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NONDESTRUCTIVE EVALUATION AND PREDICTION OF BENDING BEHAVIOR OF FIBER REINFORCED LAMINATED TIMBER

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ABSTRACT

This paper presents the results of a study conducted to investigate the bending properties of glue laminated timber reinforced with three different materials, jute fiber, glass fiber and carbon fiber respectively. To determine the modulus of elasticity and modulus of rupture both in flatwise and edgewise directions destructive and non-destructive testing methods were used. According to the results the strengthened beams show improved load-carrying capacity and energy absorption capacity by when compared to unstrengthened counterparts. It was further noted that the integrity of the bond depended not only on the adhesive used but also on the FRP type. The predicted MOE values had a good agreement with the static MOE values but the agreement varies in function of FRP type.

Key words: Glue laminated timber, fiber reinforcement, mechanical properties, nondestructive modeling, jute fiber

1. INTRODUCTION

Glue laminated timber or the so called glulam is a beam type structural product produced by gluing together parallel oriented and finger jointed wood lamellas with similar width and thickness. Glulam is mostly used for long span applications such as residential, industrial or farm structures, sport arenas, swimming pools, etc. (Motoc, M. 2004).

The most important characteristics of glulam are as follows:

- parallel orientation of the lamellas with the main axis of the beam;
- horizontal or rarely vertical orientation of the component lamellas;
- straight, tapered, plain or spaced curved shape of the beam with uniform or variable cross section;
- incorporates low quality or small dimensional lumber, making possible the uniform distribution of solid wood defects;
- the structure of these beams can integrate lamellas with different quality;
- the most stressed zones (faces) are made of superior quality lamellas without any defect, in the less stressed zone (core) low quality lamellas are placed.

Major advantage of the glulam structures lay in their high strength and stiffness providing increased load bearing capacity and permit the utilization for high span applications (Furdui 2009). Another advantage of these engineering wood products is the possibility of reinforcement in terms of introduction and adhesion between two adjacent timber lamellas different high strength bands. Reinforced glulam beam costs less because the use of reinforcement will reduce the need of a top grade lamina on the extreme tension face and the volume of wood used is reduced also. Reinforced glulam beams have lower variability of properties and the manufacturing process is under control. Studies in this direction have been made by Issa and Khmeid (Issa and Khmeid 2005) using metal strips as reinforcement materials and carbon fiber bands (CFRP). Previous research results have shown significant increase in flexural strength and overall mechanical properties.

For quality classification of laminated beams the modulus of elasticity (MOE) is used as one of the most important parameter. The table below shows the value of MOE values for various classes of glulam.

Table 1: The modulus of elasticity of glulam strength classes (Porteous and Kernani 2007)

	Homogeneous glulam			Combined glulam		
Glulam Strength classes	**GL 24h**	**GL 28h**	**GL 32h**	**GL 24c**	**GL 28c**	**GL 32c**
Modulus of elasticity, MOE (kN/mm^2)	11,6	12,6	13,7	11,6	12,6	13,7

2. EXPERIMENTAL METHODS

The longitudinal vibration method was used for modulus of elasticity determination. The elastic modulus characterizes the material tendency to be deformed elastically when a force is applied to it. This value is a key parameter in the case of structure dimensioning in bending based on Eurocode 5 (for example: roof structure) (Porteous and Kernani 2007). Modulus of elasticity correlates well with bending strength; therefore it can be used for the determination of strength quality class.

2.1. Theory of elastic vibration propagation in long beams

In the case of elastic vibration propagation elastic connections between volumetric parts of material plays an important role (Divós 1999). The propagation speed of elastic vibration in long beams it can be easily determined by dynamics laws. A beam with length L, cross section A, density ρ, modulus of elasticity E is loaded with a force F parallel with the main axis at one of the ends for a short time τ (for example hammering). This shock compress the material and induce a longitudinal wave with the speed c and after the time τ reaches distance $l = c \cdot \tau$; When the beam length is equal with l, at the time $t = \tau$ the opposite end of the beam displaces with Δl and the first end return in the relaxed position. At the time $t = 2\tau$ the first end displaces with the distance Δl because of the wave reflection.

According to the Hooks low:

$$\Delta l = \frac{l \cdot F}{E \cdot A}[\mathrm{mm}] \ \textbf{or} \ F = \frac{E \cdot \Delta l \cdot A}{l}[\mathrm{N}] \qquad \textbf{(1)}$$

where: Δl – displacement after hit, in [mm];

l – sample length, in mm;

E – modulus of elasticity, in [N/mm^2];

A – cross sectional area, in [mm^2];

F – sample action force, in [N].

As a result of the force $F\tau$ action each segment of the cross section will shift with the speed of $v = \frac{\Delta l}{\tau}$. In conclusion the whole mass moves $m = \rho \cdot A \cdot c \cdot \tau$. After the law of impulse displacement:

$$F \cdot \tau = m \cdot v = \rho \cdot A \cdot c \cdot \tau \cdot \frac{\Delta l}{\tau} \qquad \textbf{(2)}$$

where: ρ – material density, in [kg/m^3];

c – velocity of wave propagation, in [m/sec];

τ – time of F force action, in [sec].

Substituting F with the previous relation and after simplification we obtain the sound velocity:

$$c = \sqrt{\frac{E}{\rho}}\,[\mathrm{m/sec}] \qquad \mathbf{(3)}$$

It is very important to underline that the above relation is valid just for long beams and longitudinal vibrations. In the case of large dimensions and other directions than parallel, the vibration propagation speed differs in function of direction:

$$c_{long} = \sqrt{\frac{E}{\rho}\cdot\frac{1-\mu}{(1+\mu)\cdot(1-2\mu)}}\,[\mathrm{m/sec}] \qquad \mathbf{(4)}$$

$$c_{trans} = \sqrt{\frac{G}{\rho}} = \sqrt{\frac{E}{\rho}\cdot\frac{1}{2\cdot(1+\mu)}}\,[\mathrm{m/sec}] \qquad \mathbf{(5)}$$

where: μ – Poisson’s ratio;

G – modulus of rigidity, in [N/mm^2].

In this case the vibration propagation speed will be determined from the frequency of the longitudinal vibration using the following equation:

$$c = 2\cdot l\cdot f\,[\mathrm{m/sec}] \qquad \mathbf{(6)}$$

where: l – beam length, in [mm];

f – the longitudinal vibration frequency, in [Hz].

Using the sound speed relation we have:

$$MOE_{dynamic} = \rho\cdot c^2 = 4\cdot l^2\cdot f^2\cdot\rho\,[N/mm^2] \quad \mathbf{(7)}$$

where: ρ – specific density, in [kg/m^3];

l – specimen length, in [mm];

The EN-338 norm is dealing with static MOE. The Portable Lumber Grader software determines the dynamic MOE first then applies a correction factor to calculate the static MOE. The following term defines the MOE (fakopp.com 2011):

$$MOE_{static} = \rho\cdot(2\cdot l\cdot f)^2\cdot 0{,}92\cdot(1+\frac{u}{50})\,[N/mm^2] \qquad \mathbf{(8)}$$

where: u – moisture difference; if $u > 18$, then $u = 18$, in %.

2.2. Principle of measurement

Using the method of determination is shown in the fig. 1:

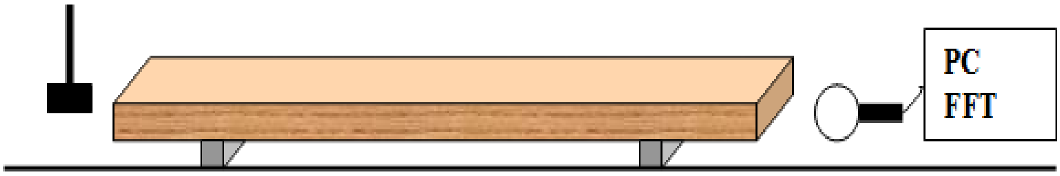

Figure 1: The principle of samples measure (Divós, 2000)

Specimen being tested is resting on a scale, with contacts of polyurethane foam (sponge) to eliminate transmission of vibration. End of the bar is hit with a small hammer in the longitudinal direction. At the other end there is a microphone that receives sound propagating through samples. A low hit should be applied to avoid the displacement of the specimens at supports. We can obtain the shear modulus of timber beams in the same mode just by repositioning the supports and microphone location (Divós, 1998).

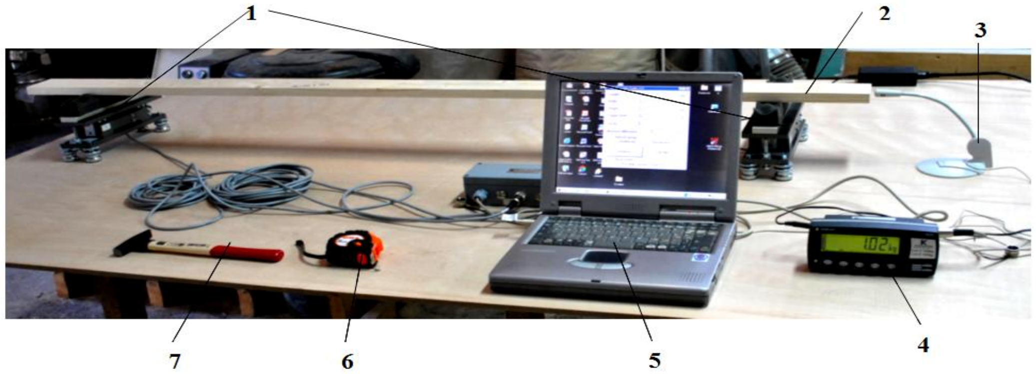

Figure 2: Test equipment: 1 – balance; 2 – sample; 3 – microfon; 4 – balance control equipement; 5 – computer; 6 - measure tape; 7 – hummer

2.3. The material

The material tested is represented by a glulam beam stock, made by spruce (Picea Abies), previously dried at u=12±3%, and reinforced glulam beams, with FRPs, i.e. unidirectional carbon fibers, woven glass fiber and jute yarns, processed to approximately final dimensions: L=1600±20mm, l=76±2mm, b=76±2mm. According to the abbreviation rules, we noted unreinforced beams with F, jute reinforced beams with J, glass fiber reinforced beams with S and carbon reinforced beams with C. Samples are noted by number 1 up to 5. For example, the 3rd sample of jute reinforced beam is noted J3.

2.4. Determination of moe by bending test

Laboratory tests were done according to the MSZ-EN 408:2003 standard using samples with same geometry as in the nondestructive method. The testing procedure is presented in Fig. 3.

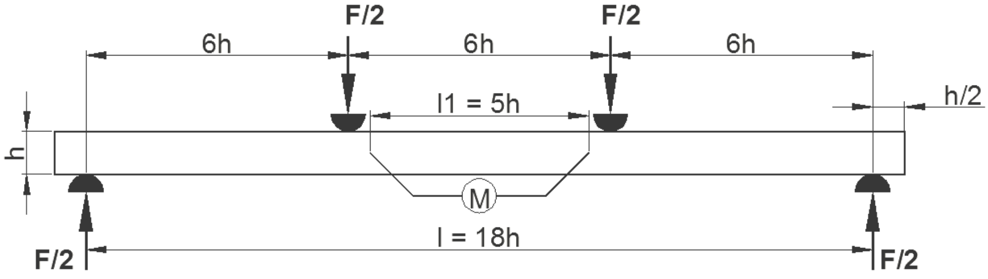

Figure 3: Four point bending test set up.

Static MOE was determined by next equation:

$$MOE = \frac{a \cdot l_1^2 \cdot (F_2 - F_1)}{16 \cdot I \cdot (w_2 - w_1)} \left[N/mm^2 \right] \qquad \textbf{(9)}$$

where: F_1, F_2 – force values measured at 10 % and 40 % of the maximum load, [N];

w_1, w_2 – corresponding displacement values to F_1 and F_2, [mm];

a – distance between load point and nearest bearing point (a= 6h), [mm];

l_1 – distance between load points, [mm];

I – moment of inertia, [mm^4].

The moment of inertia for prismatic cross sections is described by the next formula (Curtu – 1995):

$$\mathrm{I} = \frac{\mathrm{b} \cdot \mathrm{h}^3}{12} \left[\mathrm{mm}^4 \right] \qquad \textbf{(10)}$$

where: b – width of beam cross section, in [mm];

h – height of beam cross section, in [mm].

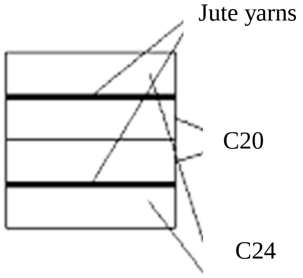

Figure 4: Reinforced beam structures in section.

In all reinforced beam structures we have the same thickness of reinforced material, and this is 0,5 mm. All lamina thickness is 19 mm, resulting in a final beam thickness of approximately 76 mm.

3. RESULTS AND DISCUSSIONS

According nondestructive method, we obtained the following values for MOE.

Table 2: The modulus of elasticity obtained by nondestructive method

	Beam code	b mean	h mean	L	U mean	Mass	Long frequency	MOE dyn.	MOE static predicted
Units	**-**	**mm**	**mm**	**mm**	**%**	**kg**	**Hz**	**N/mm^2**	**N/mm^2**
Unreinforced beams	F1	75,4	73,7	1595	8,5	3,94	1528	10603	11413
	F2	75,7	74,0	1600	8,6	3,98	1501	10246	11048
	F3	76,0	73,7	1601	8,5	3,96	1504	10243	11025
	F4	76,2	73,6	1601	9,2	3,68	1563	10195	11105
	F5	76,1	73,8	1601	9,1	3,68	1563	10252	11149
Jute reinforced beams	J1	76,0	75,3	1601	9,8	4,02	1519	10379	11420
	J2	75,9	74,9	1598	7,8	4,24	1464	10235	10885
	J3	75,9	75,3	1600	9,5	3,86	1523	10020	10969
	J4	75,9	75,2	1602	9,2	4,10	1471	9930	10817
	J5	75,8	75,8	1597	8,6	3,98	1569	11257	12138
Glass fiber reinforced beams	S1	77,1	76,2	1518	9,3	3,79	1830	13118	14305
	S2	77,3	76,4	1504	8,5	3,97	1831	13558	14594
	S3	77,0	76,2	1515	9,6	3,86	1832	13380	14682
	S4	77,3	76,2	1522	9,3	3,93	1807	13263	14464
	S5	77,6	76,2	1525	9,5	3,86	1822	13219	14464
Carbon fiber reinforced beams	C1	77,2	76,3	1505	9,7	3,97	1852	13916	15278
	C2	77,8	76,5	1504	8,8	4,02	1843	13802	14941
	C3	75,6	76,8	1525	9,4	4,13	1779	14738	16117
	C4	77,9	76,7	1524	8,9	4,00	1837	13772	14925
	C5	77,4	76,8	1497	10,2	3,96	1867	13905	15402

Based on the table values it can be stated that dynamic modulus of elasticity of reference samples are similar with those of jute fibers reinforced samples and both differ significantly from glass and carbon fiber reinforced beams, the lasts having 29 % and 36% higher values. The static MOE values predicted from dynamic modulus of elasticity using formula 8 shows slightly higher values than those of dynamic values and the reinforcement effects are similar. The measured static modulus of elasticity values are presented in Table 3.

Table 3: The modulus of elasticity obtained by bending test

MOE bending [N/mm²]				
Sample nr.	**Unreinforced beams**	**Jute reinforced beams**	**Glass fiber reinforced beams**	**Carbon fiber reinforced beams**
1	12363	11721	12397	12698
2	11495	11177	11230	14270
3	11190	10960	12185	14471
4	10607	11724	12511	12964
5	10320	12648	11878	14527

Comparing the static MOE values determined by destructive method with the static MOE values predicted by non-destructive method we can conclude that in the case of reference glulam and glulam reinforced with jute fibers the two mean values are similar, i.e. the adequacy of MOE predicting formula is appropriate. Opposite to this the predicted and measured MOE values for glass and carbon fiber reinforced beams shows a difference of 20% and 11%, respectively (Fig. 6). These significant differences are explained by an imperfect adhesion between reinforcement layers and wood lamina which was underlined by delaminations occurred during the four point bending tests.

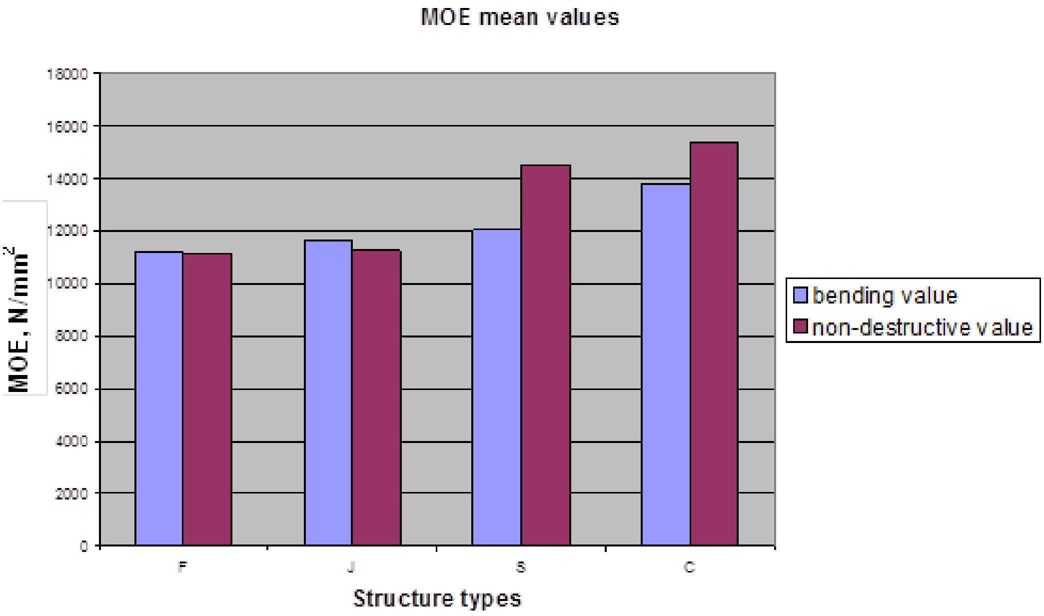

Figure 5: Mean values of MOE for different types of beam structures

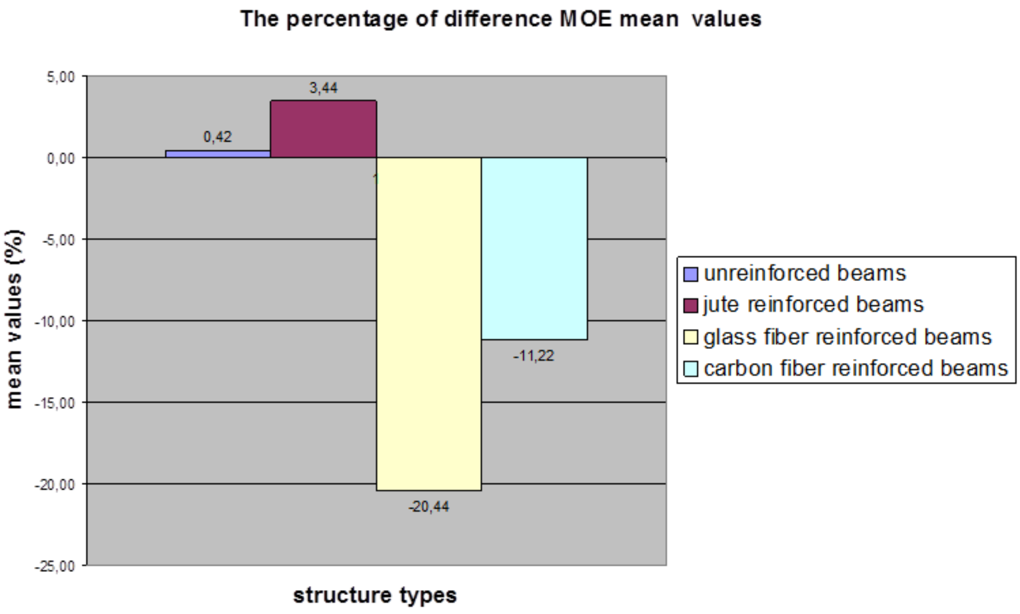

Figure 6: The difference of MOE mean value, in %.

4. CONCLUSIONS

According to the results we can state that the non-destructive method used in this study is able to classify the embedded lamella's quality class as well as the whole glulam structure and makes possible the design of beam structures with planned properties. The MOE predicting model shows higher consistency in the case of jute reinforced beam and reference beams. However, the model's adequacy is lower in case of glass and carbon fiber reinforced beams due mainly to the gluing imperfections between reinforcement layers and wood lamina.

The method can be utilized to determine the elastic properties of the beams and for the comparison of static and dynamic data. As a quick and efficient grading method – especially in case of unreinforced beams and jute reinforced beams -, can be a rapid method of classifying laminated beams, given its usefulness both for classification of timber as well as ready-made beams. This non-destructive method may facilitate mechanical testing procedure and classification of wood laminates.

Because of its usefulness, this method is planned to be used for lamella classification, reinforcement effect of different materials such as striated metallic bands, fiberglass and carbon fiber.

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