frac{P^2}{EIb}\left(\frac{3EId}{2P}\right)^{2/3} \ . \qquad (5)$$

Eq. (4) usually overestimates the value of *G*, therefore ASTM standard [5] recommends to correct results by using some fictitious crack size $a+\Delta a$, where Δa is determined by generating a least-square plot of the cube-root compliance $(d/P)^{1/3}$ as a function of the crack length *a*. The method is called "Modified Beam Theory (MBT)". It is clear that the introduction of an artificially increased crack size will improve the results of Eq. (4). However, the MBT method has two disadvantages. First, the reduction techniques assume that the energy release rate of a material has a constant value during the crack propagation, and, therefore, it cannot be used for materials with extensive bridging. Second, the fitting procedure requires many experimental points in order to increase the accuracy. Applying this method in situations where only few experimental points are available can lead to large errors.

Eq. (5) is free of such drawback, it gives very accurate results even for very short cracks and, since it doesn't use regression technique, it can be used in situations, where fracture toughness in not constant along the specimen.

Another interesting expression for energy release rate calculations was derived by Paris and Paris [6]. Let us consider a DCB specimen, as is shown in Figure 1. Evaluation of the *J*-integral along exterior boundary of the specimen lead to the simple expression of the energy release rate:

$$J = \frac{2P\alpha}{b}, \quad (6)$$

where α is the rotation of the arms evaluated at the load points and b is the specimen width. The Eq. (6) is valid for any elastic material without any knowledge of the load-displacement diagram, material properties, and crack length measurements. However, this result was obtained with assumptions of small strains and small rotations, therefore application of this method to stiff specimens, when angle at the load point are small, requires special equipment to measure the angles with high accuracy. This method was used in [7-10] to measure the fracture toughness of different materials.

Nilsson F. [11] considered the same problem with the assumptions of large displacement and obtained corrected analytical expression for J-integral:

$$J = \frac{2P\sin\alpha}{b}. \quad (7)$$

Eq. (7) coincides with Eq. (6) in case of small angles and can be applied for slender DCB specimens, where large displacements aspects can be important. For the very flexible materials (or very long specimen), when the angle at the loading point approaches 90 degrees, Eq. (7) gives the same result as standard peel test: $J=2P/b$.

3. SPECIMENS PREPARATION AND EXPERIMENTS.

Due to the nature of new material, usage of conventional DCB method is complicated in several ways.

- Specimens have to be manufactured by hands from narrow and thin tows of the binder yarns (about 7×0.1 mm). Assembling of many layers of such yarns may result in imperfections inside thick specimens, needed for DCB test.
- It will take long time to achieve uniform temperature distribution inside thick specimen during activation in electric oven.
- It could be expected, that properties of the material will be non-uniform during development stage, with large scatter of adhesion properties even along single specimen. Standard DCB methods based on the regression techniques can’t be used in this case.
- Elastic properties of activated binder yarn are highly anisotropic, its shear modulus is about 300 times lower, than longitudinal modulus. Accuracy of the energy release rate calculation methods for standard thick specimens is questionable.

Therefore new method was developed, which allows performing many experiments in short time using long flexible specimens.

Specimens were assembled on a thin (2 mm) brass plate. Each specimen has two binder yarns in the width direction, 6 layers in thickness direction and is about 30 cm long. The specimens are then located between two other brass plates and heated in temperature chamber under pressure. Four specimens (two on each side) can be assembled and activated simultaneously using the same conditions. To apply uniform pressure thick steel plates are used with a gap between steel and brass plates for better hot air ventilation, as is shown in Figure 2.

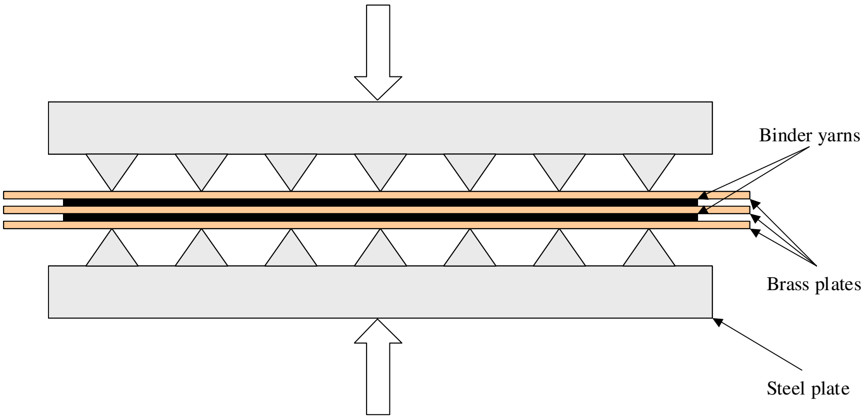

Figure 2: Preparation of the specimens.

Eq. (7) was used to calculate critical energy release rate of binder yarns. Light thin pieces of wire were glued to the specimen near the loading point, so that bending angle of specimen arm during testing can be easily measured. The specimen was loaded using displacement control with speed 0.4 mm/sec. Digital photo of the specimen was taken several times during loading for angles measurements (Figure 3).

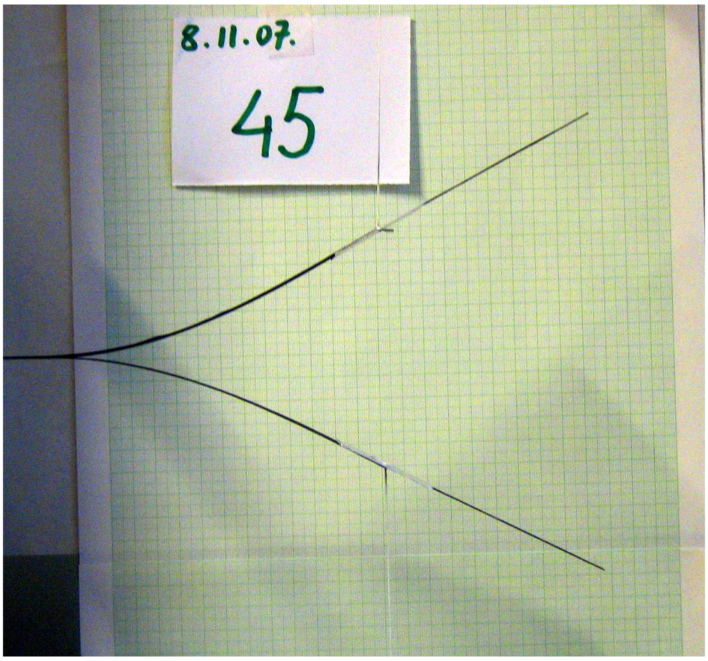

Figure 3: Delamination of slender DCB specimen.

4. SIMULATION OF DELAMINATION GROWTH WITH COHESIVE MODEL

Cohesive (or interface) models have been widely used in the past years for modelling of delamination growth in composites. Cohesive models have several advantages over the fracture mechanics based methods. They are particularly useful in tracking of delamination growth, since no remeshing of the finite element model is required. Cohesive model is used in this work as a benchmark for the new test method. The crack propagation in the specimen has been modelled using finite element method and results are compared with experimental data.

General purpose finite element code ABAQUS has been used for simulations. Finite element mesh is shown in Figure 4. Cohesive elements (built-in in ABAQUS) are inserted between upper and lower parts of the specimen. The traction-separation law for the cohesive element was chosen such that the energy required for total separation of the elements is equal to the experimentally measured fracture toughness of the specific specimen (20 J/m^2 were used in simulations). Young's modulus and Poisson's ratio used in simulations equal 140 GPa and 0.25 respectively.

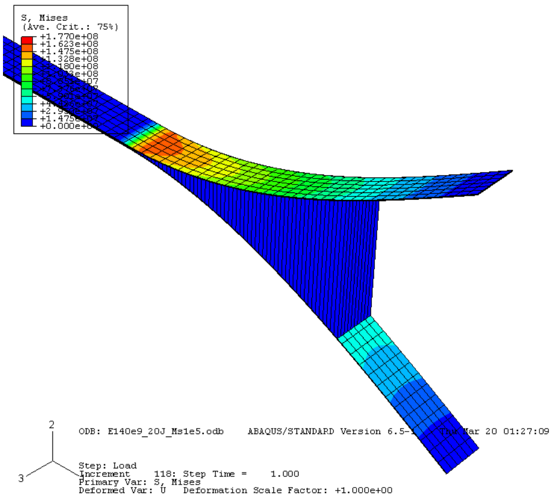

Figure 4: Finite element simulation of delamination of slender DCB specimen.

5. RESULTS AND DISCUSSION

In Figure 5 a load-deflection curves together with calculated critical energy release rate are shown for two specimens. The critical energy release rate was calculated using *J*-integral method and Eq. (5). The dots indicate moments when digital image was taken for measurements of angles at the specimen's arms. For the first specimen the critical energy release rate was almost constant for whole length of the specimen, while in second case a large variation of the adhesion properties along the specimen is observed. It can be concluded, that two used methods for G_{IC} calculations perform equally well in both situations for relatively short cracks. Increasing difference for long crack is due to large displacements and rotation effect. For slender specimens used in experiments the angle at the specimen's arms end can be higher 45° and correction should be used for the methods based on beam theory. The *J*-integral method doesn't require any correction and can be used even for larger angles. Both methods do not require crack length to calculate critical energy release rate, therefore it was not measured during the experiments for simplicity reasons. The energy release rate is plotted as a function of specimen's opening in Figure 5.

Finite element method with cohesive elements was used to model the delamination of the specimen. The fracture toughness of the modelled specimen, calculated using *J*-integral method, was equal 20 J/m^2 and this value was used in traction-separation law for cohesive elements. The experimental load-deflection curve (thin line in Figure 6) and results of simulation (thick line) show that numerical prediction of overall response of the model and delamination growth is very close to the experimental one.

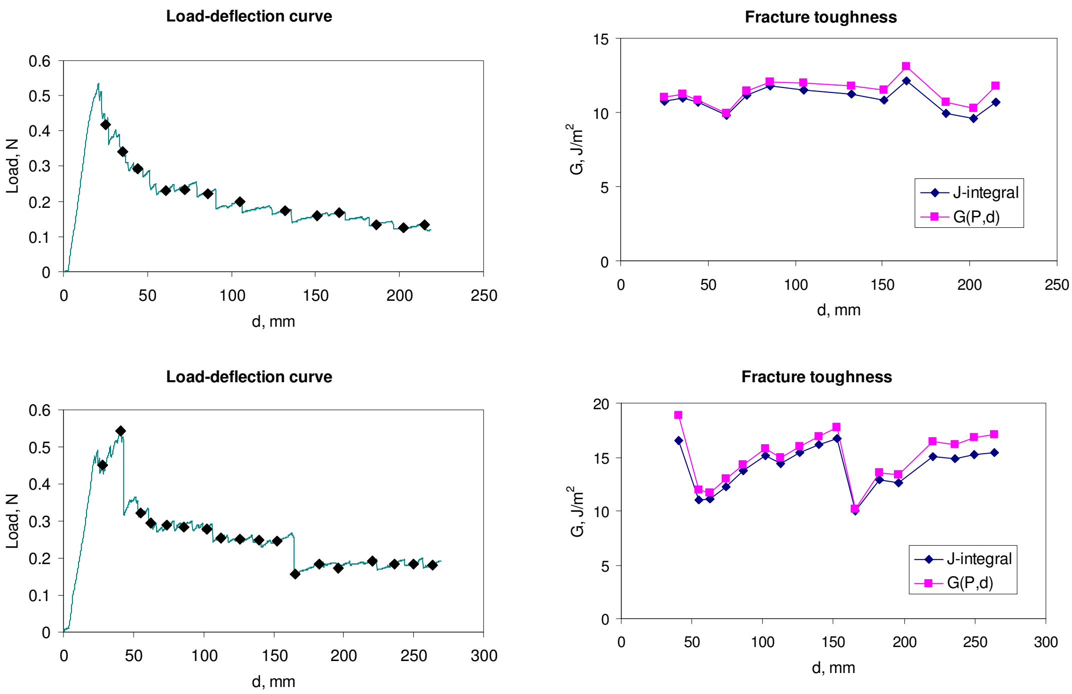

Figure 5: Typical load-deflection curves of the flat specimens (on the left) and calculated critical energy release rate (on the right). Dots indicate moments, when digital image was taken.

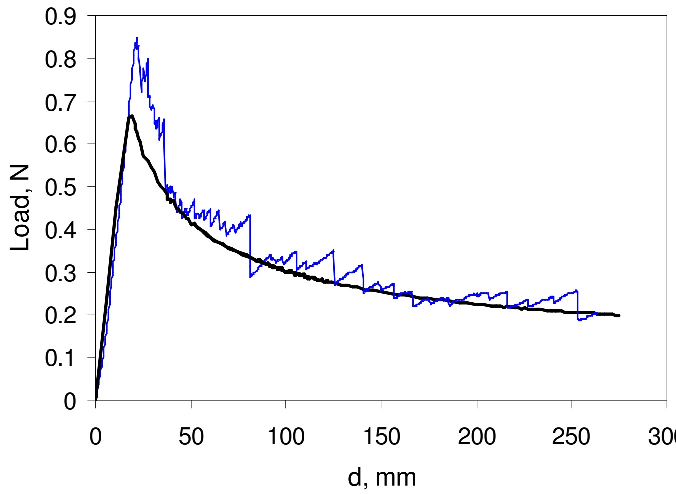

Figure 6: Load-deflection curve, thin line – experiment, thick line – FE simulation.

6. CONCLUSIONS

A new test method for the fracture toughness measurements is presented in this work. The method is based on the result obtained by F. Nilsson for the *J*-integral evaluation along the external boundaries of the specimen, taking into account large displacements and rotation of the specimen's arms during loading. The expression obtained by F. Nilsson requires only the measurements of the peeling force and the angle of the specimen's arm at the loading point. No material data, specimen thickness or the crack length is necessary to calculate fracture toughness, which makes this method very attractive for the testing of elastic flexible specimens. In this method small errors in measured parameters give small error in calculated fracture toughness and the accuracy

of the obtained results can be easily estimated. Presented method can be applied in situations, when critical energy release rate is not constant along the sample or only few experimental point are available, since no fitting of the experimental data is required.
The results of *J*-integral calculations are compared with Eq. (5) and sufficiently good agreement was obtained. As it was found in [4], Eq. (5) gives very accurate results, comparing with other methods based on beam theory. The difference between these two methods for long cracks is due to the large displacements, which are not taken into account in Eq. (5).

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