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Róbert Németh, Christian Hansmann, Holger Militz, Miklós Bak, Mátyás Báder

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Bending test results of small-sized glued laminated oak timber consisting of 2, 3 and 5 layers

Dénes Horváth[1*], Sándor Fehér[1]

[1] University of Sopron, Institute of Basic Sciences. Bajcsy-Zs. Str. 4, Sopron, Hungary, 9400.

E-mail: horvath.denes@uni-sopron.hu; feher.sandor@uni-sopron.hu

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ABSTRACT

This paper deals with glued-laminated timber (GLT) built up of low quality oak lamellae. Two-layered (40 mm), three-layered (45 mm) and five-layered (50 mm) GLTs were assessed to dynamical and statical tests in order to get the modulus of ruptures (*MoR*) and modulus of elasticities (*MoE*). The results showed that *MoR* is more than 60 MPa for the weaker samples and 80 MPa for the five-layered samples with low variance. *MoE* showed a decrease of altogether 7.7% with the increasing of the thickness. Non-destructive and destructive tests gave similar results. It can be concluded that the quality of the outer layers is very important for a GLT. But the inner layers may contain wood failures such as dead knots, slope of grain, etc.

INTRODUCTION

There is a growing interest in using hardwoods, such as oak, in glued-laminated timber, and efforts are underway to assemble the basic knowledge that would lead to standardization for the use of hardwoods in manufacturing glued-laminated timber (Morin-Bernard et al. 2020). Glued laminated timber made from oak has been gaining importance in structural applications, with the first national and European technical approvals issued for oak glulam (Aicher and Stapf 2014). Hardwoods, including oak, have the potential for the production of glued laminated timber with favourable mechanical characteristics and provisional approvals for construction use (Glavinić et al. 2020). Oak GLT has shown particularly good mechanical performance under both monotonic and cyclic loading regimes, indicating its potential for use in construction projects. Destructive tests, such as four-point bending tests, push-out shear tests, and cyclic tensile tests, have been undertaken to evaluate the mechanical properties of oak timber for structural applications (Kytka et al. 2022).

The bending strength of oak glulam is influenced by the size of the beams, with a clear effect of size on bending strength observed (Aicher and Stapf 2014). - The size of the laminated timber beams was found to have an impact on the bending strength, with the material exhibiting a size effect associated with quasi-brittle behavior (Blank et al. 2016). The distribution of knots and finger joints in glued laminated timber plays an important role in the onset of damage evolution and the final failure pattern, highlighting the significance of considering these factors when conducting bending tests (Tran et al. 2016; Melzerová and Šmídová 2019). Melzerová and Šmídová (2019) found that the bending properties of glued laminated timber made from combinations of wood species were affected by cyclic temperature variation, with the bending strength being negatively affected by temperature, especially for hardwood species. It was observed that cyclic temperature variation negatively affected the modulus of elasticity (*MoE*) and modulus of rupture (*MoR*) of single species beams, while GLT showed an increase in bending strength, especially for hardwood species (Kytka et al. 2022).

The bending capacity and size effect of high-strength hardwood glulams, including oak, can be well predicted using a serial model that accounts for the bending stress gradient between adjacent laminations (Aicher and Stapf 2014). The type of adhesive used in the production of glued laminated timber affects its mechanical properties (Gáborík et al. 2016; Gaff et al. 2016; Gaff et al. 2017). For instance, beech wood lamellae showed the highest impact bending strength (IBS) when glued with polyvinyl acetate (PVA) adhesive (Gaff et al. 2016; Gaff et al. 2017). The method of adhesive application, including the thickness and location of the glue joint, can impact the shear strength and stiffness of glued laminated timber (Ido et al. 2022).

In conclusion, the bending strength of glued laminated oak timber is influenced by various factors including wood species, adhesive type, size effect and environmental conditions. Industry standards and best practices are being developed to optimize the use of hardwoods in glued-laminated timber, reflecting the increasing interest in utilizing hardwoods for structural applications. Our aim is to lay the foundations for the use of lower quality timber in hardwood GLTs. Accordingly, bending tests were carried out on various small-sized glued oak elements. In evaluating the results, particular emphasis was placed on wood failures.

MATERIALS AND METHODS

One of our raw materials was noble oak (*Quercus* spp.) lamella with a cross-section of 20x50 mm and a length of 500 (the latter is the direction of fibres) with planed surfaces taken from the sawmill of Zalaerdő Erdészeti Zrt, Lenti, Hungary. Our other raw material was thin oak board with dimensions of 5x100x1000 mm derived from SEFAG Erdészeti és Faipari Zrt, Barcs, Hungary. The 736 planed lamellae contained sapwood, slope of grain, sawed surfaces due to the smaller thickness, both sound and decayed knots of various sizes (Figure 1). Low quality lamellae were selected, which meet at most the appearance grade QF3 and QF4 of standard EN 975-1 (2009). All lamellae have been photographed and a detailed quality description has been obtained. The thin oak boards were free of failures.

Figure 1: Typical wood failures in the lamellae used for the specimens

The wooden raw materials were stored in a workshop after kiln drying, where they reached an average equilibrium moisture content of 11.2%. Uniform climatic conditions prevailed throughout the specimen preparation. The lamellae were finger-jointed in length and simply glued together in width with the same emulsion polymerized isocyanate glue, to produce 20x100x1000 mm elements. The finger-joints were placed side by side in the middle of the element to test the weakest assembly. The gluing of the finished elements was done similarly with PVAc glue.

Three types of small-sized GLT beams were prepared from the elements. By gluing two elements together, 2-layer GLTs of 40x100x1000 mm were produced, 20 pieces in total. The strengthened version of this one was 45x100x1000 mm with a 5 mm thick oak board in the middle. 27 pieces of them were made. The third sample is 50x100x1000 mm. The structure in thickness of the 20 specimens is 5 mm thick oak board - 16 mm lamella - 5 mm thick oak board - 16 mm lamella - 5 mm thick oak board (Figure 2). The reason for thinning the elements was to minimise the size effect, in order to be able to compare *MoR* and *MoE* of the three samples.

Figure 2: Three types of small-sized GLT beams prepared for the tests

After conditioning the samples (20 °C and 65% relative humidity), a 4-point bending test was performed with different support spans and distance between the 30 mm diameter rollers of the crosshead, as seen in Table 1. The crosshead rollers were symmetrically spaced between the supports, in accordance with EN 408: 2010 + A1 (2012).

Table 1: Test settings

Sample thickness [mm]	Sample width [mm]	Support span [mm]	Crosshead roller distance [mm]
40	90	720	240
45	90	810	270
50	90	900	300

The bending tests were performed on an Instron 4208 (Instron Corporation, USA) universal material testing machine. The load rate was 6.0 $mm.min^{-1}$, which meets the requirements of the standard.
Before bending tests, the specimens were first subjected to a non-destructive test. The natural longitudinal vibration frequency was used, which gives a good estimation of *MoE* (Divós et al. 1994). The measurements were performed with a Portable Lumber Grader Plus (PLG+) timber classification equipment (Fakopp Bt, Hungary). It automatically determined both ρ and MoE_{dyn} based on the Timosenko theory (Sismándy-Kiss 2012, Bejó et al. 2022). The vibration was applied with a hammer at one end of the specimen, while the signal was detected with a microphone at the other end of the specimen. The specimen was supported at two points by scales with vibration damped pads to minimize vibration distortion. The exact length of the specimens was monitored by a laser distance meter and automatically transmitted to the computer, while the cross-section had to be specified manually. After sequential decoding of the recorded vibrations, the software determined the longitudinal wave propagation velocity, the vibration spectra and frequencies of the vibration modes and automatically selected the most relevant frequency peak.

RESULTS AND DISCUSSION

The low variances of all the test results suggests that the selection of raw materials and specimen preparation was well performed, and that the tests were carried out with sufficient accuracy. In most cases, a variance of less than 10% were achieved. For wood material tests 10% variance is very good, especially considering that the highest variance among all test results was only 14.2% in this study.
In order to determine the comparability of the samples, it is worth analysing their densities first. Figure 3 shows the averages and standard deviations of the three samples as determined by the dynamic tests. It can be seen that density values increase with thickness from 729.0 to 766.7 kg/m^3. Given the otherwise low standard deviations, no significant difference between the sample groups is likely.

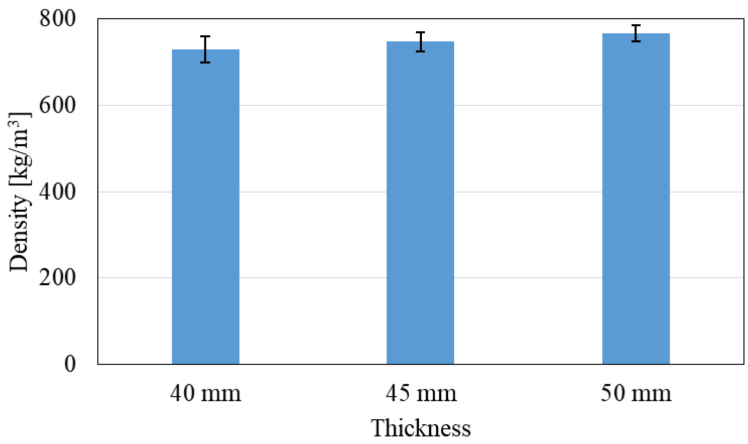

Figure 3: Densities of the small-sized GLT beam samples

Bending strength is one of the most important properties of structural elements. The diagram in Figure 4 shows that *MoR* of 40 mm and 45 mm thick specimens is almost the same. They are also statistically identical when the standard deviations are taken into account. It can be concluded that the addition of a thin oak board between the two lamellae is unnecessary and does not improve the *MoR* of the specimen. However, the 50 mm thick sample gave a 30% higher result of 80.0 MPa, i.e. the thin oak boards glued on both outer layers significantly increased the *MoR*. This is also due to the fact that the finger joints were no longer located at the outer layers of the specimens, where the highest forces located, but further inwards. They were therefore less exposed to the breaking forces and their weaker system compared to solid oak had less influence on the final result.

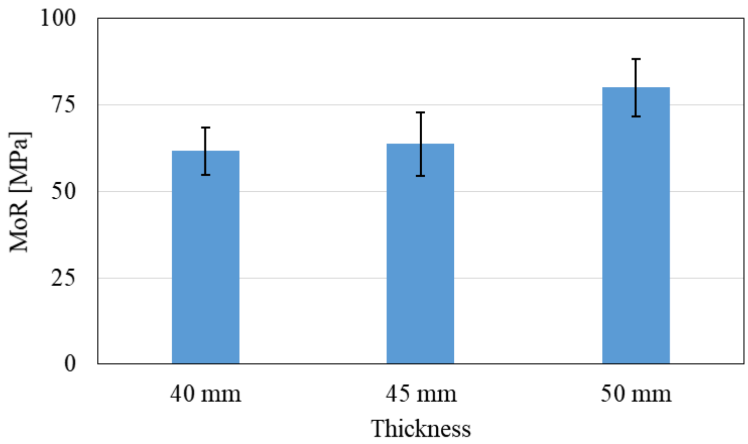

Figure 4: Modulus of Rupture (MoR) of the small-sized GLT beam samples

Regarding *MoE*, the results of two different measurement methods can be compared. The results obtained from the bending tests in the blue columns of Figure 5 are based on the requirements of the current standard EN 408: 2010 + A1 (2012). The non-destructive results obtained from the dynamic test, although not determined by direct measurement, are clearly very close to the static bending test results. Moreover, their standard deviations are similar or lower. The *MoE* of the specimens shows a slight decrease with increasing thickness. Between 40 and 50 mm thick specimens it is only 7.7%, but this is likely to be a statistically significant difference. However, the difference between 12.7 GPa and 11.7 GPa seems to be negligible in terms of strength grading.
An analysis of the fracture images shows that in most cases the failure occurred at the finger joints. A typical example is shown in Figure 6. Even for the 50 mm thick specimens, the outer layers were free of finger joints, which were subjected to the highest forces.

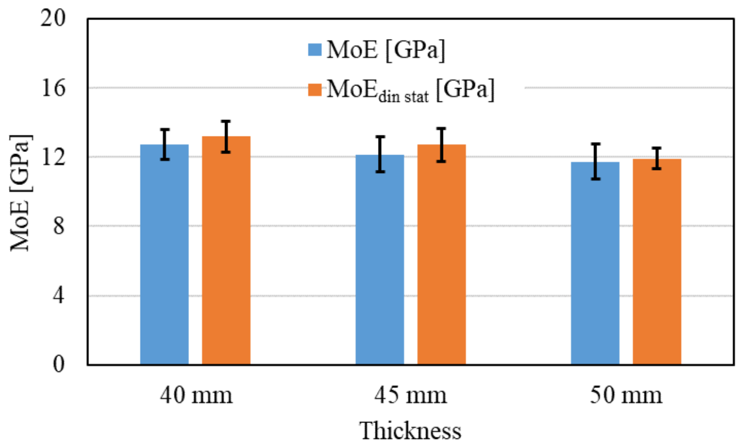

Figure 5: Modulus of Elasticity (MoE) of the small-sized GLT beam samples

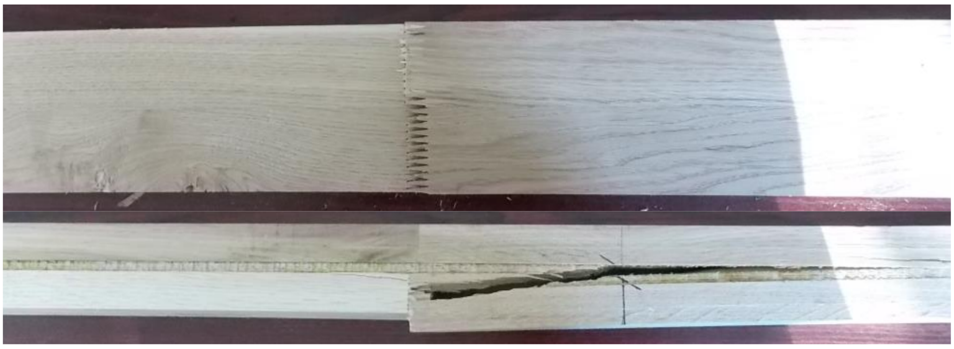

Figure 6: Pictures of a typical finger joint failure in specimen 38

CONCLUSIONS

The study presents the bending tests of small-sized structural specimens of 2, 3 and 5 layers, with thicknesses of 40, 45 and 50 mm, respectively. Non-destructive testing and bending tests according to EN 408: 2010 + A1 (2012) were performed. The lamellae were not failure-free.

On the one hand, the test results showed that there was very little difference between the static bending test and the dynamic test. On the other hand, the modulus of rupture of 80 MPa for 50 mm thick sample was significantly higher than that of 40 mm thick specimens. This implies that particular attention should be paid to the quality of the most stressed, outer layers of the GLT. The modulus of elasticity decreased slightly with increasing thickness. In most cases, the bending test failures were caused by PVAc adhesive failure, not by wood defects.

In conclusion, the mechanical properties of glued laminated oak timber are influenced by factors such as adhesive type, layer structure and quality of outer layers variation. When conducting bending tests on oak GLT, it is important to consider the distribution of knots and finger joints. The advantages of using glued laminated oak timber in construction projects include its satisfactory performance under various loading conditions and its potential for structural applications. Further research specifically focusing on oak timber and different adhesive types would be beneficial to provide more direct insights into this specific query.

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