Investigation of mode II interlaminar fracture toughness of lignocellulosic laminated specimens – an experimental and numerical approach

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Abstract. Mode II interlaminar fracture toughness of lignocellulosic laminate composite materials made of beech veneer with urea formaldehyde resin and rye flour was investigated using the end notched flexure specimens (ENF). In order to determine the critical value of the strain energy release rate $\mathcal{G}_{IC}$ associated with the interlaminar crack onset, the experimental data analysis was conducted by means of a mixed mode bending device in conjunction with a compliance calibration approach for data reduction. The interlaminar crack propagation under pure mode-II loading was also simulated by finite element analysis using general contact in Abaqus/Explicit, with Virtual Crack Closure Technique (VCCT) as fracture criterion. Good agreements between the load-displacement curves obtained through the use of finite element analyses and the experimental testing results were obtained.

1. Introduction
With the increased use of lignocellulosic composite laminates over a variety of industrial fields, the ability to understand and predict their failure modes becomes essential. As well known, the fibers lying in the plane of a laminates do not provide reinforcement through-the-thickness direction and consequently this leads to interlaminar failures which significantly reduce the overall strength and stiffness of lignocellulosic composite structures. As noted in reference [1], one of the primary failure modes of lignocellulosic composite laminates is the delamination induced due to interlaminar stresses caused by inherent factors such as manufacturing processes or interlaminar separation of two adjacent layers during in-service loading.

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 new products development.

The most common experimental procedure to determine the critical strain energy release rate in mode II is the so-called End Notched Flexure (ENF) test. It consists in loading by three point bending a specimen with a predefined crack located at the midplane interface. It is generally admitted that mode-I cracks propagate in abrittle manner with low energy consumption, whereas for mode-II cracking much energy is consumed by friction between fractured surfaces. Moreover, the interlaminar fractures propagate predominantly under mode II, also known as the in-plane shear fracture.

In order to obtain the mode-II fracture toughness propagation values, the critical strain energy release rate of the ENF test configuration must be calculated. Numerous studies have been carried out so far on the analysis, modeling, and design of ENF specimens made of carbon or glass-epoxy reinforced fibres [11-15]. In this regard, considerable efforts have been focused on getting accurate relationships between the critical value of strain energy release rate and the applied load corresponding to the interlaminar crack onset and propagation under pure mode-II. Some authors have also addressed the issue of mode-II fracture for solid wood and its composites [16-18], both by experiments and/or finite element analysis. Nevertheless, no data are available in literature related to the fracture parameters and the behavior of lignocellulosic beech veneer-based composite laminates under mode-II in-plane shear loading.

This paper is focused towards the determination of the critical value of the strain energy release rate under mode-II in-plane shear loading, by experimental tests performed on a mixed mode bending device (MMB) using ENF specimens made of lignocellulosic beech veneer laminates. The paper also presents a comparison assessment of the experimental load-displacement data with the load-displacement curves simulated through a quasi-static finite element analysis using general contact in Abaqus/Explicit with shell elements and the virtual crack closure technique (VCCT) as 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/m². An electrically heated hydraulic press was used to compress the laminate up to 0.2 MPa at a temperature of 110°C, 5 minutes pressing time.

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 during the manufacturing of the base plate (i.e., layers 3 and 4 having both having 0 degree orientation). A total number of 21 ENF specimens with different predefined crack lengths, from 28 mm up to 46 mm, were used to perform the mode-II interlaminar fracture tests.

The ENF test was conducted through a mixed mode bending (MMB) device proposed by Reeder and Crews [10]. Figure 1 shows the MMB testing device mounted on a universal testing machine Walter-Bai, type LFV 50-HM. As shown in Figure 2, the MMB device allows to adjust the loading ratio so that the pure mode-II can be obtained by positioning the saddle at the middle of the specimen span [9,10]. The arms of the specimen were mounted on the MMB device by means of an assembly thread bolts - metallic plates - hinge blocks. After fixing the bolts into the holes of metallic plates, these were glued to the outside faces of the specimen using a high strength adhesive.

The 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 the deviation from linearity. As the interlaminar crack tends to close due to the applied load at the saddle, the visual inspection is difficult and is highly operator dependent.
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.

According to reference [9], an experimental compliance calibration approach can be used to determine the critical value of the strain energy release rate:

$$G_{IIc} = \frac{3F_c^2ma^2}{2b}$$  \hspace{1cm} (1)$$

where $F_c$ is the critical load, $b$ is the specimen width, $a$ is the predefined interlaminar crack length and $m$ is the slope of the best fit straight line determined by plotting the cube of compliance against the predefined interlaminar crack length.

Figure 4 shows the regression line fitting the cube of compliance versus predefined crack length for lignocellulosic beach veneer laminate specimens.
Based on the aforementioned methodology, a critical value of the strain energy release rate, $G_{IIc}$, corresponding to pure mode-II interlaminar fracture, equal to 255 $J/m^2$ was obtained for the investigated lignocellulosic veneer based material made of 6 cross plies of 1.65 mm, symmetrically stacked.

**Figure 4.** The regression line fitting the cube of compliance versus predefined crack length.

### 3. Finite element analysis of ENF 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 [8] 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 ENF 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-II was simulated based on the Benzegagh-Kenane mixed mode fracture criterion [20]. 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 30 mm, 40 mm and 45 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. |
|-----------|
| E₁ | E₂ | ν₁₂ | G₁₂ | G₁₃ | G₂₃ |
| 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 [8]. Since the method does not imply 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 examples of load-displacement curves obtained by experiments for three particular predefined crack lengths of 30 mm, 40 mm and 45 mm. Crack initiation appears where the first change of the slope in the diagram is visible. It can be also seen that the loads are increasing up to a point where the interlaminar crack propagation started, then gradually decrease for specimens having 40 mm and 45 mm initial crack length. Unstable interlaminar crack propagation behavior can be observed for the specimen with the initial interlaminar crack length of 30 mm.

A comparative plot of experimental and finite element analysis load-displacement curves for two specimens with 30 mm predefined interlaminar crack length is presented in Figure 7. Both specimens exhibit unstable propagation. One can also observe that the nonlinear behavior of experimental load-displacement curves is much more obvious with respect to one obtained by simulation. On the other side, even the peak of finite element analysis curve, with local rising and declining segments, is shifted toward a higher value of critical load, if an average trend line is considered it matches well the value of the critical load corresponding to the propagation onset.

Figures 8 and 9 show comparative experimental and finite element load-displacement curves for the specimens having 40 mm and 45 mm predefined crack length. It can be observed that as the
predefined crack length increases the curves tends to match each other. In the same time it can be observed that VCCT determines about 15% percent increase of the critical load relative to the experimental ones. On the other hand, the corresponding critical displacement is decreasing with the increase of the predefined crack length.

Figure 6. Samples of ENF loading-displacement curves obtained by experiments.

Figure 7. Experimental and FEA load-displacement curves (30 mm initial crack length).

The above outlined differences can be explained by the limitations of VCCT which does not simulate likely the local damages. Moreover, the VCCT assumes that the specimen arms are perfectly built and it ignores the correction factors specified by experimental determinations.

The examples shown in Figures 7, 8 and 9 shown the importance of the comparison assessment to identify the critical analysis input parameters.

Figure 8. Experimental and FEA load-displacement curves (40 mm initial crack length).

Figure 9. Experimental and FEA load-displacement curves (45 mm initial crack length).

5. Conclusions
The value of the critical strain energy release rate recovered through an experimental ENF testing procedure applied to lignocellulosic laminate specimens made of beech veneer, was used as material input parameter to simulate the test by finite element analysis. In summary, good agreement between
the load-displacement curves obtained from finite element analysis and the testing results were achieved.

The ENF experiments performed using a MMB testing device proved useful by revealing the critical value of the strain energy release rate for mode-II in-plane interlaminar shear fracture, but the actual values of critical load corresponding to crack initiation were not conceivably be well measured by visual inspection since the applied load at the saddle of MMB device tends to close the crack. All tested specimens exhibit an unstable interlaminar crack propagation.

Selecting the suitable 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. Judicious application of the method allows a conservative estimation of critical loads corresponding to crack propagation as well as the overall interlaminar fracture behavior. However, further investigations by finite element analysis using cohesive zone modeling is required.

6. References

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