ON THE NUMERICAL EVALUATION OF THE MIXED MODE DELAMINATION TOUGHNESS FOR LIGNOCELULLOSIC COMPOSITES

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Abstract: This paper reports a summary of our studies on delamination fracture toughness (critical strain energy release rate) of lignocellulosic laminated composite specimens by finite element analysis. For finite element analysis, a 2D finite element model using plane finite elements was used. The strain energy release rate was computed using the virtual crack closure technique, a user programming subroutine being employed to obtain the variation of the energy release rate with respect to the crack length, after the propagation onset.

Key words: interlaminar fracture toughness, LEFM, strain energy release rate, lignocellulosic laminated composite.

1. INTRODUCTION

Lignocellulosic laminated composites are particularly susceptible to failure by delamination initiation and growth owing to the relatively low tensile strength of the interface between two adjacent plies. Energy-based linear elastic fracture mechanics has been extensively used for delamination modeling of composites. To determine if a given loading on the structure would cause delamination growth, the strain energy release rate (G) at the crack front is tested against some criterion involving the *delamination fracture toughness* or *critical strain energy release rate* (Gc) of the

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material.

As is well known, traditional lignocellulosic composites consist of wood fiber used in conjunction with some other materials, such as various adhesives, cement, plastic, other natural fibers (flax, jute, kenaf, etc.) or fiberglass. The common lignocellulosic laminated composites include plywood, hardboard, medium density fiberboard (MDF), glulam beams, and laminated veneer lumber (LVL).

For mixed mode the commonest test uses the mixed mode bending (MMB) specimens, according to ASTM D 6671-01, for unidirectional fiber reinforced polymer matrix composites. Alternatively, one can use the European Structural Integrity Society (ESIS) protocol for interlaminar fracture testing of composites, which is believed to be more appropriate to reproduce the interlaminar crack propagation of a real composite structure. However, one should mention that these standards and protocols have been established and evaluated in “round robin” trials by standards organizations only for unidirectional fiber reinforced composites. The purpose of this research is to establish the fracture toughness of lignocellulosic composites by using the finite element method. It is important to mention that, areas of focus for this research not include moisture content cycling, temperature changes, dimensional stability, internal stress, and how these affect the interlaminar fracture at the level of interface between two adjacent plies.

In the topic of wood composites and adhesion, the debonding of two adjacent plies is one of the most important damage mechanisms in failure. The appearance of an interlaminar crack, or delamination, does not necessarily mean that the structural element is not further capable of sustaining any loading, but it implies an important reduction in functionality. Delaminations facilitate a premature buckling of the structure, a direct way for moisture to enter the laminate, a stiffness degradation, excessive vibration, etc. Taking into account that delamination is likely to grow in a combination of fracture modes in laminated structures, mixed mode delamination tests I/II are of great interest for the determination of interlaminar fracture toughness.

2. ANALYSIS OF THE MMELS TEST USING THE VCCT METHOD

The mixed mode end load split test (MMELS), also known as asymmetrical double cantilever beam, is a variation of the mode II ELS test. In this case, only one of the beams of the specimen is loaded while the other remains unloaded, what means that the interlaminar crack is forced to propagate under mixed mode. In fact, the MMELS test can be seen as the superposition of the DCB and ELS tests. Compared to the most used mix-mode test (the MMB test) the way in which the external load is applied to the specimen can be more easily assimilated to a loading situation of a real structure.

As can be seen in the figure 1, to avoid the inclusion of the axial forces on the beams of the specimen, the claming end of the specimen is fixed between rollers. In this way, while the specimen is free to move on the horizontal direction, the vertical movement of the clamped end remains restricted and no axial forces are originated.

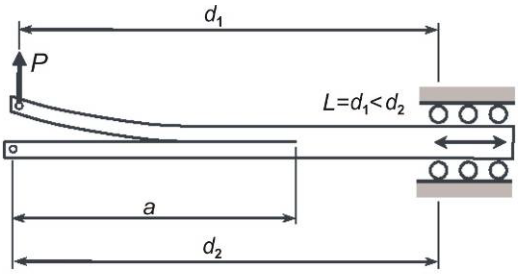

Fig. 1. MMELS test as superposition of DCB and ELS tests

Theoretical background

The virtual crack closure technique (VCCT) is based on Irwin's crack closure integral (Reeder, J.R, 1990) in combination with the results of 2D or 3D finite element analysis. This approach assumes that the energy ΔE released when the crack is extended by an increment Δa, from a to $a + \Delta a$, coincides with the energy required to close the crack to its original condition, from $a + \Delta a$ to a.

If a 2D plane stress finite element analysis is considered, the crack of length a is represented as one-dimensional discontinuity by a line of nodes. At the initial stage, when the loading is not applied to the system, the nodes attached to both crack surfaces have the same coordinates but they are not connected to each other. The crack propagation analysis requires the use of two nodes with identical coordinates, one per crack surface, coupled through multi-point constraints. These multipoint constraints are afterwards released to simulate the extension of the crack by one element size. Taking into account the 2D finite element analysis represented in figure 2, according to the VCCT, the energy required to extend the crack between the node *j* and *k* is related to the nodal forces acting at node *j* and the nodal displacements present at node *i'* and *i''*.

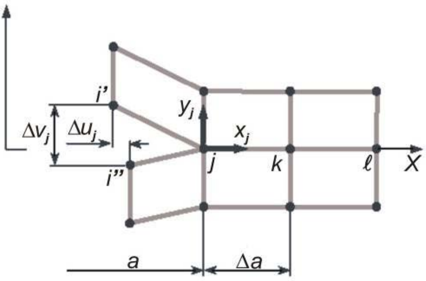

Fig. 2. Representation of the virtual crack closure technique

The energy ΔE required to extend the crack along one finite element size from node *j* to node *k*, that is from a to $a + \Delta a$, can be calculated as:

$$\Delta E = \frac{1}{2}\left(x_j \cdot \Delta u_i + y_j \cdot \Delta v_i\right) \tag{1}$$

where x_i and y_i are the shear and opening forces at the node to be opened, j, and Δu_i and Δv_i are the differences in shear and opening displacements between nodes behind the original crack tip, i' and i''. Tacking into account that the energy release rate can be assumed as the energy per unit of new created surface and that the mode III component is zero for a 2D analysis, the mode I and mode II components of the energy release rate can be calculated as []:

$$G_{\mathrm{I}} = \frac{y_j \cdot \Delta v_i}{2b \cdot \Delta a} \tag{2}$$

$$G_{\mathrm{II}} = \frac{x_j \cdot \Delta u_i}{2b \cdot \Delta a} \tag{3}$$

where b is the width considered during the analysis.

Materials

The analysis was performed by considering a lignocellulosic laminate structure (0/90/0/90/0), as shown in Figure 3, for which the effective engineering properties have been determined through the macromechanical analysis.

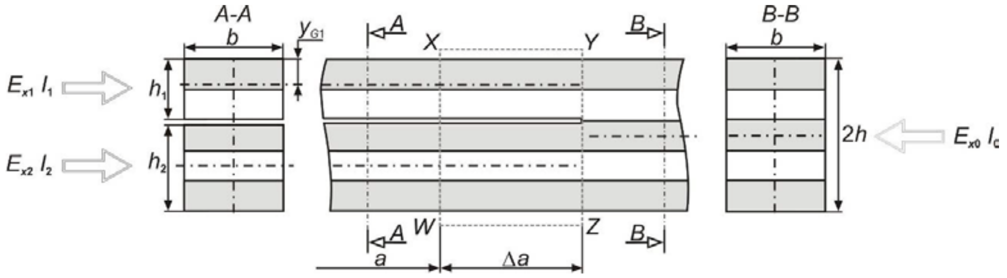

Fig. 3. The location of the interlaminar crack and the effective engineering properties for the three different sections of the laminate structure

The values of the effective mechanical properties, corresponding to three different sections of the structure, as a function of the position of the interlaminar crack are presented in Table 1.

Finite element modeling

The present analysis is carried out using the commercial Ansys finite element program. Figure 4, shows a schema of the MMELS lignocellulosic laminate specimens modeled with an effective length of 150 mm and a sliding clamped area of 50 mm. As most of the commercial finite element codes (Pastrama, 2004), Ansys does not include an implemented virtual crack closure method.

Table. 1. *The values of the effective mechanical properties, corresponding to three different sections of the structure*

Geometric ratio	**Effective mechanical properties, MPa**					
	The upper arm of the crack		The lower arm of the crack		The laminated structure without crack	
	E_{x1}	G_{xy1}	E_{x2}	G_{xy2}	E_{x0}	G_{xy0}
$\xi = \frac{h_1}{2h} = 0{,}2$	54310	20260	36650	15390	41410	17310
$\xi = \frac{h_2}{2h} = 0{,}4$	32360	13590	43620	17830		
$\xi = \frac{h_3}{2h} = 0{,}6$	43620	17830	32360	13590		
$\xi = \frac{h_4}{2h} = 0{,}8$	36650	15390	54310	20260		

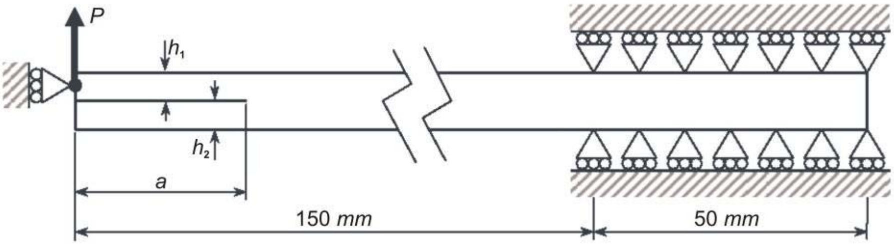

Fig. 4. Schema of a MMELS specimen for the VCCT analysis

Therefore, during the analysis different user programming subroutines are employed to obtain the energy release rate components (ANSYS Parametric Design Language - APDL). The simulations are carried out using the 2D four-nodded plane stress finite element, PLANE 42. This is an isoparametric finite element with bilinear interpolation functions, four integration points and two degrees of freedom, horizontal and vertical displacements. Figure 4, shows a zoom of the finite element mesh at the initial crack tip zone, in case where the initial crack is located between the first ply and the second ply.

3. RESULTS OF THE VCCT ANALYSIS

The results of the VCCT analysis in case where $\xi = 0{,}2$ are summarized in the following. It is important to be mentioned that, a unit load or displacement is applied to the loaded beam of each model and propagation analyses are conducted in order to obtain the variation of the energy release rate components.

Figure 7, shows the variation of the stresses σ_x, σ_y and τ_{xy} in the vicinity of the crack tip in case where the initial crack is located between the third ply and the forth ply. The variation of the mixed mode energy release rate as a function of the crack length according to VCCT in case where the geometric ratio $\xi = 0{,}2$, is shown in figure 8. To validate the obtained results, the MMELS test, have to be further analyzed in detail, both analytical and experimental.

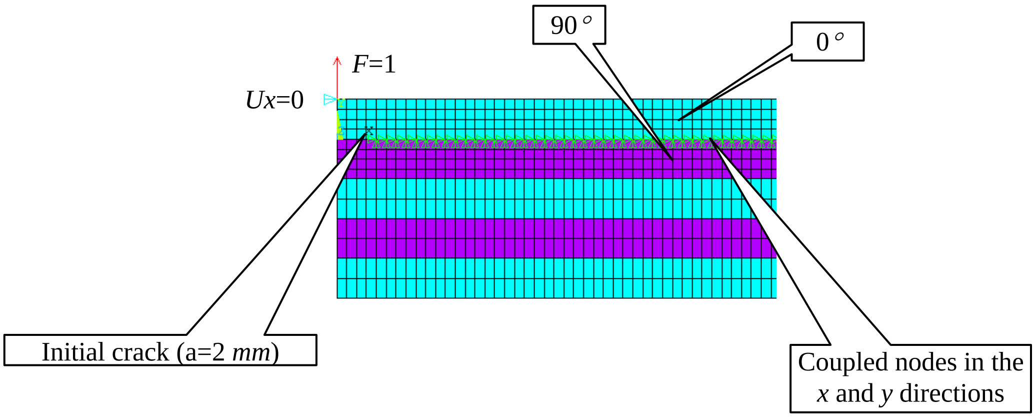

Fig. 5. Finite element mesh of the initial crack tip zone (ξ=0,2)

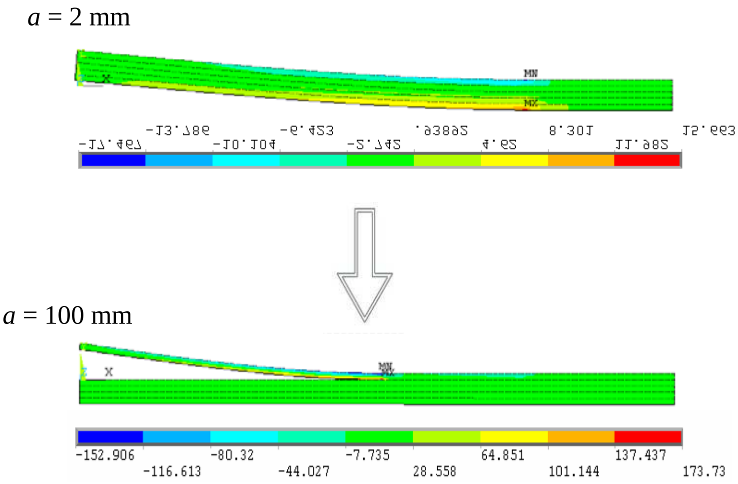

Fig. 6. The shape of the specimen before and after the propagation onset (case $\xi = 0{,}2$), from a = 2 to 100 mm, simulated by running the APDL subroutine

4. CONCLUSIONS

The critical strain energy release rate (G) values for different locations of the initial crack in MMELS specimens made of lignocellulosic laminated composites have been presented in this paper. Finite element analysis was carried out using ANSYS plane elements, as well as 2D four-nodded plane stress finite element, PLANE 42. A user programming subroutine was employed to obtain the energy release rate components in the ANSYS Parametric Design Language (APDL). The stable crack propagation and the *R*-curves have to be further analyzed in detail, both analytical and experimental. A was mentioned above, areas of focus for this research not include moisture content cycling, temperature changes, dimensional stability, internal stress, and how these affect the interlaminar fracture at the level of interface between two adjacent plies.

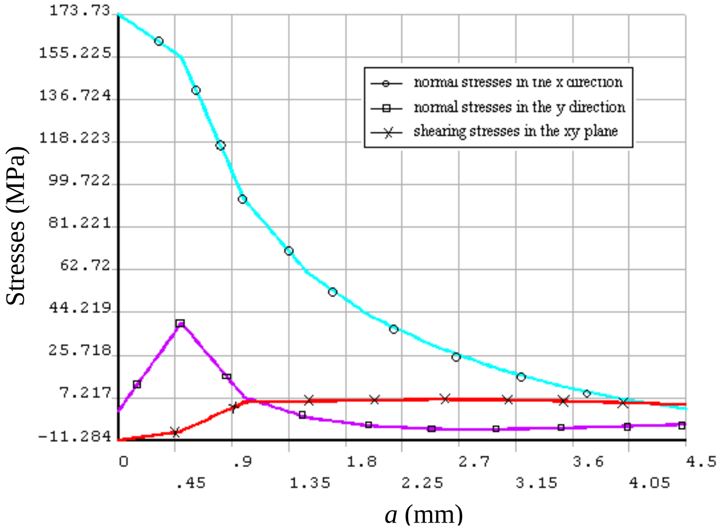

Fig. 7. Variation of stresses σ_x, σ_y şi τ_{xy} in the vicinity of the crack tip (case $\xi = 0{,}4$)

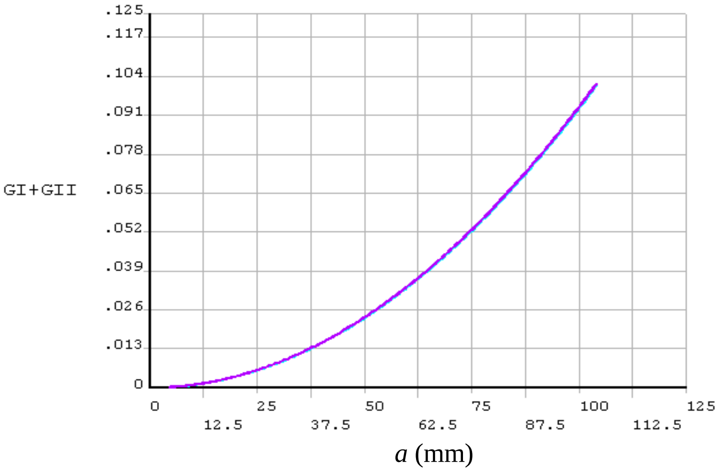

Fig. 8. The variation of the mixed mode energy release rate as a function of the crack length $\xi = 0{,}2$

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