

The effect of plasticity to interlaminar fracture toughness of adhesive bond of composite

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Abstract. In this paper the effect of plasticity of an adhesive to interlaminar fracture toughness of adhesive bond of thin-walled layered composite is investigated. The characteristics of failure of low toughness adhesive layer were obtained using the double cantilever beam (DCB) sample. The main features of plasticity effect are obtained. The procedure of results use for strength analysis of structure with the plasticity affected adhesive joint is proposed.

1. Introduction

Adhesive joints of structural components are attractive as for manufacturing of the new aircraft or for repair of structural elements during operation. This type of joint is a good alternative to traditional joining systems (e.g., riveting or welding) for a wide class of components assembling to electronic, automotive, and aerospace industries. There are huge number of publications in this field and the wide range of review-articles dedicated to different aspects of research and developments, production and applications [1-14].

There are many different parameters for strength introduction of the adhesive joints. One of the most important properties of this kind of joint is its resistance of debonding under mechanical load. Like delamination of composite laminates, it can be characterized by the interlaminar fracture toughness. It is known that for the ideally brittle components of adhesive joint the Griffith theory can be used for prediction of strength of an adhesive joint with partial debonding. Only one parameter, the interlaminar fracture toughness, defines condition of delamination propagation.

However, usually one-parametric estimation of crack (delamination) growth is not sufficient for different type of material and configuration of the damaged structural component. In these cases the additional parameters and models are needed for adequate description of a damaged component fracture. Nowadays the most popular is so called the cohesive zone model, that was founded in [15,16] and improved in many further research. This model allows to describe small crack growth and is used also for describing of the stable crack propagation (R-curve). The concept of the R-curve was developed for crack stable propagation in the plane stress and the first stage of research in this field is given in [17]. Further development and applications of the cohesive zone model and the concept of the R-curve for layered composites and adhesive joints are given in [18-24] and many others publications.

Problem of adhesively bonded joints with ductile adhesive materials is investigated much less [25,26]. The interesting is the work [27] in which the process of crack stable growth in the elastic-plastic material is described using only one constant of material.



In this paper the effect of plasticity of an adhesive to interlaminar fracture toughness of adhesive bond of thin-walled layered composite is investigated. The characteristics of failure of low toughness adhesive layer were obtained using the double cantilever beam (DCB) sample.

2. Experimental study

2.1. Test setup, sample material and sizes

The glass/epoxy laminate reinforced by glass fabric was used for preparation of the test samples. The 25x125 mm strips were cut from the GFRP 2 mm thick plate and they were used as the adherents of adhesive joint manufacturing in the form of the DCB sample (figure 1) with initial deboning 55-60 mm. The adherents were connected by the two-component epoxy paste EPON 828/EPICURE 3140 and were cured at room temperature. The curing time for samples of group 1 was 1 day but for group 2 it was more than 7 days. The thickness of adhesive layer was not more than 0.5 mm. Operating forces are applied to the specimen by mean of the loading blocks.

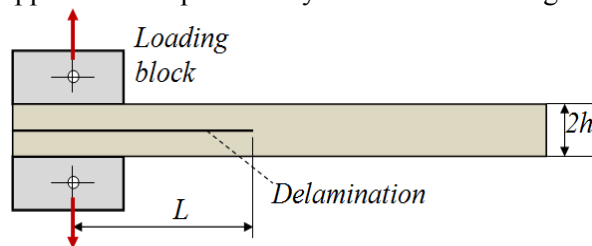


Figure 1. Schematic view of the DCB sample.

During the test with the controlled displacement of 3 mm/min rate the data force /extension (load points relative displacement) was digitally stored permanently with periodic stops for accurate fixing of the current size of delamination, further unloading and determination of residual extension of sample. Delamination continues growth during loading was observed without the unstable increment of delamination front in contrast, for example,

with the high-strength laminate. The significant residual extension after unloading also was indicated.

2.2. Procedure of testing and primary test data

The quasi-static tests of DCB samples, according to the standard, were carried out on an Instron 8800 hydraulic testing machine with controlled displacements at the constant rate of movable clamp 3mm/min. To increase the accuracy of measurement of small values of the load, the S2M meter of small loads (HBM Test and Measurement), with the upper measurement limit of 1 kN, was connected in series in the loading circuit as the basic force sensor.

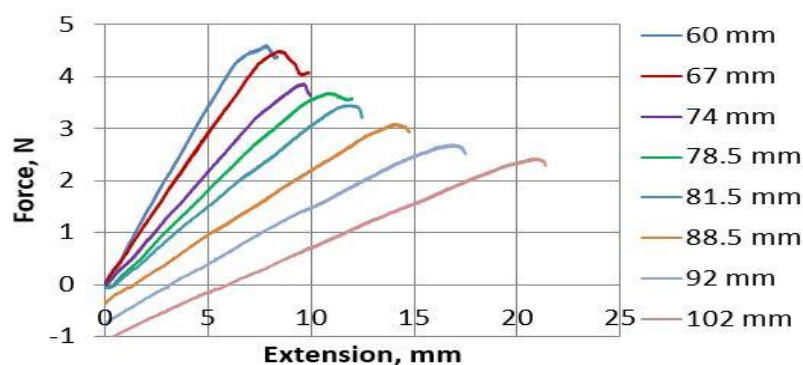


Figure 2. Force/extension function for a sample of group 1.

The test procedure generally corresponds to ASTM Standard [28] with some deviations caused by specific features of elastic-plastic deformation during test of the DCB sample of group 1. The standard provides for a continuous loading of the sample at a constant rate moving jaws until a final increment of delamination. A closing step test is supposed to discharge with the same speed as the loading rate. In the present experiment, the step-to-step loading/unloading after each 5-7 mm increment of

the delamination length was realized. Such modification of the test procedure provides an adequate definition of the elastic compliance on the linear portion of the force/extension record, as well as a more accurate measurement of the initial crack length at the beginning of each loading step.

The curves of loading are showed in figures 2 and 3 for a sample of group 1 and group 2 respectively. In the legend of the plot right side the delamination initial length before each next step of loading is shown.

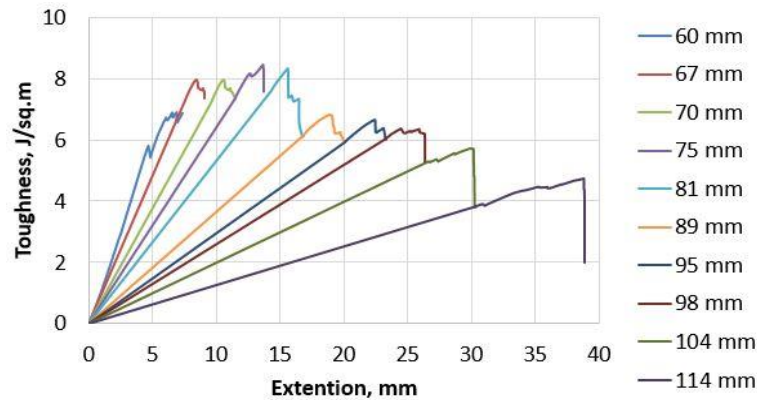


Figure 3. Force/extension function for a sample of group 2.

3. Test data processing, analysis and discussion

3.1. General comparison of test results of two groups of samples.

Common for both groups is a linear relationship between the extension and the load before the start of the delamination growth. However, there is significant difference in the behaviour of samples under stress. The delamination of a sample of group 1 grows smoothly without of sudden jumps of load. In contrast, in the sample of the group 2 the jump-like growth of delamination and sharp drop of load is observed. The linear dependence of load/extension remains up to a jump.

Other feature of behaviour of the sample of group 1 is also observed: if there is large increment of delamination, the compressive load is needed for complete closure of the sample unloading (in figure 2). Obviously, this behaviour is caused by plastic deformation of adhesive layer and the roughness of surface of delamination due to residual strain.

In general, it can be concluded that the adhesive layer in the samples of group 1 have pronounced elastoplastic properties. A sample of the group 2 is characterized by an elastic behaviour and brittle fracture of adhesive layer.

3.2. Interlaminar fracture toughness

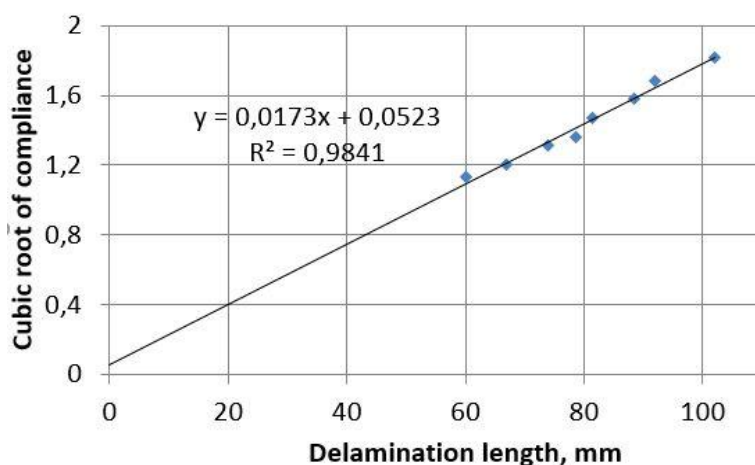


Figure 4. For of the effective length of delamination.

The standard [28] normally is used in practice of the determination of the mode-I interlaminar fracture toughness of a brittle adhesive joint. Here this standard is used formally also for the elastoplastic adhesive joint. Three options of processing were used: modified beam theory (MBT), compliance calibration method (CC) and modified compliance calibration method (MCC). It is known that the MBT method assumes use of the effective length of delamination to correct DCB arms rotation at delamination front. In figure 4 the cubic root of a

DCB elastic compliance is presented as a function of delamination length for the sample of group 1. So, the elastic compliance C of the DCB sample can be introduced as follow

$$C = \frac{\delta}{P} = (\alpha L + \beta)^3, \quad (1)$$

where P is applied load, δ is load point extension, α and β are regression coefficients (in figure 4 above).

The DCB elastic compliance was obtained as the slope of linear part of the experimental function extension/ delamination length (figure 4). It shows that there is close correlation of these two variables.

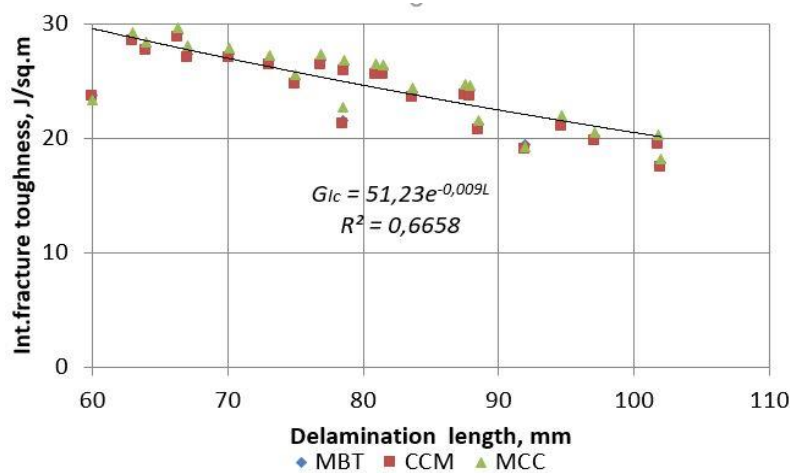


Figure 5. Interlaminar fracture toughness as a function of delamination length of the group 1 sample.

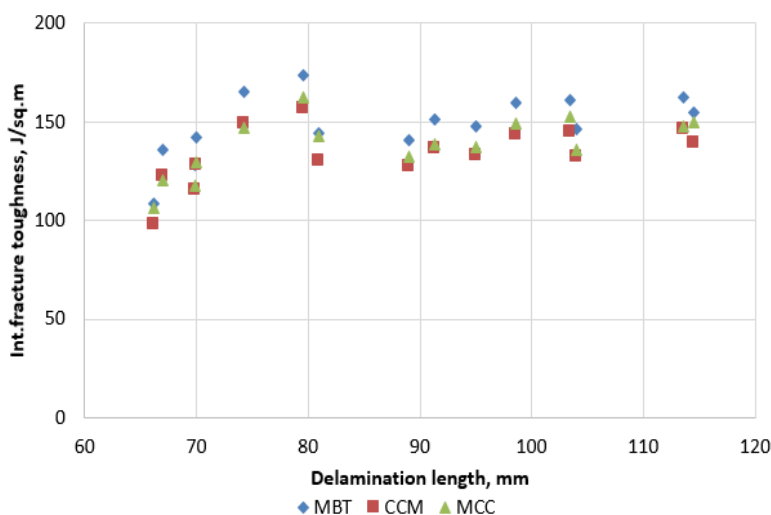


Figure 6. Interlaminar fracture toughness as a function of delamination length of the group 2 sample.

The exponential regression equation (figure 5) was used for determining of the effective length of delamination during the linear portion of a sample loading, and to estimate the actual length of delamination at its growth.

In figure 5 the results of test data processing are presented for samples of group 1. Each point of this graph corresponds to the maximum of the experimental curve load/extension of corresponding step of test. The length of delamination is estimated using mentioned regression equation.

In the figure 6 the outcome of test data processing is presented for samples of group 2.

It is seen that for the samples of group 2 beginning since the 70-mm delamination length G_{Ic} approximately is constant about 150 J/m². Only for the initial length of delamination the G_{Ic} is smaller. Usually this effect is called as **R-curve**.

For the samples of group 1, this parameter is significantly lower, and the monotonic decrease is observed with the increase of delamination length.

3.3. Analysis of unsteady growth of delamination

In figures 5 and 6 the stress energy release rate is defined by standard procedure for the steady state at which the force is maximal. But because test loading is process with extension non-zero rate, there is some specific evolution both the force and the length of delamination.

After some simple operations, the rate of delamination growth can be expressed in equation (2)

$$\frac{dL}{dt} = \frac{1 - C \frac{dP}{d\delta} \frac{d\delta}{dt}}{3P \frac{dC}{dL}} \quad (2)$$

The $P(\delta)$ is the main outcome of test of the DCB sample. Nonlinear portion measured function (growth of delamination) $P(\delta)$ were approximated by fifth-degree polynomial for determination of a derivative $dP/d\delta$. The derivative dC/dL is defined by equation (1). So, the rate of delamination growth was calculated as time function, and integrating of equation (2) gives current delamination length.

As a result, the strain energy release rate can be also calculated for any time moment. The MBT approach gives

$$G_I = \frac{3P\delta}{2H(L + \Delta)} \quad (3)$$

where $\Delta = \beta/\alpha$ is the correcting member of delamination length.

In figure 7 the evolution of load and rate of delamination growth is presented for 67 mm initial length of crack. Note that because the rate of extension is constant, then the evolution of mentioned parameters

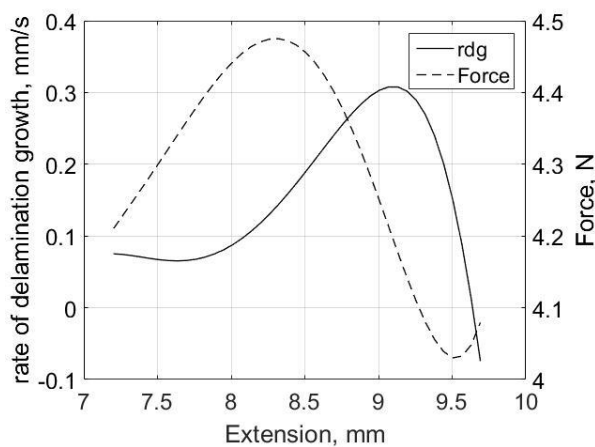


Figure 7. Evolution of load and rate of delamination growth for its initial length 67 mm.

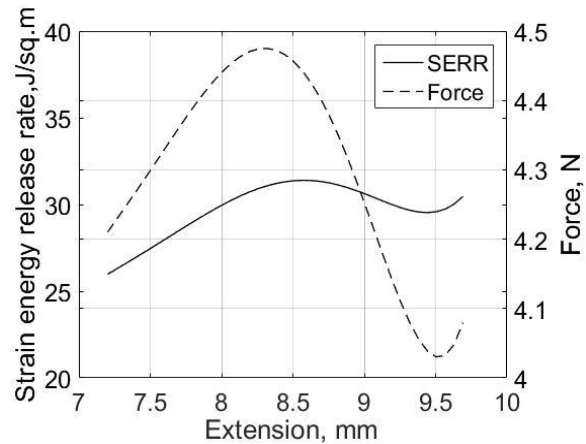


Figure 8. Evolution of load and strain energy release rate for delamination length 67 mm.

in time is similar. It is seen that the rate of delamination a few increases before load maximum, but its peak is reached significantly later. In figure 8 comparison of two processes (force and strain energy release rate) evolution is presented for the same step of loading. It is seen that maximum of the strain energy release rate corresponds the downward part of the $P(\delta)$ function.

Integrating of equation 2 was done using MATLAB code *ode45*. As a result, the evolution of delamination was predicted for unsteady growth at all steps of loading. Finally the resistance curve can be obtained. In figure ` for each step of loading are introduced. It is seen that for all steps of test there is unsteady process of delamination growth: stable increasing of the strain energy release rate, its maximum, and next decreasing (sometime to the minimum).

The increment of delamination length to maximum of the strain energy release rate for all steps of loading is presented in figure 10.

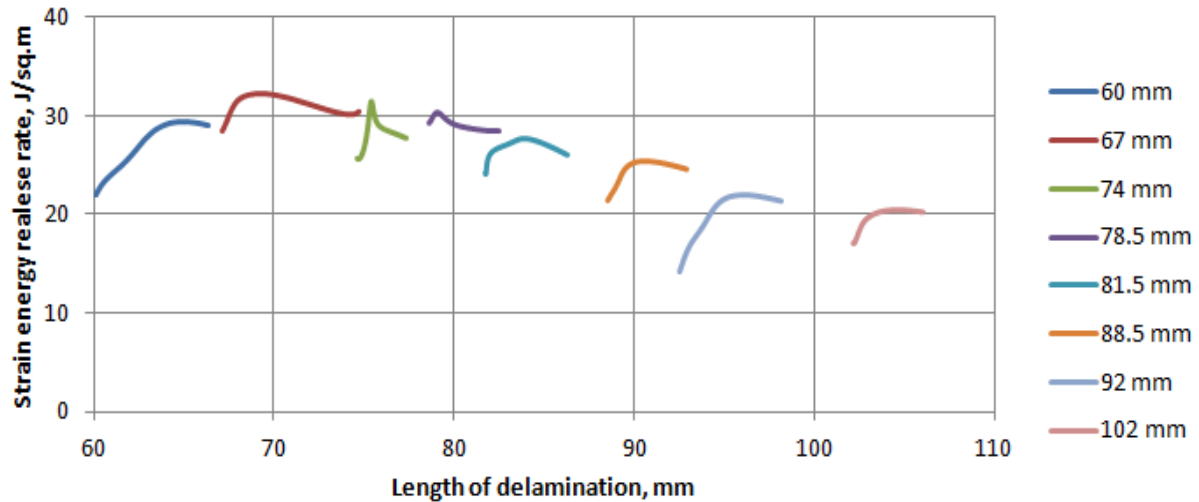


Figure 9. The strain energy release rate as function of delamination increment at different initial length of delamination.

3.4. The approximate evaluation of the critical parameters of interlaminar fracture

Results of this research show that at elastic-plastic behaviour of adhesive material there is specific continuous smooth growth of delamination without jump-like propagation that is observed for brittle material. Formally, the interlaminar fracture toughness can be evaluated also at the elastic-plastic behavior of the adhesive material, if to use the maximum load and corresponding extension or length of delamination. As easy see in figure 9 the maximum of strain energy release rate at each step of loading only a few more than defined by Standard procedure (figure 5). But from other hand, in both cases the critical strain energy release rate can be dependent from delamination length.

It could be assumed that this effect is defined by bending moment/shear force relation in the cross-section of DCB arm at the front of delamination. For the DCB sample this relation is equal to a length of delamination.

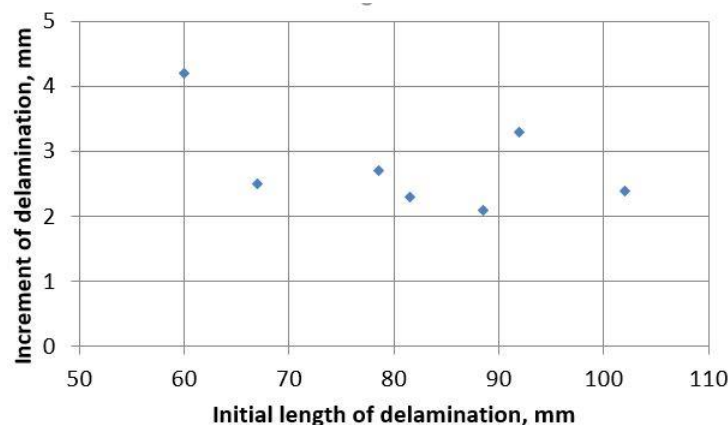


Figure 10. The increment of delamination length as a function of its initial length.

Therefore, adhesive joint strength at a given initial length of delamination is determined by the maximum of strain energy release rate. But since this time a stable growth of the delamination is preceded, the calculation should take into account the actual length of the delamination. It means that adhesive joint strength of some structure should be defined by follow equation

$$G_I(l, l_0, m) = G_{Ic}(L, L_0) \quad (4)$$

where l_0 is initial length of delamination of analysed structure (initial value), l its critical value, but $L_0 = m$ and $L = L_0 + \Delta L$ are initial and critical delamination length of DCB respectively.

4. Conclusions

Adhesive materials based on epoxy resins, most often, are brittle. To evaluate the interlaminar strength of these type adhesive joints is required to know a single constant - interlaminar fracture toughness. If the adhesive material is elastoplastic, then the process of progressive delamination is much more complicated. In the present study, the effect of plasticity on its interlaminar strength was investigated. A comparative analysis of the test data was carried out for two groups of samples from the same two-component adhesive material. For one of the groups the curing time was reduced in comparison with the standard. As a result, it became possible to assess the influence of technological faults to the strength of the adhesive joint. However, the main purpose of the analysis was to examine the patterns of delamination growth caused by plasticity of the adhesive material.

Plasticity effect has been studied in the DCB sample for mode 1 interlaminar fracture. The main conclusions about the features of the delaminating process of the elastoplastic adhesive layer are presented below.

1. The delamination of a sample grows smoothly, without of sudden jumps of size and load (in contrast the jump-like growth of delamination for brittle adhesive).
2. The compressive load is needed for complete closure of the sample at unloading that caused by plastic deformation of adhesive layer and the roughness of surface of delamination due to residual strain.
3. Formally defined the mode-I interlaminar fracture toughness is not a material constant and monotonically decreases as a function of delamination length.
4. At constant extension rate the relationships between strain energy release rate, load and rate of delamination growth in the elastoplastic stage of loading are complex and mutually disproportionate.
5. A possible means for an approximate evaluation of the critical parameters of interlaminar fracture of the DCB sample involves the use of a regression between the maximum of strain energy release rate and the size of delamination, corrected for its increment in a stable stage of growth.

Finally, it should be noted that the proposed means of fracture parameters estimation is applicable only to the DCB sample and the mode 1 of its loading. For practical application to other configurations of adhesive joints the specifics of the delamination progress should be investigated additionally.

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