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Finite element analysis of mode-I interlaminar fracture of lignocellulosic laminate specimens by virtual crack closure technique

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Abstract. The paper aims to study the interlaminar fracture of lignocellulosic laminate specimens made of beech veneer with urea formaldehyde resin and rye flour under pure mode-I loading. In order to determine the critical value of strain energy release rate G_{Ic}, representing one of the material input parameters for a finite element analysis involving the interlaminar fracture behaviour of a laminate structure under complex loading conditions, a lot of double cantilever beam (DCB) specimens processed from a lignocellulosic laminate beech veneer plate were tested by applying the specific standard procedures in conjunction with the modified beam theory method for data reduction. The propagation of interlaminar fracture under pure mode-I was then simulated by finite element analysis using layered conventional shell elements, based on the Virtual Crack Closure Technique (VCCT) in Abaqus/Explicit. Good agreements between the load-displacement curves obtained through the use of finite element analyses and the experimental testing results were obtained.

1. Introduction

The use of lignocellulosic composite laminates across a variety of industrial fields is becoming increasingly common due to their weight saving potential with respect to conventional metallic materials. Nevertheless, a particular note is that the overall strength and stiffness of load-carrying members or structures made of lignocellulosic composite laminates may reduce significantly due to some inherent factors such as imperfect bonding caused through the manufacturing processes or interlaminar separation of two adjacent layers during in-service loading. Delamination is a term commonly used to express the separation of adjacent layers of composite laminates, and as noted in reference [1], is the most frequently observed failure mechanism of wood-based laminate composites. Besides the large number of design parameters involved in, the complex stress and strain states developed across the laminate thickness make its analysis a tremendous challenge.

Structural lignocellulosic laminated products include plywood, various composites of veneer and of wood based laminates such as laminated veneer lumber, glued laminated lumber, wood fiber-reinforced polymer composites, etc. [1]. Although the fracture properties of such lignocellulosic structural elements taken separately "as bulk materials", from the ensemble of the composite, are generally known and/or are straightforward to be determined, not the same applies when the design purposes involve the damage tolerance capabilities of the overall laminate structure. Thus, in view of the disadvantages of actual testing protocols designed for wood-based composite materials that generally only lead to approximate average values of critical stresses occurred within the adhesive

layer, more detailed studies focused on the prediction of interlaminar crack onset and propagation, experienced by the laminate structures made of lignocellulosic materials are required.

As the delamination is a crack propagation phenomenon, the application of fracture mechanics concepts to determine the resistance to interlaminar fracture toughness of lignocellulosic veneer-based laminate composites is justified not only to establish the design allowable values for damage tolerance analyses of lightweight structures made of such materials but also for the development of new products.

The double cantilever beam specimen (DCB) is widely used to determine the mode I interlaminar fracture toughness of composites. The specimen geometry has a predefined interlaminar crack located at the midplane interface so as two arms that can be treated as cantilever beams are obtained. The loading is applied via two equal forces at the free end regions of the arms, about opposite directions perpendicular to the predefined interlaminar crack plane. For unidirectional composite materials the DCB test is described by ASTM D 5528-94a [4]. Various testing protocols based on this specimen have been elaborated so far both for multidirectional and textile laminates, especially carbon fiber-reinforced composites [2,7,10-14]. In this regard, considerable efforts have been focused on getting an accurate relationship between the critical value of strain energy release rate and the applied load corresponding to the interlaminar crack onset and propagation.

At present, many researches have also addressed the issue of mode-I fracture for solid wood and its composites [1,15-17], both by experiments and/or finite element analysis. However, no data are available in literature related to the fracture parameters and the behavior of lignocellulosic veneer-based composite laminates under pure mode-I loading.

The scope of this paper is focused towards the determination of the critical value of the strain energy release rate under mode-I opening by experiments performed on DCB specimens made of lignocellulosic beech veneer laminates. The paper also reports a comparison study of the load-displacement data obtained by experiments versus the load-displacement curves simulated through a quasi-static finite element analysis using general contact in Abaqus/Explicit with conventional layered shell elements and the virtual crack closure technique (VCCT) as interlaminar fracture criterion.

2. Specimen and test set-up description

The experimental tests were performed on specimens processed from a lignocellulosic veneer-based laminate plate manufactured at laboratory scale. The laminate plate having a symmetric cross-ply sequence of [0°/90°/0°/ 0°/90°/0°], was obtained by stacking out 6 beech veneers of 1,65 mm thickness, bonded each other with urea formaldehyde resin and the addition of rye flour filler. The average adhesive consumption was 200 g/m^2. An electrically heated laboratory hydraulic press was used to compress the laminate up to 0.2 MPa, 5 minutes pressing time at a temperature of 110°C.

The specimens having the span 2L 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 at the midplane interface of the base laminate plate (i.e., layers 3 and 4 having both having 0 degree orientation). A total number of 12 DCB specimens with different predefined crack lengths, from 20 mm up to 55 mm, were used to perform the mode-I interlaminar fracture tests.

Figure 1 shows the DCB test setup on a multipurpose servohydraulic universal testing machine Walter-Bai, type LFV 50-HM. The DCB lignocellulosic layered specimens were mounted on the grips of the testing machine by means of an assembly thread bolts - metallic plates - hinge blocks, as shown in Figure 2. After fixing the bolts into the holes of metallic plates, these were glued to the outside faces of the specimen arms by a high strength adhesive.

The experimental tests were performed under displacement control at a constant crosshead speed of 0.5 mm/min [4]. For each tested specimen the interlaminar crack onset was determined by marking the intersection of the load-displacement curve with a straight line corresponding to a 5% increase of compliance relative to the deviation from linearity of the initial loading slope. However, the points corresponding to deviation from nonlinearity and the ones determined by 5% increase of compliance are almost identical while visual inspection point is located much lower. Furthermore, the visual

inspection is difficult and is highly operator dependent. Thus, 5% increase of compliance looks to be a clear enough indication of interlaminar crack onset in case of mode-I fracture testing of lignocellulosic veneer based specimens.
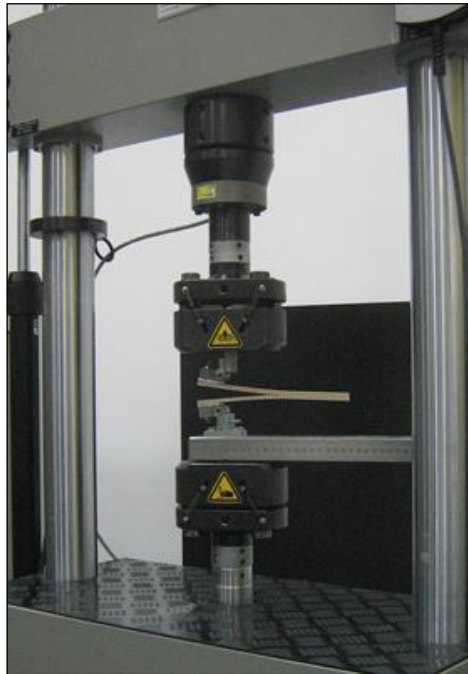

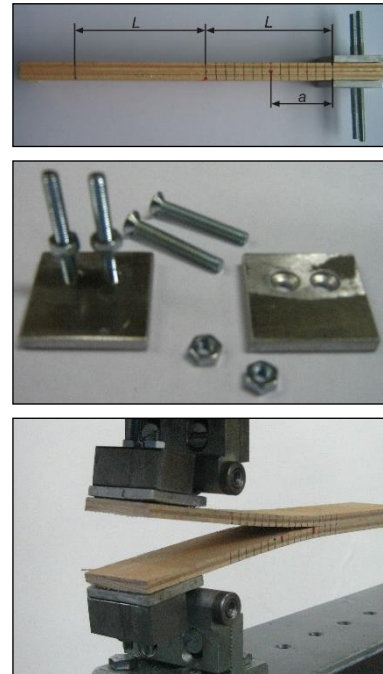**Figure 1.** DCB testing setup on a universal testing machine.

Figure 2. Mounting the DCB specimen in the testing machine grips.
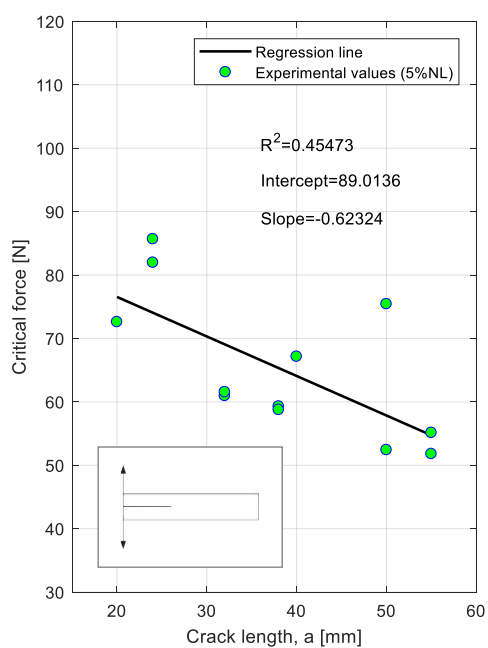

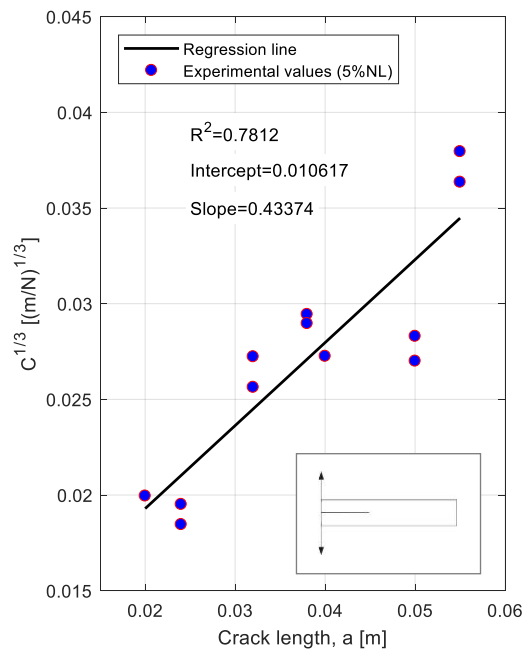**Figure 3.** The regression line fitting the values of the critical load.

Figure 4. The regression line of the cube root of the compliance.

Figure 3 shows the regression line that fits the values of critical load corresponding to the onset of interlaminar crack for different predefined crack lengths.

Since, in general, the lignocellulosic veneer-based laminate composites are relatively thick, the modified beam theory for data reduction was applied to determine the critical value of the strain energy release rate. With this method the initial delamination length is adjusted through a certain correction denoted by Δ which accounts for shear deformation and rotation at the interlaminar crack front. Therefore, the fracture toughness was calculated based on the relationship [9]:

$$G_{Ic} = \frac{3F_c\delta_c}{2b(a + \lfloor\Delta\rfloor)}$$
(1)

where δ_c is the critical displacement corresponding to the critical load, b is the specimen width, a is the predefined interlaminar crack length and the value of Δ is determined experimentally by fitting a least square curve to a plot of the cube root of compliance as shown in Figure 4. As reported in reference [9], on this plot the value of Δ represents the value of the predefined crack length at $C^{1/3} = 0$.

Based on the methodology outlined so far, a critical value of the strain energy release rate, G_{Ic}, corresponding to mode-I interlaminar fracture, equal to 0,125 Nmm/mm^2 was obtained for the investigated lignocellulosic veneer based material made of 6 cross plies of 1.65 mm, symmetrically stacked. This value converted into the metric International System of Units, gives $G_{Ic} = 125$ J/m^2.

3. Finite element analysis of DCB specimens

The Virtual Crack Closure Technique (VCCT) is a well-established method commonly used in the interlaminar fracture simulation of composite laminates [7]. The method relies on the definition of strain energy release rate in terms of crack closure integral as described in reference [7] whereby, under the assumption of a linear elastic material behaviour, the strain energy released when an existing crack is extended by a certain amount equals the work required to close the crack by the same amount. Built on the supposition that the crack extends along a predefined path, particularly at the layers interfaces, the virtual crack closure technique allows an efficient computation via a quasi-static finite element analysis performed in a single step. No assumptions about material homogeneity around the crack front are involved in, so that it can be either anisotropic or orthotropic as is the case of lignocellulosic veneer-based laminate material under investigation within the present study.
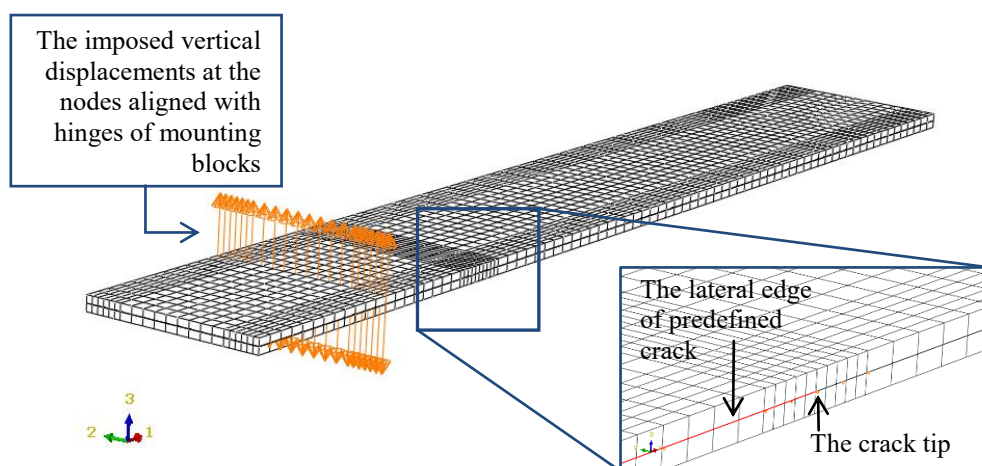

Figure 5. The shell-based finite element model of DCB specimen (general and detailed view on the edge of the predefined crack).

The geometry of double cantilever beam (DCB) specimen is obtained from stacking up two parts modelled by conventional layered shell elements, S4. As shown in Figure 5, over the length and width of the specimen, the finite element model is divided into several regions with different mesh refinements. A minimum element size of 1 mm at the edge of the predefined crack tip is considered.

Delamination by interface debonding is modelled using general contact in Abaqus/Explicit based on VCCT approach. The crack propagation under pure mode-I was simulated based on the Benzeggagh-Kenane mixed mode fracture criterion [18]. Thus, once the energy release rate reaches its critical value, the nodes at the crack tip are released in the following increment, which allows the interlaminar crack to propagate [7].

Three finite element models with 24 mm, 28 mm and 32 mm interlaminar predefined crack length located at the middle interface have been created.

The elastic properties of beech veneer laminae that were considered in the finite element analysis are reported in Table 1.

Table 1. The elastic properties of beech veneer lamina.

E_1	E_2	ν_{12}	G_{12}	G_{13}	G_{23}
14490	2240	0.45	1600	1055	460

As well-known, a quasi-static analysis relies on an explicit algorithm that calculates the state of a system at the later time from the state of the system at the current time. Basically, the nodal displacements at the end of an increment time (t +Δt) are computed by adding the displacements during the time increment Δt to the displacements at time t. Constant accelerations are assumed during each time increment in order to obtain the nodal velocities at later time (t +Δt). The explicit dynamic procedure provided by the finite element analysis package Abaqus/Explicit uses an explicit central-difference time integration in conjunction with diagonal or lumped mass matrices that allow to perform a large number of small time increments [1]. Since the method does not implies the inversion of a global stiffness matrix, the advantage of a quasi-static VCCT analysis as an explicit solution approach to simulate the DCB test is that it requires less computational resources with respect to the implicit procedure. However, when applying the explicit dynamic procedure to solve quasi-static problems some specific issues have to be considered. Provided that the static solution is, by definition, a steady time solution, it is often computationally expensive to simulate an event in its real time scale as it requires an excessive number of small time increments. Hence, the event must be accelerated somehow in order to obtain a reasonable computational solution. On the other hand, as the event is accelerated, the state of static equilibrium may evolve into a state of dynamic equilibrium in which the inertia effects might become important. Thus, to properly simulate the quasi-static behaviour of DCB lignocellulosic laminate specimens through an explicit dynamic analysis, the inertia effects should be kept as low as possible by ensuring that the ratio of kinetic to internal energy does not exceed 5% for the whole model and also by using an appropriate loading rate and/or a suitable density scaling factor.

4. Results

Figure 6 shows some examples of load-displacement curves obtained by experiments for three particular predefined crack lengths of 24 mm, 32 mm and 38 mm. Crack initiation appears where the first change of the slope in the diagram is visible. It can be also observed that the loads are increasing up to a point where the interlaminar crack propagation started, then gradually decrease for all the specimens. Stable interlaminar crack propagation behavior can be noted for all specimens loaded under pure mode-I opening.

A comparative plot of experimental and finite element analysis load-displacement curves for two specimens with 24 mm predefined interlaminar crack length is shown in Figure 7. One can observe that the finite element analysis curve fits well the experimental load-displacement curves. It can also be seen that VCCT determines the same critical value of the load that corresponds to the interlaminar

crack propagation onset even the curve is shifted toward a smaller value of the corresponding critical displacement.
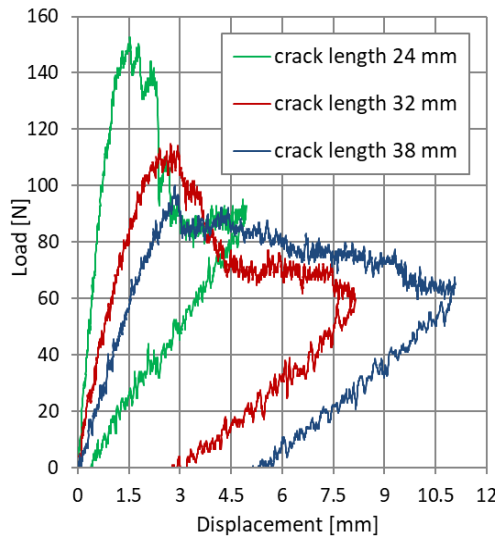

Figure 6. Samples of loading/unloading-displacement curves obtained by experiments.
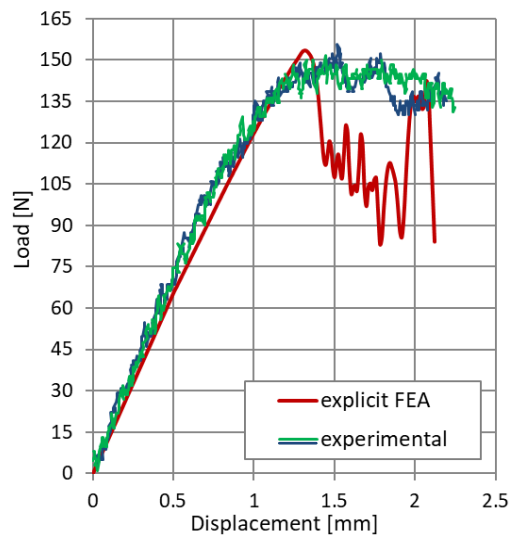
Figure 7. Experimental and FEA load-displacement curves (24 mm initial crack length).

Figures 8 and 9 present comparative experimental and finite element load-displacement curves for the specimens having 32 mm and 38 mm predefined crack length. Up to the point corresponding to the propagation onset a good agreement between the results obtained by experiments and the VCCT ones can be observed.
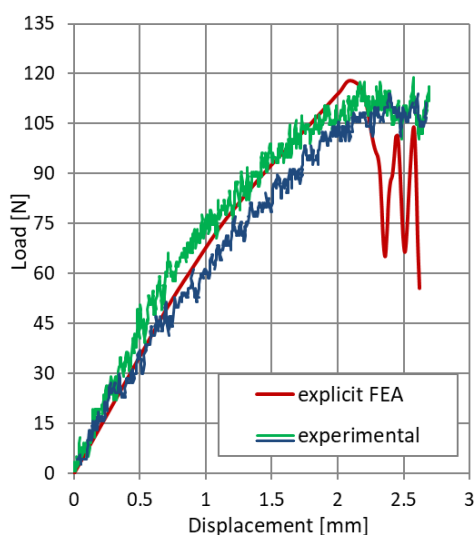

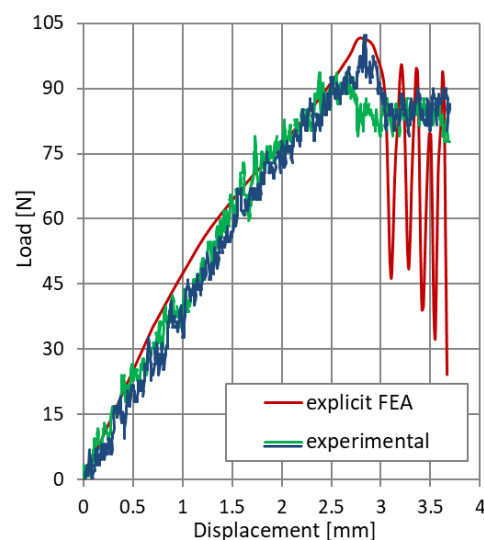**Figure 8.** Experimental and FEA load-displacement curves (32 mm initial crack length).

Figure 9. Experimental and FEA load-displacement curves (38 mm initial crack length).

For all specimens, after the point corresponding to propagation onset the VCCT curve gradually decreases following a saw tooth curve, with local rising and declining segments, shifted to lower load values. This can be explained through the limitations of VCCT approach which does not simulate likely the local damages.

Figure 10 shows the displacements state corresponding to the value of G_{Ic} at starting point of crack propagation onset for the specimen with 24 mm initial crack length. The corresponding distribution of G_{Ic} across the specimen width is presented in Figure 11. Higher values of the critical energy release rate at the specimen edges is observed.
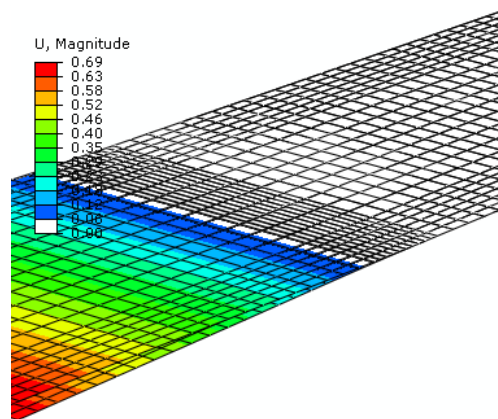

Figure 10. The displacements state corresponding to the value of G_{Ic} at starting of crack propagation (24 mm initial crack).
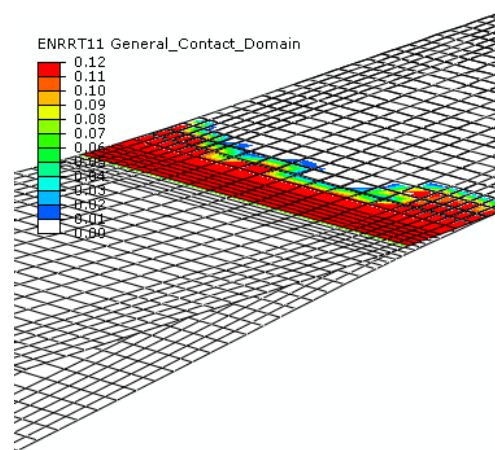
Figure 11. The distribution of G_{Ic} over the specimen width during crack propagation (24 mm initial crack).

5. Conclusions

The critical value of the strain energy release rate determined through the experimental testing procedure applied to lignocellulosic laminate specimens made of beech veneer, using the DCB test, enabled a good agreement of load-displacement test data with the simulation results obtained from the finite element analysis.

The experimental approach proved useful by revealing the critical value of the strain energy release rate for mode-I opening fracture, but the actual values of critical load corresponding to crack initiation were not conceivably be well measured by visual inspection. A 5% increase of compliance looks to be a clear enough indication of interlaminar crack onset in case of mode-I fracture testing of lignocellulosic veneer based specimens. Stable interlaminar crack propagation behavior can be noted for all specimens loaded under pure mode-I opening.

Selecting the suitable quasi-static finite element analysis and VCCT input parameters, such as the analysis time period, the material parameter of fracture criterion as well as the element size, was not straightforward and hence an iterative approach has been applied to overcome the issues related to the analysis setup data. The finite element analysis results using four-node shell element in Abaqus/Explicit were found to be satisfactory.

6. References

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