Compression Parallel to Grain of Finger-Jointed Pine Specimens: Experiment and Modeling for Determination of Elastic Modulus

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Abstract: The practical realization of sustainable development concepts implies the application of new material processing technologies, among which wood as a renewable resource with a low carbon footprint occupies a special place. Researchers have developed many promising technologies for wood processing, but this paper discusses only one of them that fully meets the requirements of sustainable development. This is a finger-jointing technology for wood. The paper deals with compression tests of pine specimens with initial dimensions of 40×40×80 mm with and without finger joints. Experiments have shown that the finger joint reduces the peak load on the specimen by 11 %. The peak load is reduced caused stress concentration, which is consistent with numerical modelling results in existing studies. In addition, the finger-jointed specimen showed a disproportionate 22 % reduction in relative strain at the peak point. These changes mean a decrease in plastic properties and an increase in brittleness under the influence of the physical and mechanical properties of the adhesive in the gear joint. This paper proposes two versions of the equation for modelling the behavior of wood in load-displacement and stress-strain coordinates. The relevance and feasibility of such research is because finger joint technology minimizes wood waste and ensures sustainable wood management to sustainable development.

1 INTRODUCTION

Rational use of resources and minimization of production and consumption waste are among the key points in the concepts of sustainable development at the global and regional levels. The practical realization of sustainable development concepts implies the application of new material processing technologies, among which wood as a renewable resource with a low carbon footprint occupies a special place (Linkevičius, 2023; Sikkema, 2023; Stanciu, 2020). Researchers have developed many promising technologies for wood processing (He, 2023; Pramreiter, 2023), but this paper discusses only one of them that fully meets the requirements of sustainable development. This is a finger jointing technology for wood (Ahmad, 2017; Faircloth, 2023; Muthumala, 2021; Stolze, 2021).

The need for rational utilization of wood has predetermined the development and widespread use of finger joint technology. This technology makes it possible to obtain almost endless blanks from small pieces of wood for building and furniture constructions (Hou, 2022; Hou, 2023). Thus, this technology minimizes wood waste and ensures sustainable use of wood, which motivates experimental and theoretical research in this field. For example, according to a study (Le, 2023), a modified "firefly algorithm" determines finger-joint parameters that maximize joint strength while reducing waste in the manufacture of timber structures. Despite the advances in this field, the issues related to modelling and experimental studies of the peculiarities of wood behavior under load remain relevant (Stolze, 2023; Walley and Rogers, 2022). One of such questions concerns the study of wood condition in joints of wooden structures under compression, bending and tension. In this direction, along with those presented in the list of cited literature, important is the study (Vega, 2020), in which the authors, using the finite element method, determined the areas of stress concentration in finger

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joints, which is important for predicting wood damage and failure in the joint zone.

Purpose of this work: experimental study of the effect of a finger joint on the strength of pine specimens in compression along the grain and modelling of their behavior.

2 METHODOLOGY AND RESULTS

2.1 Experiment

To achieve this goal, we tested specimens made of pine with initial dimensions of 40×40×80 mm with and without finger joints. The relative humidity of the specimens was 12 %. A SHIMADZU testing machine was used in the experiments (Fig. 1).

Figure 1: Testing machine.

Figure 2 shows pine specimens without joints, before and after testing.

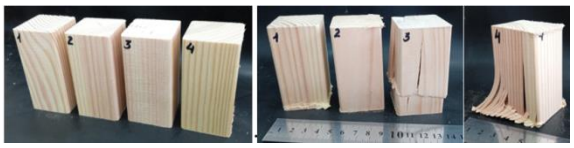

Figure 2: Specimens without joints before and after testing.

Figure 3 shows the curves in load-displacement coordinates for the specimens in Figure 2 under controlled displacement at 5 mm/min. The average force and displacement values at the peak are 73.9 kN and 1.484 mm, respectively.

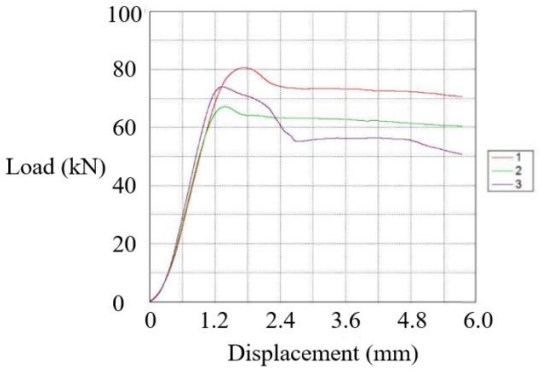

Figure 3: Experimental curves for specimens according to Figure 2.

Figure 4 shows specimens with initial dimensions of 40×40×80 mm, with finger joints.

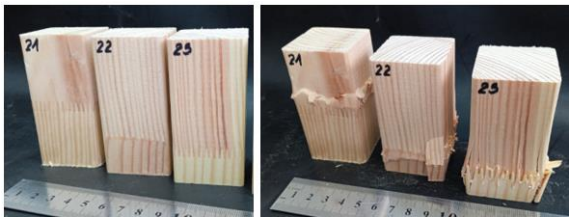

Figure 4: Specimens with finger joints before and after testing.

Figure 4 shows that finger joints localize wood damage, i.e. they are damage attractors. This fracture pattern is consistent with the results of numerical simulations (Vega, 2020), which predict an increase in stresses in the region of each vertex (Fig. 5) and, consequently, the localization of the onset of fracture in the joint. As a result, the predicted strength of specimens with finger connections decreases compared to the strength of similar specimens without connections.

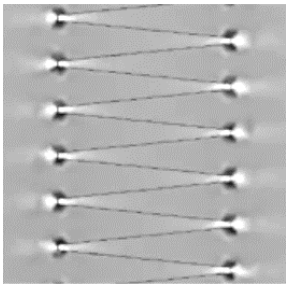

Figure 5: Stress concentration in a finite element model of joint (Vega, 2020).

Fig. 6 shows curves in load-displacement coordinates for specimens from Fig. 4 under controlled displacement at a speed of 5 mm/min. The

average values of force and displacement at the peak point are 65.816 kN and 1.155 mm, respectively.

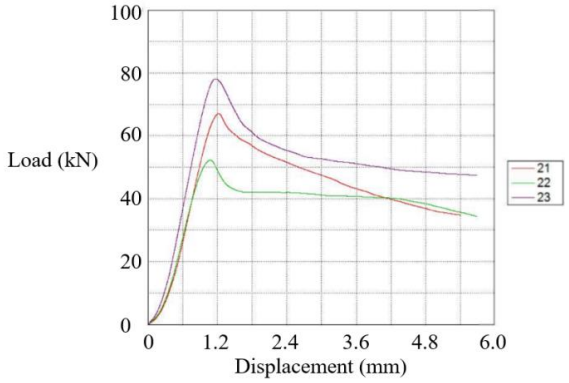

Figure 6: Experimental load-displacement curves for specimens according to Figure 4.

Table 1 combines data for specimens with and without joints for further analysis.

Table 1: Averaged experimental data for specimens with and without joints.

Specimens:	In peak point:			
	Displacement, mm	Load, kN	Stress, MPa	Strain
Without joints	1,484	73,9	46,2 (100%)	0,01855 (100%)
With joints	1,155	65,8	41,1 (89%)	0,01444 (78%)

Comparison of the experimental data (Table 1) shows that the average value of the load at the peak point for specimens with finger connections is 89 % of the strength of the specimen without connections. Accordingly, the conditional stiffness is 73.9 / 1,484 ≈ 49.8 kN/mm.

The average displacement (i.e., height reduction) for specimens with finger joints decreased disproportionately to 78% of the displacement for the specimen without joints. Accordingly, the conditional stiffness is 65.8 / 1,1554 ≈ 57.0 kN/mm. The relative strain decreased by 22 %, while the strength decreased by only 11 %, which can be interpreted as a decrease in plastic properties and an increase in brittleness in the finger joint area. These changes caused by the physical and mechanical properties of the adhesive that was used in the finger joint (Vega, 2020).

Thus, the finger connection reduces the strength of the specimens but increases the stiffness compared to specimens without connections.

2.2 Modelling

This part of the paper focuses on the determination of the tangent modulus of elasticity of wood using experimental data and mathematical modelling. Note that the values of the modulus of elasticity of wood depend on a number of factors (Sun, 2022; Verbist, 2020; Arriaga, 2023). E.g., the angle of deviation of the grain from the longitudinal axis of the specimen affects the value of the elastic modulus. The reduction in elastic modulus compared to a sample without deviations can exceed 50 % (Mania, 2020).

We use the following approach to determine the tangent modulus of elasticity of wood.

We approximate the experimental data (Figures 3 and 6) by a curve line with the equation from (Shekov, 2023). This equation can be written in coordinates load (F) – displacement (u) (1) or stress (σ) – strain (ε) (2):

$$\frac{F}{F_{peak}} = \left(\frac{u}{u_{peak}} e^{\frac{1}{n}\left(1-\frac{u^n}{u_{peak}^n}\right)} \right)^B ; \qquad (1)$$

$$\frac{\sigma}{\sigma_{peak}} = \left(\frac{\varepsilon}{\varepsilon_{peak}} e^{\frac{1}{n}\left(1-\frac{\varepsilon^n}{\varepsilon_{peak}^n}\right)} \right)^B . \qquad (2)$$

The parameters n and B are determined during model calibration, e.g., using the least squares method, as shown (Stojković, 2017). However, for equations (1) and (2), it is simpler to apply the random search method (Arora, 1995), which is implemented in this paper. To ensure the universality of the model, but not to increase the number of equations, we use equation (1) (or (2)) but with different parameters n and B for the left (pre-peak) and right (post-peak) branches. For example, for the left branch: $0 \le u \le u_{peak}$, $n = n_l$, $B = B_l$; for the right branch: $u_{peak} \le u$; $n = n_r$; $B = B_r$. Figure 7 illustrates the approximation of the experimental data from Figure 3.

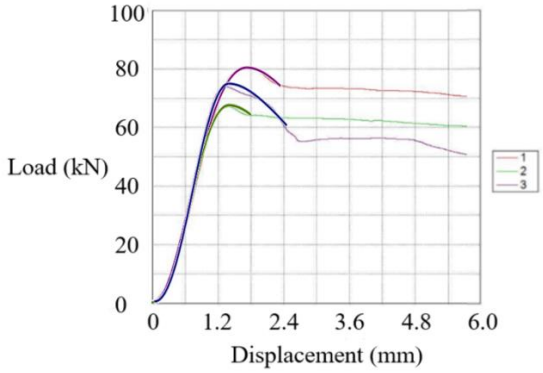

Figure 7: Approximation of the experimental data from Figure 3 (thickened curves).

Using equation (2) we determine the inflection point on the ascending branch of the curve from the condition $\frac{d^2\sigma}{d\varepsilon^2} = 0$. Since the second derivative is zero, the value of the first derivative is extreme at this point. Thus, we determine the largest value of the tangent modulus of elasticity $E = \frac{d\sigma}{d\varepsilon}$.

For specimens 1, 2 and 3 (Figure 2), we obtained, respectively, the following values of elastic modulus: 3.812, 4.195 and 4.457 GPa; the average value is 4.155 GPa. In specimen 1, the fibers are significantly deviated from the longitudinal axis of the specimen (Fig. 2), which reduces the value of elastic modulus. These results are in agreement with existing studies (Mania, 2020).

For specimens 21, 22 and 23 (Figure 4), we obtained, respectively, the following elastic modulus values: 4.850, 3.908, and 4.664 GPa; the average value is 4.474 GPa, which is 7.7 % higher compared to specimens without finger joints. The increase in the elastic modulus can be explained by the above-mentioned influence of the glue in the joint, but the influence of the natural variation of the physical and mechanical properties of wood cannot be ruled out either (Mania, 2020; Vega, 2020; Walley and Rogers, 2022). In general, the obtained values of elastic modulus are low, which is characteristic of low-density wood of immature forests.

3 DISCUSSION

The use of Equation (1) provides an acceptable accuracy of approximation of wood test results in compression parallel to the grain (Figure 7). Equations (1) and (2) use the same parameters n and B, respectively, and the accuracy of approximation of the experimental data in load-displacement and stress-strain coordinates is the same. The main result of the modeling is an accurate analytical determination of the tangent modulus of elasticity at the inflection point of the pre-peak curve. For specimens 1, 2, and 3 without connections (Figure 2) discussed above, the inflection point corresponds to a load equal to 40-50% of the peak load (Figure 8). For specimens with finger connections (Figure 4), the load at the inflection point is 50-60 % of the peak load (Figure 9).

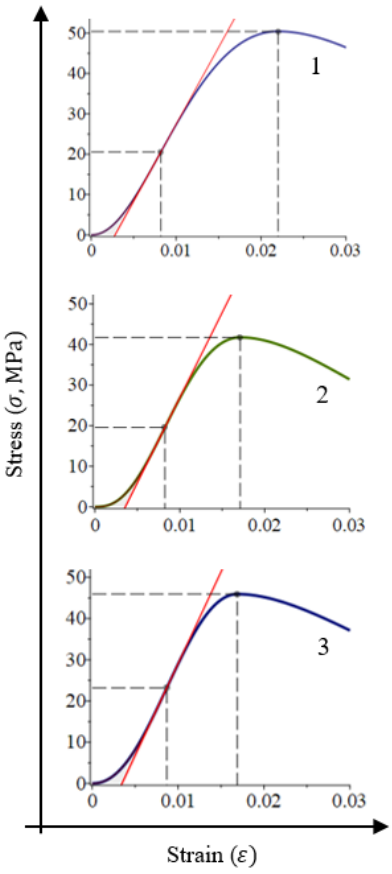

Figure 8: To determination of elastic modulus of specimens 1, 2 and 3.

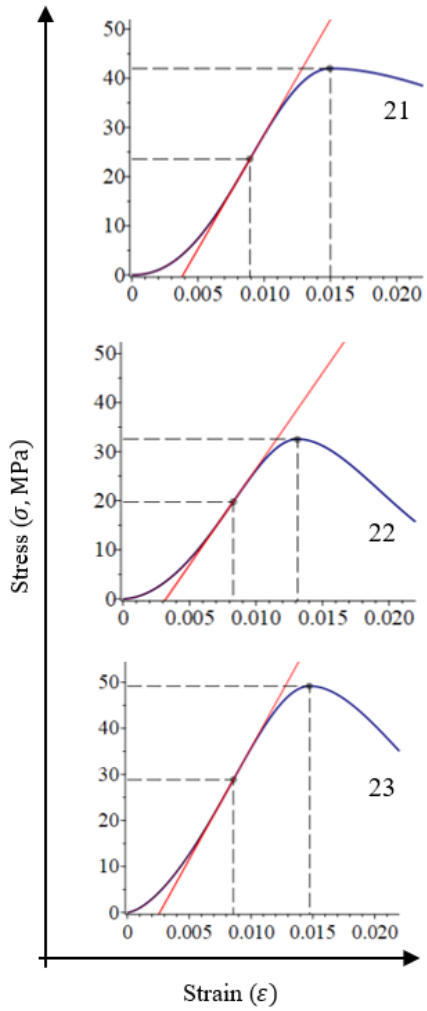

Figure 9: To determination of the modulus of elasticity of specimens 21, 22 and 23.

4 CONCLUSIONS

In this study, a methodology for determining the modulus of elasticity of wood with and without finger joints in compression parallel to the grain is proposed based on the analysis of experimental data using mathematical modeling.

The experiments showed that the presence of the finger joint reduced the peak load on the specimen by 11 %. The peak load reduction is due to the effect of stress concentration near the tops of the finger joint elements.

The finger joint disproportionately decreased the relative strain at the peak point by 22 %, i.e., decreased ductility and increased brittleness. Other things being equal, these changes depend on the properties of the adhesive in the finger joint.

Two versions of the equation for modeling the behavior of wood in load-displacement and stress-strain coordinates are proposed. The largest value of the tangent modulus of elasticity was determined using the condition $\frac{d^2\sigma}{d\varepsilon^2} = 0$. A distinctive feature of this approach is the reduction of uncertainty in selecting the coordinates of the point with the highest elastic modulus (Figs. 8 and 9).

The results obtained are consistent and adequate from the physical point of view. However, the amount of experimental data is small, so the research should be continued. Research in the indicated direction is relevant and expedient, as the finger-joint technology allows minimizing the amount of wood waste and ensuring rational use of wood for sustainable development.

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