BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Tomul LIV (LVIII), Fasc. 4, 2011
Secţia
CONSTRUCŢII. ARHITECTURĂ

THE LAMINATION EFFECT FOR GLULAM BEAMS ACCORDING TO FRACTURE MECHANICS

BY

DANIEL PASCU[*]

Technical University of Constructions, Bucureşti

Received: October 28, 2011
Accepted for publication: November 24, 2011

Abstract. The paper determines how manufacturing defects occurring in glued laminated wood beams can lead to further cracking effects of laminated component layers.

Key words: glulam; wood; laminated; glued; beam; mechanics; fracture.

1. General Observations

We consider a glued laminated wood beam (also known as *glulam*) comprising of several laminated layers, each having the Δh thickness (Fig. 1).

This case studied refers to a normal bending beam. The beam resistance is given by its behaviour in the area of the stretched fibre, the material having a linear, elastic behaviour in case of compression.

On the outside of the stretched fibre, the extremity, the beam shows a weak area represented either by a knot or a fault joint. When this weak area starts to yield, its resistance and the beam behaviour can modify according to

[*]*e*-mail: pasconmat_eu@yahoo.com

the crack development on its entire length. The previously mentioned situation is described in Fig. 1.

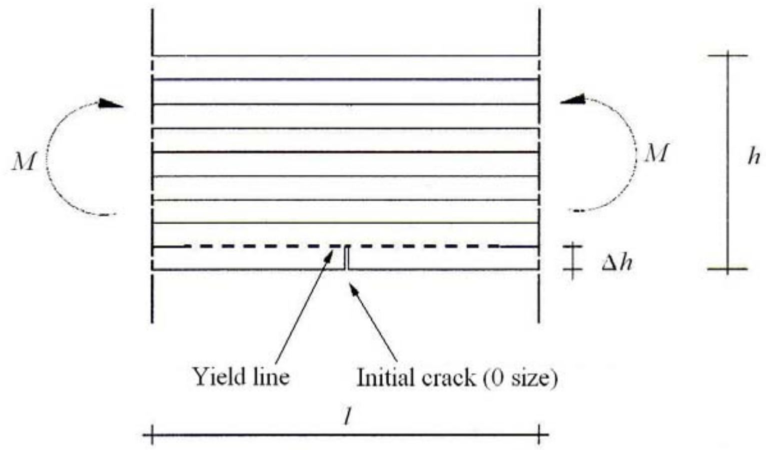

Fig. 1 – The laminated beam, having an initial crack with a length equal to the laminating line thickness; the dotted line represents the crack propagation direction.

2. Manual Calculation Method

Based on hypothesis from fracture mechanics in the linear elastic field (LEFM), Petersson (1994) suggests a modality for evaluating the critical bending moment, M_c, when the crack starts to propagate again

$$M_c = \sqrt{\frac{2G_c b E_x I}{\frac{1}{\alpha^3} - 1}}, \tag{1}$$

Where: E_x is the modulus of elasticity in the fibre direction, G_c – the fracture energy at crack propagation (the necessary energy for extending the crack on a surface unit), I – the inertia moment of the beam ($I = bh^3/12$, b is the beam width and its height, h), as well as the relation $\alpha = (h - \Delta h)/h$.

In order to apply eq. (1) we must know the fracture energy. Since wood fracture energy varies from approximately 200...400 J/m^2 for mode I to approximately three times this value for mode II, we must estimate a combined yield mode for efficiently choosing the G_c value to be used.

Nevertheless, in case the value used for G_c in eq. (1) corresponds to mode I, the obtained responses give quite precise estimates.

For a more sophisticated analysis we require more than the precise fracture yield and propagation mode, namely also the effect of fractured area staged development and its non-null size.

As presented in this paper, an approach based on the nonlinear fracture mechanics allows a solution to this problem. In order to verify eq. (1), a series of element analyses were conducted based on a nonlinear fracture mechanics model described by Wernersson (1994). This model considers gradual fracture propagation, as well as the behaviour of studied elements.

3. Finite Elements Analysis

The case study refers to a beam with height $h = 450$ mm and length $l = 1{,}600$ mm, according to Fig. 1. We assume as valid Bernoulli's hypothesis of plane sections and the results of numerical simulations are presented as unitary stress (M/W, $W = bh^2/6$). In order to investigate the lamination effect, five different thicknesses of laminated Δh, namely 50, 25, 12.5, 6.25 and 3.125 mm were studied. For each case the length of the initial crack was assumed equal to the laminate thickness, as presented in Fig. 1.

The elements representing the fixture line located along the crack have 0.80 mm in length. The data from the fixture line are necessary in order to define its behaviour, including resistance from behaviour modalities I or II, as well as the corresponding fracture energy. These values were chosen according to those reported by Wernersson (1994), namely resistances of 6.50 and 10 MPa for behaviours I and II, the fracture energies being 360, respectively, 960 J/m^2.

Wood was modelled as a linear elastic and orthotropic material, having $E_x = 16{,}800$ Mpa, $E_y = 560$ MPa, $G_{xy} = 1{,}050$ MPa, and $\nu_{xy} = 0.45$, chosen from Serrano's work (1997).

The elements representing wood are place isoparametric elements, having 3 or 4 sides, for a more refined distribution of finite elements. The beam deformation at maximum load corresponds to a unitary bending stress of 37.9 MPa,at the perimeter lamination border and is shown in Fig. 2.

The results of numerical simulations with five different lamination degrees are shown in Fig. 3. The five simulations are represented by small circles, inasmuch that dotted lines are the results based on eq. (1) with $G_c = G_{\mathrm{I}c} = 360$ J/m^2 and $G_c = G_{\mathrm{II}c} = 980$ J/m^2.

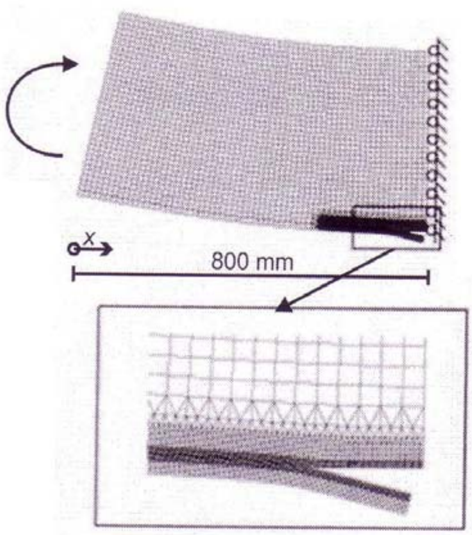

Fig. 2 – The deformed beam at maximum load; the crack has expanded by 50...60 mm.

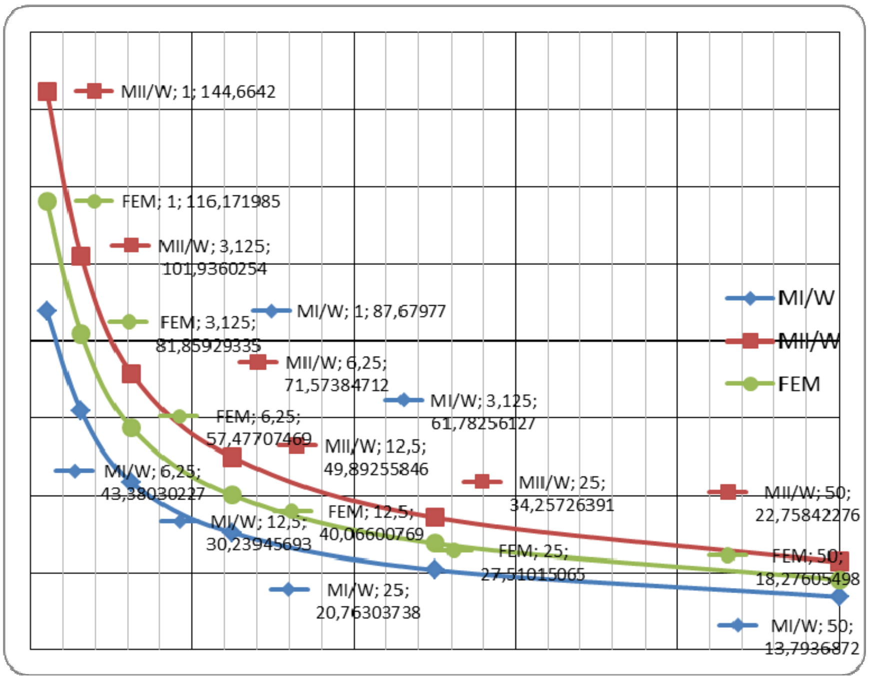

Fig. 3 – Bending resistance (*M*/*W*), compared to laminated thickness for a beam having 450 mm height; the circles are results of FEM simulations. The lines with squares and diamonds are determined based on eq. (1) for $G_c = G_{\mathrm{I}c}$ (diamonds) and $G_c = G_{\mathrm{II}c}$ (squares).

A major result of simulations is that together with the lamination thickness decrease, crack propagation depends more on the II[nd] mode. This figure illustrates unitary bending stress in extremity fibres during the fracture process (measured from the symmetry line). For all these analysis the load reached a torque value. Since this corresponds to a fully developed propagation within the fracture process, having s constant shape, LEFM can render a correct estimate of the maximum load, with a coherent G_c value.

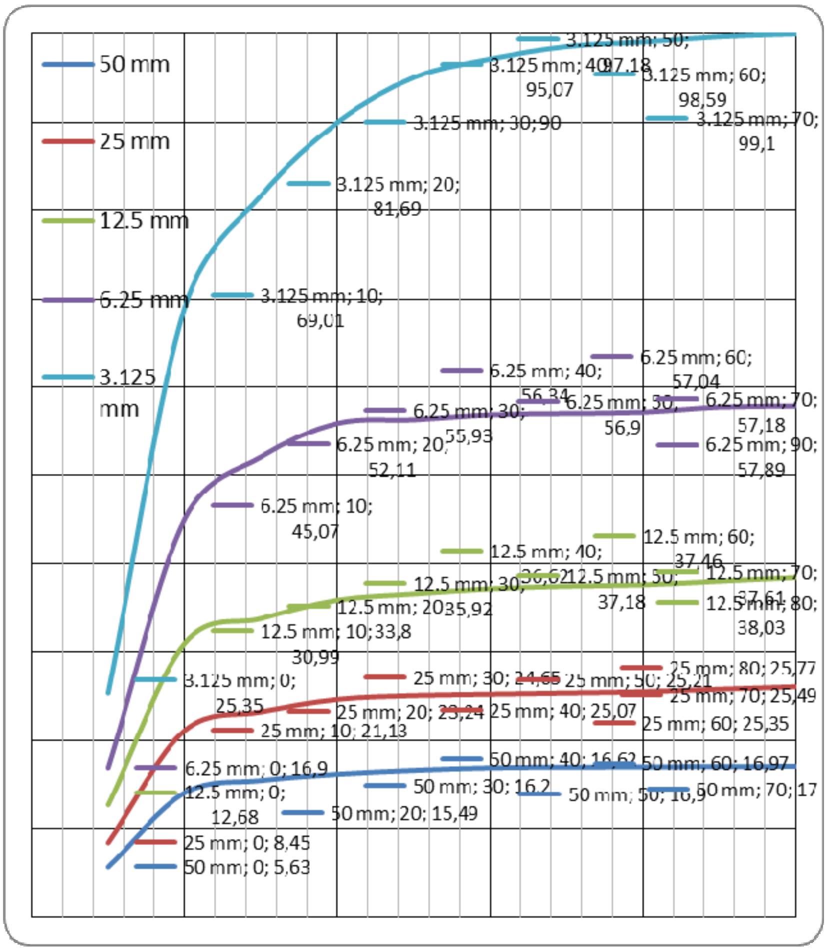

Fig. 4 – Unitary bending stresses (*MW*), *vs*. tip crack position for different laminate thicknesses.

Fig. 5 shows the distribution of unitary stress along the fixture line of ultra-peripheral laminate at top load, when Δh = 50, 12.5 and 3.125 mm.

In a damaged area, unitary stress distribution is more even for thicker laminates. More important is the fact that the size of fractured areas differs according to laminate thickness. For a 3.125 mm laminate, the fracture area is approximately 48 mm long, whereas in case of other thicknesses used within the study, it is approximately 25 mm long. This happens because thicker laminates require a larger normal unitary stress which, in turns, leads to mixed yielding fracture modes, associated to smaller fracture energy than the fracture corresponding to mode, thinner laminate elements. For laminates having 12.5 and 50 mm, the maximum normal unitary stress is 2.3 MPa, respectively, 2.8 MPa, whereas it has only 0.50 MPa for laminates of 3.125 mm (according to Fig. 5). Taking into account the fact that the size of the fractured area is associated to the fracture energy, this leads to reduced fracture areas in case of thicker laminates.

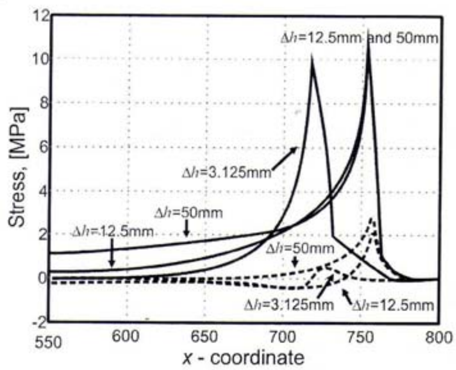

Fig. 5 – Stress distribution along the fixture line of ultra-peripheral laminates having top load; continuous lines show shearing stress and the discontinuous line shows normal stress.

It appears that the mixed modes of behaviour vary during crack propagation. The current status for mixed modes of behaviouris defined by

$$\varphi = \text{arctang}\left(\frac{\delta_s}{\delta_n}\right), \tag{2}$$

where δ_s and δ_n are the relative displacements between two points on each side of the fixture area.

Indexes *s* and *n* show the shearing deformation and, respectively, normal deformation. An yield according to mode I corresponds to $\delta_s =$

= 0 *i.e.* $\phi = 0°$ and a shearing propagation of cracks corresponds to $\delta_n =$ $= 0$ *i.e.* $\phi = 90°$. The curves in Fig. 6 are represented according to angle ϕ

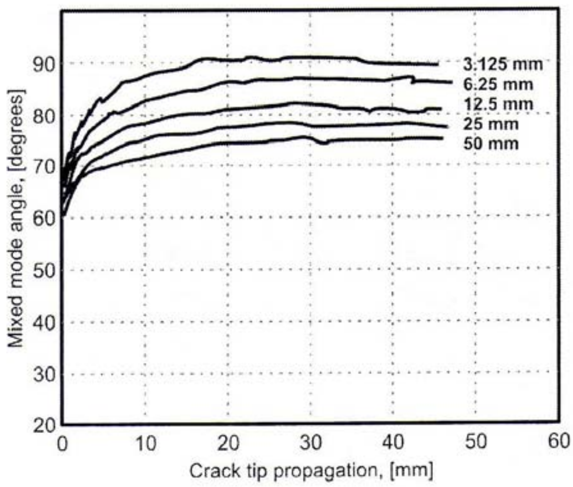

Fig. 6 – ϕ angle for mixed yielding modes, as defined in eq. (2), *vs*. the crack tip position for laminates having different thicknesses.

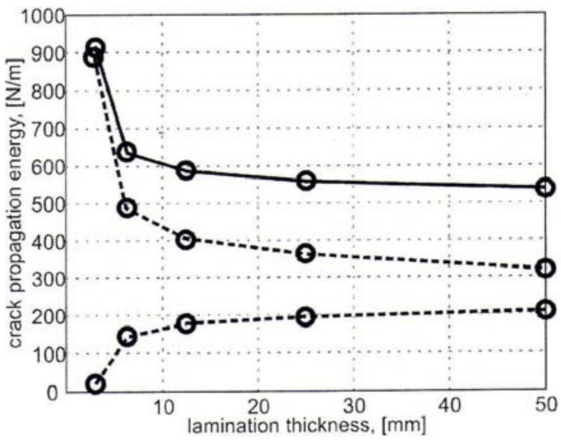

Fig. 7 – Energy consumption for the propagation of a fully developed (solid line) fracture area with various laminated thicknesses; the discontinuous line shows the contribution of mode I and the dotted line the contribution of mode II.

of the mixed behaviour mode, as shown in eq. (2), as compared to the crack tip position. The ϕ value is calculated at the tip position of the unitary shearing stress. Clearly, as laminated thickness decreases, the yields come from the IInd (shearing along laminations).

Ultimately, Fig. 7 shows how different fracture modes (I and II) depend on laminate thickness. We can again notice that in case of thinner laminates, fractures occur according to fracture II mode.

4. Conclusions

According to the previously presented and studied features, we can draw the following general conclusions:

1. For a glued laminated wood beam having a weak area, small as compared to beam size, located in ultra-peripheral laminated elements, the redistribution of stress around this weak area is highly reduced as compared to the conventional beam theory predictions.

2. The yield mode along the extreme fixture line of a wooden laminated beam with initial crack depends on the laminate thickness. Thinner laminates tend to yield by shearing around the fixture area, whereas thicker laminates tend to yield from combined fractured ways.

REFERENCES

Pascu D., *Contributions to Developing Efficient Building Systems for Wooden Structure Buildings, in Accordance with European Standards, as Compared to Other Standards* (in Romanian). Ph. D. Diss., Techn. Univ. of Constr., UTCB, Bucharest, 2011.

Serrano E., *Finger-Joints for Laminated Beams. Experimental and Numerical Studies of Mechanical Behaviour*. Report TVSM, Lund Univ., Sweden, Div. of Struct. Mech.

Serrano E., *Glued-in Rods for Timber Structures. A 3-D Model and Finite Element Parameter Studies*. Accepted for publ., Internat. J. of Adhesion a. Adhesives.

Serrano E., *Glued-in Rods for Timber Structures. An Experimental Study of Softening Behaviour*. Submitted for publ., Materials a. Structures.

Wernersson H., *Fracture Characterization of Wood Adhesive Joints*. Report TVSM, Lund Univ., Sweden, Div. of Struct. Mech.

EFECTUL DE LAMINARE LA GRINZILE DIN LEMN ÎN CONCORDANȚĂ CU PREVEDERILE MECANICII FRACTURILOR

(Rezumat)

Se determină modul în care defectele de fabricație apărute la grinzile realizate din lemn lamelat încleiat pot conduce la efecte ulterioare de fisurare a straturilor laminate componente.

Se consideră o grindă de lemn lamelat încleiat (glulam) constând din mai multe straturi de elemente laminate, fiecare având aceeaşi grosime.

Cazul de încărcare studiat este pentru o grindă solicitată la încovoiere pură. Pentru această analiză se folosesc două metode de calcul şi anume metoda de calcul manual şi analiza cu elemente finite.

În urma acestor analize s-a stabilit că:

a) pentru o grindă din lemn lamelat încleiat reprezintă o zonă de slăbire, de dimensiuni mici în comparaţie cu dimensiunile grinzii situate în elementele laminate ultraperiferice, redistribuirea eforturilor în jurul acestei slăbiri este mult mai redusă faţă de predicţiile teoriei convenţionale a grinzilor;

b) modul de cedare de-a lungul liniei de fixare extreme al unei grinzi din lemn lamelat cu fisura iniţială depinde de grosimea de laminare. Laminările mai subţiri tind să cedeze prin forfecare în lungul zonei de fixare în timp ce laminările mai groase tind să cedeze din moduri de fracturare combinate.