Experimental Determination of Interlaminar Fracture Toughness of Wood Laminated Composite Specimens under DCB Test

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Modulus I interlaminar fracture toughness of wood laminated composite materials has been evaluated using the critical strain energy release rate associated with the onset of crack growth in double cantilever beam specimens (DCB). The advantage of using the DCB test for determining the critical strain energy release rate in the case of wood laminated composites relies on the working method which is focused on failure analysis in adhesive layer through the presence of initial interlaminar crack, but also due to the energetic approach in deduction of calculus relations. Data analysis was conducted by two methods namely, the corrected compliance method which is based on the linear elastic fracture mechanics principles, and the area method which accounts the whole shape of load-displacement curve obtained through a complete loading-unloading cycle. In general there is a good agreement between the results obtained by the two methods and those reported in literature.

Keywords: wood laminated composites, interlaminar fracture, critical strain energy release rate, Double Cantilever Beam (DCB) specimen.

The most common working methods used for modulus I interlaminar fracture testing of unidirectional polymeric composites are described by the standard ASTM D 5528 – 94a, where the so called DCB specimens are loaded perpendicular to the crack extension plane. Regarding the delamination fracture of unidirectional reinforced composites, some researches were conducted [1]. Concerning the multidirectional composite laminates, it was shown that the major problems arisen during the interlaminar fracture testing are related to the appearance of intralaminar cracks and the crack branching phenomena [2]. Practically, the testing method established by the ASTM D 5528 – 94a is based on the assumption that the crack onset and propagation depend upon the fracture toughness of the material, expressed through the critical value of the energy release rate, usually denoted by G_{Ic}. In other words while the crack is advancing in modulus I, the critical crack onset point is reached when the energy release rate G_I associated with the crack extension takes its critical value G_{Ic}.

Regarding the wood based laminated composites, both the American standard ASTM D1037 and its European equivalent EN 1067 rely on the evaluating of bond strength perpendicular to the adhesive layer through the measuring of opening force that causes debonding of two adjacent layers, however in such case the test results can only offer a rough average value of the adhesive layer stresses. Moreover, a deep analysis on how to achieve the adhesion between the composite layers and therefore to asses the behaviour of the delamination fracture is difficult to perform. Thus, in the case of wood based composite laminates, the advantage of using DCB tests for determining the critical value of the energy release rate associated with the crack extension relies on the working method which is focused on adhesive layer failure analysis through the presence of initial interlaminar crack, but also due to the energetic approach in the deduction of calculus relations.

Experimental part

To perform the experimental tests, the specimens were cut out from 6 cross-ply laminates made by superposing beech veneers with a stacking sequence of 0°/90°/0°- 0°/90°/0°, the laminae of 1,65 mm thickness being glued together by urea formaldehyde resin and the addition of rye flour filler, with an average adhesive consumption of 200 g/m^2. The layered plates were compressed with an electrically heated laboratory hydraulic press up to a temperature of 110°C, with 5 min pressing time and a pressure of 0.2 MPa. The specimens having the length of 140 mm and the width of 30 mm were provided with an initial interlaminar crack by inserting a non-adhesive polyethylene foil of 10 μm thickness into the midplane of the plate (i.e., between the 0 degree plies), so that the bending rigidity modulus of the two crack arms are assumed to be equal. Mounting the specimen on the universal testing machine grips was done by means of an ensemble hinge – metallic block plate, as shown in figure 1.

According to ASTM D 5528 – 94a indications, the tests have been done through the displacement control of the grips at a constant speed of 1 mm/min. The value of the critical load corresponding to the crack onset has been determined by deviation from linearity method (NL), through marking this point on the load – displacement curve.

When the delamination has extended 25 mm beyond the insert edge, the specimen was unloaded with a constant speed of 1 mm/min and the test was finished. The load – displacement curve obtained after a complete load – unload cycle, for a specimen with the initial crack length of 20 mm, is shown in figure 2.

Figure 3 shows the graphical representation of the critical load at the onset of the crack propagation for different initial crack lengths. The values were determined by marking the deviation point from linearity (NL) on the

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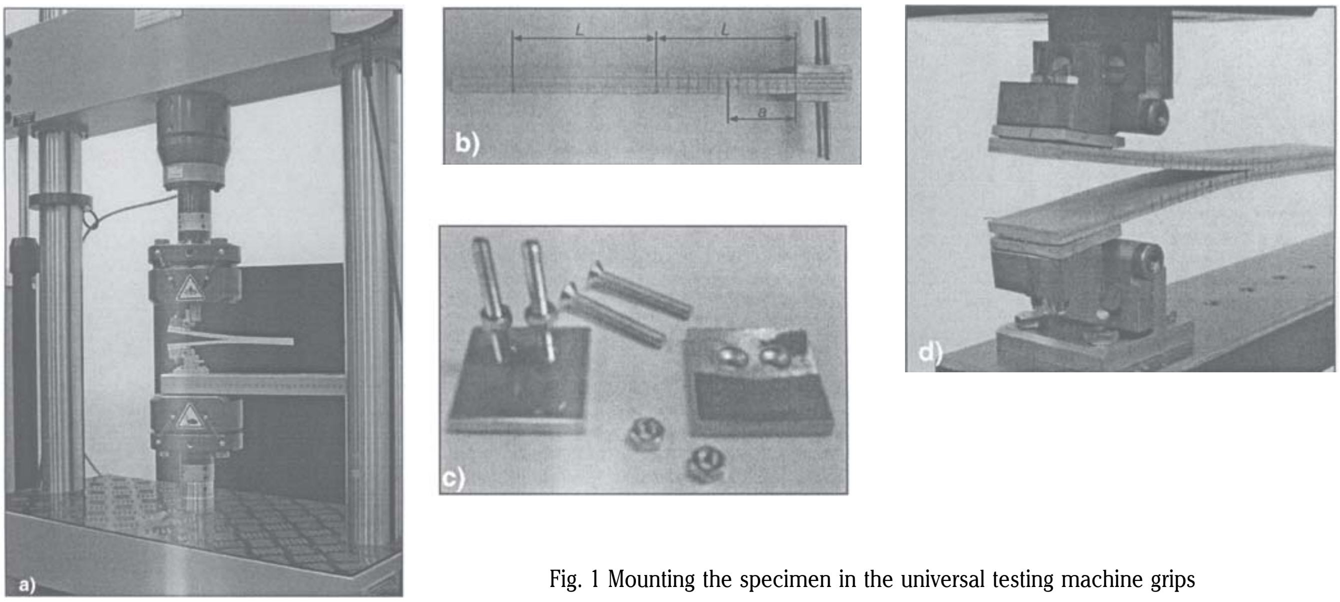

Fig. 1 Mounting the specimen in the universal testing machine grips

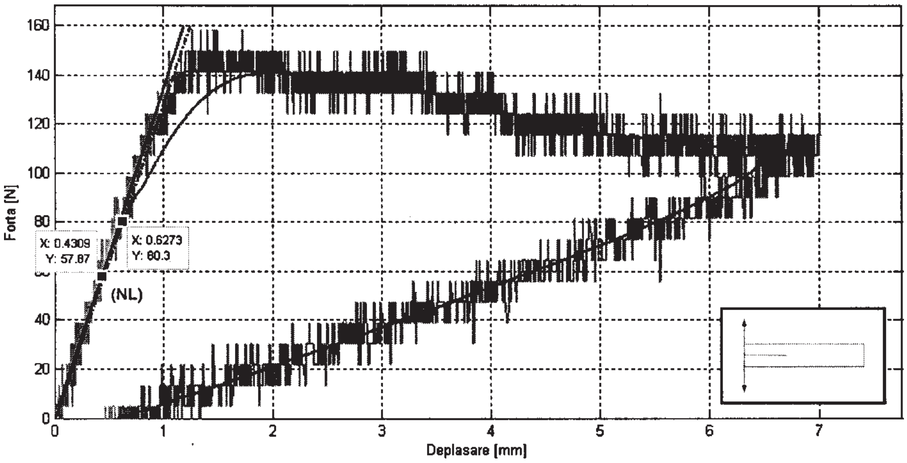

Fig. 2 Typical shape of the load – displacement curve for a specimen with a = 20 mm crack length

load – displacement curve, the dependence between the two variables being estimated by a straight line whose regression equation obtained by the method of least squares is:

$$\hat{F}_{cr}(a) = 66 - 0{,}8 \cdot a, \qquad (1)$$

where $\hat{F}_{cr}(a)$. is the estimated value of the critical load at the onset of the crack propagation in [N], and a is the initial crack length in [mm].

According to ASTM D 5528 – 94a specifications, data analysis was first conducted by the corrected compliance method through the following steps:

- the compliance of each tested specimen was calculated as a function of the slope of the linear portion of the load - displacement curve;

$$C[m/N] = \frac{1}{\hat{m}} \cdot \frac{1}{1000}, \qquad (2)$$

where $\hat{m}$ is the slope of the linear portion of the load - displacement curve.

- the graphical representation of the cube root of compliance versus crack length has been made, as shown in figure 4, resulting in a linear relationship of the form:

$$\sqrt[3]{C} = \tilde{m} \cdot x + \tilde{b}, \qquad (3)$$

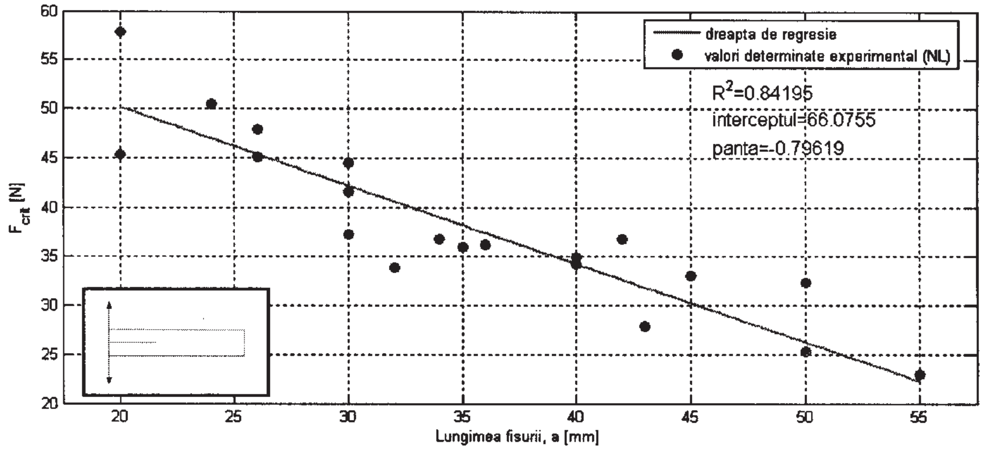

Fig. 3. The experimental values of the critical load vs. crack length

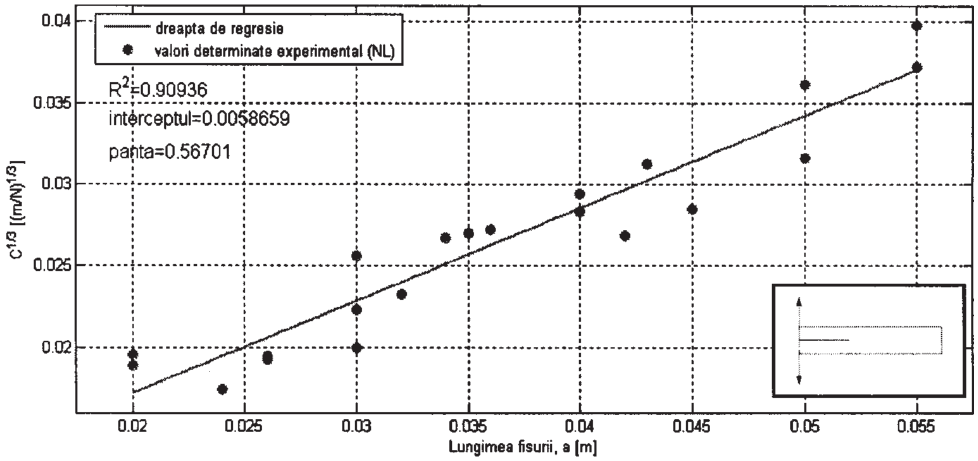

Fig. 4. The regression line of the cube root of the compliance asa function of the crack length

where $\tilde{m}$ = 0.567 is the slope of the regression line, and $\tilde{b}$ = 0.00586 represents its intercept.

- the value of the correction factor Δ was determined as the ratio between the value of the intercept and the slope value of the regression line [3 4];

$$\Delta = \tilde{b}/\tilde{m}, \qquad (4)$$

and respectively the effective stiffness of the tested specimens was calculated with the relationship [91];

$$EI_{efectiv} = \frac{2/3}{\tilde{m}^3}, \qquad (5)$$

and finally, the critical value of the strain energy release when the load direction is perpendicular to the crack propagation plane (modulus I), was calculated with the equation [3- 5]:

$$G_{Ic}[Nmm/mm^2] = \frac{F_{cr}^{\ 2}}{b}\frac{(a+\Delta)^2}{EI_{efectiv}}, \qquad (6)$$

where:

F_{cr}- the critical load at the onset of the crack propagation [N];

a - the initial crack length [mm];

b - the specimen width [mm].

Another method for calculating the critical value of the strain energy release rate, the so-called “area method” takes into account the whole shape of the load - displacement curve obtained after a complete load/unload cycle. Using the area method the critical value of the strain energy release rate was determined as the ratio between the surface area closed by the load-displacement curve and the crack extension surface, according to the relation:

$$G_{Ic}[Nmm/mm^2] = \frac{S_{F-\delta}}{b(a_2 - a_1)}, \qquad (7)$$

where:

$S_{F-\delta}$- the surface area closed by the load-displacement curve [Nmm];

b: the width of the specimen [mm];

a_1: the initial crack length [mm];

a_2: the crack extension length [mm].

Practically, the determination of the critical value of the strain energy release rate through the area method was found by integrating the load – displacement curve using the trapezoidal rule with the help of a Matlab routine. Figure 5 shows the way of displaying the integration results obtained by running the Matlab routine, for a specimen with an initial crack length a = 24 mm.

Results and discussions

Figure 6 shows the data spread and average critical values of the strain energy release obtained by using the two methods as a function of the initial crack length.

It is easier to observe that in both cases the calculated value of the linear correlation coefficient R^2 very close to zero means a critical average value of the strain energy release rate which does not depend on the crack length, being only a material parameter. Very small difference between the two averages could be explained due to the working method (by visual observation) used in assessing the length of the crack extension during the test, followed by the specimen unloading.

Figure 7 shows a comparative plot of the critical values of the strain energy release rate in modulus I, determined by using both methods and with some specific values reported in literature [6, 7]. It can be seen that the average critical values of the strain energy release obtained using the two methods as described above, falls roughly in the same order of magnitude with the specific values of some wood laminates like LVL – Douglas/Phenol formaldehyde and Beech/Phenol formaldehyde. However, the average

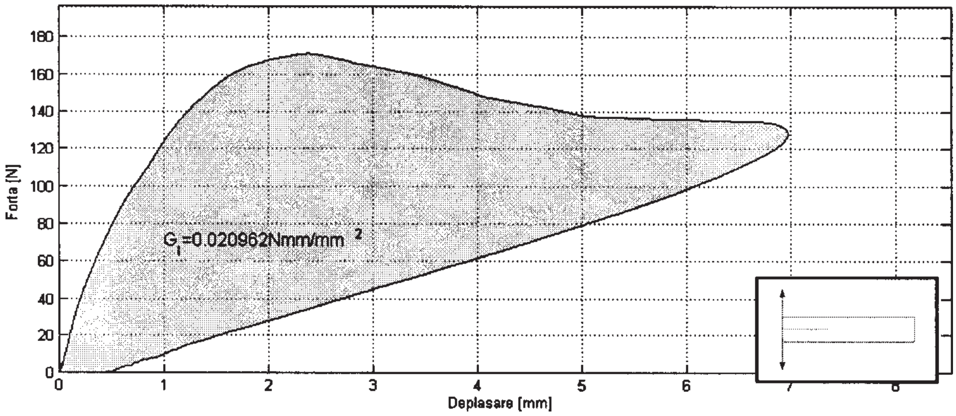

Fig. 5. The integration output of the load curve for a specimen with an initial crack length, a = 24 mm

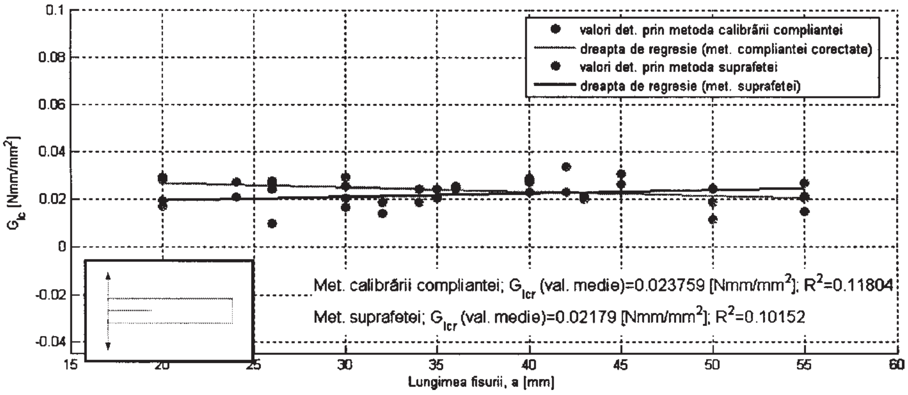

Fig. 6. The data spread and the average critical values of the strain energy release rate versus initial crack length

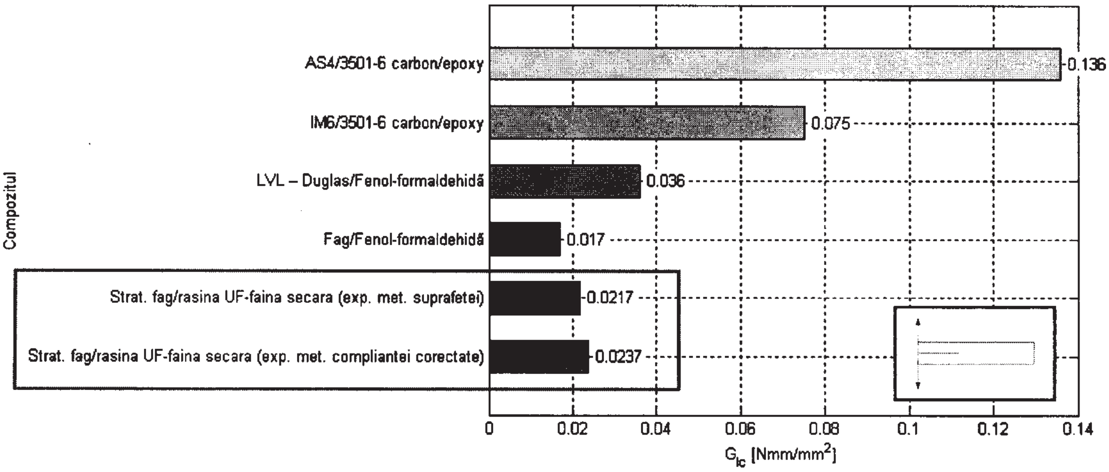

Fig. 7. A comparative plot of the critical values of the strain energy release rate in mode I for some wood based laminated structures

specific values for the wood laminated structure under study (Beech/Urea formaldehyde resin – rye flour filler) are about 2.5 times smaller than the unidirectional AS4/3501 - 6 carbon/epoxy resin.

Conclusions

As regards the wood-based layered composites produced at this stage, it is found that gluing with the help of adhesives or resins represents the basic process for structural coupling, the quality of the gluing process being influenced by a multitude of factors depending on the nature of the lignocellulosic raw materials (clear wood or other natural fibers), the adhesives, the gluing process, and the conditions of use. The complex interaction of these factors is reflected in the performances of the manufactured composite materials, which in turn ensures their successful use in various engineering applications.

Although the mechanical properties of structural elements (veneers, chips, fibers, adhesives) taken separately "as a bulk materials" within the ensemble of the lignocellulosic structure, are known or may be easier to be determined, not the same thing can be said about the mechanical properties of interphase layer between two adjacent laminae, their values being variable on the thickness between the ones of the adhesive and the ones of the adjacent laminae.

Thus in view of the disadvantages of the tests recommended by the specific standards for wood-based composite materials, a deep analysis on how to achieve the adhesion between the composite layers and therefore to asses the behavior of the delamination fracture is difficult to perform (the test results can only offer an approximate average of the stresses that develops in the adhesive layer). The advantage of using DCB tests for determining the critical value of the energy release rate associated with the crack extension relies on the working method which is focused on adhesive layer failure analysis through the presence of initial interlaminar crack, but also due to the energetic approach in the deduction of calculus relations. By analyzing the results of experimental tests for the cross-layered wood based composite specimens made by beech veneers glued together with urea formaldehyde resin and the addition of rye flour filler, the following conclusions can be highlighted:

- in the case of modulus fracture, the critical values of the strain energy release rate obtained by using both the corrected compliance method and the area method were G_{Ic} = 0.0237 Nmm/mm^2 and G_{Ic} = 0.0217 Nmm/mm^2 respectively.
- the calculated value of the linear correlation coefficient vanishing to zero, obtained through the application of both methods, demonstrates that the critical average value of the strain energy release rate does not depend on the crack length, being only a material parameter.
- the average critical values of the modulus I strain energy release rate obtained through the corrected compliance method and area method respectively, fit about into the same range with the specific values available in literature for LVL – Douglas/Phenol formaldehyde and Beech/Phenol formaldehyde laminated composites.
- however, the average specific values of the strain energy release rate for the wood laminated structure under study (Beech/Urea formaldehyde resin – rye flour filler) are about 2.5 times smaller than the unidirectional AS4/3501 - 6 carbon/epoxy resin.

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