

## Article

# The Usefulness of Pine Timber (*Pinus sylvestris* L.) for the Production of Structural Elements. Part II: Strength Properties of Glued Laminated Timber

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**Abstract:** The paper assessed the feasibility of manufacturing glued structural elements made of pine wood after grading it mechanically in a horizontal arrangement. It was assumed that the pine wood was not free of defects and that the outer lamellas would also be visually inspected. This would result in only rejecting items with large, rotten knots. Beams of the assumed grades GL32c, GL28c and GL24c were made of the examined pine wood. Our study indicated that the expected modulus of elasticity in bending was largely maintained by the designed beam models but that their strength was connected with the quality of the respective lamellas, rather than with their modulus of elasticity. On average, the bending strength of the beams was 44.6 MPa. The cause of their destruction was the individual technical quality of a given item of timber, which was loosely related to its modulus of elasticity, assessed in a bending test. Although the modulus of elasticity of the manufactured beam types differed quite significantly (11.45–14.08 kN/mm<sup>2</sup>), the bending strength for all types was similar. Significant differences occurred only during a more detailed analysis because lower classes were characterized by a greater variation of the bending strength. In this case, beams with a strength of 24 MPa to 50 MPa appeared.

**Keywords:** beams; glued laminated timber; modulus of elasticity; pine wood; laboratory tests

## 1. Introduction

Developments in the construction industry and searching for ways to use conventional and alternative structural materials have provided new materials: EWPs (Engineering Wood Products). In the case of EWPs, the idea is to obtain a full-quality product from a material that was originally not suitable for specific uses due to its size or insufficient quality [1,2]. Nowadays, Europe and the world have seen developments in the technology of the manufacturing and application of glued timber, mainly GLT (Glued Laminated Timber). This material fits very well with the EWP technology trend. GLT has the typical features of solid timber: light weight, good strength, elasticity, durability, easy processing and a unique feature, i.e., it is readily shaped into cross-sections. Its cross-section has a layered structure, enabling the manufacturing of components with variable cross-sectional heights, as needed [3–6].

Wooden components are glued with binding agents that guarantee a high strength under static and dynamic loads. Structural timber layers, especially those for making load-bearing structures, are nearly always combined by means of resorcinol-phenol-formaldehyde (PRF) or melamine-urea-formaldehyde (MUF) glues. Apart from these, polyurethane-based glue is becoming more and more popular. All these adhesives should provide a high durability in variable environmental conditions [7–11].

Studies on the durability of straight and bent beams composed of wooden layers glued together with synthetic resins indicate that such elements have comparable load-bearing capacities to those made of solid timber. Moreover, the layered timber structure has resulted in an improved quality of the material [3,12–21].

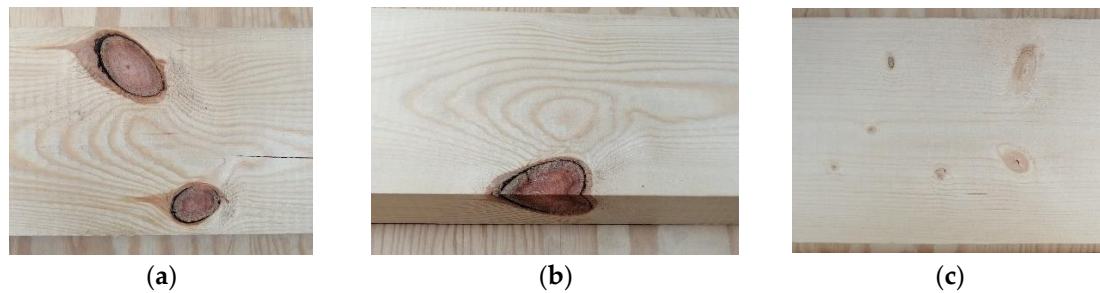
Recent research studies on glued laminated timber have focused, among other things, on materials glued lengthwise and crosswise. Test results for high-grade solid timber and glued laminated timber, even that obtained from lower-quality timber after grading, indicate that the latter has better strength properties. This is mostly attributed to the distribution of defects and to the gluing process. For instance, the studies focused on the shaping of cross-sections of items made out of thin timber that was comprised of different grade materials with respect to their strength [22–30].

According to JCR (Journal Citation Reports), more than 700 scientific papers on glulam timber were published in the last 20 years. They considered, among other things, the component's reinforcement methods by using glass or carbon fibers [31–34], the effect of different factors on the behavior of steel-timber composites (STC) [35–37] and glulam-concrete beams [38–40].

As mentioned earlier, in the case of glued laminated timber, the cross-sections of the obtained elements can be shaped as required. However, what is important is that the strength is also improved, and it is generally higher than the combined elements. The coefficient of variation for the bending test is also improved [41,42]. In the works of Tomasi [43] and Gonzales [37], a significant improvement in the mechanical properties of glued laminated beams reinforced with steel rods was indicated. However, they pointed out that the quality of the steel-wood joint was of significant importance in these systems. The abovementioned authors draw attention to systems made of different lamella qualities; however, there is the possibility of having the lamellas be joined in their width [44,45] or having them made of different species [46,47]. The created systems result from certain fixed concepts, as described in appropriate standard or the model described in the works of Fink [48], Foschi and Barrett [49], or Hernandez et al. [50] may be the basis for their creation. Predicting the future quality of the produced GLT elements is an overriding task for engineers who support this branch of the wood industry because, in contrast to the mass production of wood-based panels with stabilized parameters, testing the produced GLT is expensive and difficult.

The parameter of GLT which determines its suitability is, first of all, the strength of lamellas with different parameters and properties, as defined in applicable normative documents, taking into consideration the acceptable classes of glued timber [51–53]. The current strength classification system (EN 338) [54] for structural timber enables the use of a single-strength class in the range of C16–C30 for beams of uniform structure and in combination with lower classes C16 and C18 in the case of a nonuniform structure (EN 384) [55]. The class C is related to the static bending strength of manufactured material. The strength of defect-free pine wood is usually in the range of 90–110 MPa. However, because of its natural features, which from a technological perspective are often recognized as defects, the mechanical properties deteriorate considerably. The strength characteristics of the majority of timbers are often below 20 MPa, which results mostly from the occurrence of knots. They appear in various sections with an interval of 40 to 60 cm. The timber properties are affected not only by the number and size of the knots, but also by their soundness. Low-quality knots are usually cut, and the obtained elements are combined with the use of finger joints. This technique is known and has been constantly developed since the Second World War [56]. The knots are an important type of defect and due to their dimensions affect in particular the pine wood (Figure 1a,b). For comparison, a spruce timber is characterized by the presence of significantly smaller knots (Figure 1c). Thus, their removal contributes to an improvement in both the technical quality and visual aspects of each piece of pine

timber. However, it seems like, in the case of glued components, the occurrence of knots has a smaller effect and the visual side is less important.



**Figure 1.** The examples of knots from: (a,b) Scots pine and (c) Norway spruce.

Consequently, the aim of the presented work was to investigate the possibility of using pine timber sorted solely on the basis of mechanical properties, with the exception of the outer layers. The outer lamellas of the eight-layer beams were also assessed visually. During the assessments, the pieces of timber having edge knots or large rotten knots were classified as unsuitable for the outer layers.

## 2. Materials and Methods

The research material was pine wood with the following dimensions: 137 mm wide  $\times$  39.50 mm thick  $\times$  3485 mm long. The average density of the timber items was 571 kg/m<sup>3</sup> (average moisture 8.98%). The pine wood was obtained by sawing timber in the form of logs having round cross sections and originating from the Forest Division Olesno (50°52'30" N 18°25'00" E). The obtained sawn timber was dried to a moisture content of 10%  $\pm$  2%. After drying, the sawn timber was organized so as to obtain a uniform thickness of all the lamellas. The preliminary assessment was performed in accordance with EN 338. The detailed description of the modulus of elasticity assessments is included in the first part of the research. Selected timber items were used for the preparation, in semi-industrial conditions, of glued beams with a diameter of 137 mm  $\times$  300 mm, i.e., comprising eight layers. With the exception of the outer layers, the choice of the lamellas for making the beams depended only on the determined value of the modulus of elasticity. The outer layers, with the exception of the required value of the modulus of elasticity, were required to have no edge knots. The raw material originating from that region is characterized by a higher percentage of timber, whose physico-mechanical parameters enable a considerable portion of it (45%) to be classified into higher classes than C24 (details will follow in the next chapter). Therefore, it was assumed that the respective beam models would satisfy the conditions for a modulus of elasticity set out for grades GL24c, GL28c and GL32c according to EN 14,080 [57]. The elastic properties of the beams layers were determined according to Bodig and Jayne [58], assuming that the beam was symmetric and contained eight lamellas (1):

$$E_{ef} = \frac{1}{J_y} \sum_{i=1}^4 E_i [J_{yi} + A_i (d_i)^2] \quad (1)$$

where:

$E_{ef}$ —effective/substitute modulus of elasticity, N/mm<sup>2</sup>,

$J_y$ —area moment of inertia, mm<sup>4</sup>,

$E_i$ —modulus of elasticity of layer, N/mm<sup>2</sup>,

$A_i$ —cross-sectional area, mm<sup>2</sup>,

$d$ —distance from the neutral axis, mm.

The adopted values of the modulus of elasticity for various types of beams are shown in Table 1.

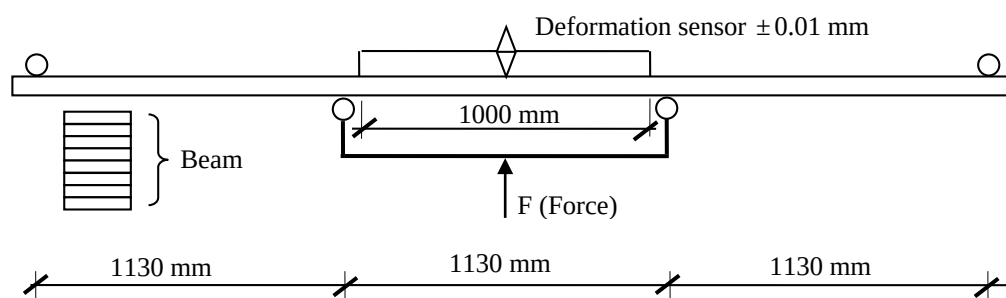
Just before being used for the preparation of glued beams, the timber items were further processed via a plan to improve their surfaces before gluing them together. The effective thickness of individual lamellas was 37.5 mm. The resulting surface was covered with an amount of glue of 220–250 g/m<sup>2</sup>. Melamine-urea-formaldehyde resin (MUF 1247) and its dedicated hardener (2526), both from Akzo Nobel (Amsterdam, Netherlands), were used as the binding agent. The mixture was prepared while taking into account the conditions prevailing in the laboratory room. The hardener was used at 20 g per each 100 g of resin, as recommended by Akzo Nobel for that resin. The glue was applied using a roller coating machine. The beams were manufactured at a room temperature range between 20 °C and 24 °C. The press loading time was around 12–15 min. Four beams were pressed at the same time under a pressure of 0.48 MPa for 20 h. Four beams were manufactured each day. Pressing was conducted with the use of an industrial press equipped with hydraulic cylinders dedicated to the production of glued, structural elements (FOST, Czersk, PL). After production, the beams were air-conditioned in the laboratory for min. four weeks. The conditions in the laboratory were controlled: the temperature was 21 ± 2 °C, and the air humidity was 55–65%. After the period of air conditioning, the beams were assessed for their mechanical properties. Due to the weight of the beams, they were not planed. Excess glue was manually removed immediately prior to testing the mechanical properties.

**Table 1.** Elastic properties of designed beams.

| Beam Type | Number of Samples | $E_{\text{mean}}$  | $E_{\text{min}}$ | $E_{\text{max}}$ | $E_{\text{mean 1st layer}}$ | $E_{\text{mean 4th layer}}$ | $\text{MOR}_{\text{declaration}}^*$ |
|-----------|-------------------|--------------------|------------------|------------------|-----------------------------|-----------------------------|-------------------------------------|
|           |                   | kN/mm <sup>2</sup> |                  |                  |                             |                             | N/mm <sup>2</sup>                   |
| GL24c     | 12                | 11.71              | 11.25            | 11.93            | 12.53/1.42 **               | 8.48/1.88                   | 24                                  |
| GL28c     | 14                | 12.82              | 11.98            | 13.50            | 13.96/5.44                  | 8.08/11.69                  | 28                                  |
| GL32c     | 22                | 14.84              | 14.13            | 16.52            | 16.45/8.64                  | 8.58/11.06                  | 32                                  |

\* Modulus of rupture (MOR)—characteristic value according to EN 14,080 [47], \*\* CoV (coefficient of variation).

The resulting beams were evaluated for their 4-point bending strength, in accordance with the diagram shown in Figure 2. Figure 3 shows the appearance of the test stand. It was equipped with: a hydraulic cylinder (50 Mg, Hi-Force, Daventry, UK), hydraulic pump (50 Mg, Hi-Force, Daventry, UK), oil flow rate regulator (Hi-Force, Daventry, UK), force sensor (CL 16 tm 500 kN, ZEPWN, Marki, PL) and deformation sensor (KTC-600-P, Variohm Eurosensor, Towcester, UK).



**Figure 2.** The scheme of the tested eight-layered beam.

In order to take into account the influence of the moisture content on the modulus of elasticity, the obtained results were calculated in accordance with Bauschinger's Equation (2):

$$E_{12} = E_{MC}[1 + \alpha_{MC} \cdot (MC - 12)] \quad (2)$$

where:

$E_{12}$ —modulus of elasticity of wood for a moisture content of 12%, N/mm<sup>2</sup>,

$E_{MC}$ —modulus of elasticity of wood for a moisture content of 4% < w < 20%,

$\alpha_{MC}$ —coefficient of variation of the modulus of elasticity of wood after its moisture content changed by 1%—assumed to be 0.02,

MC—absolute moisture content of wood, %.

The destructive test included the assessment of the point and cause of failure for each specific beam.

The results of the experimental measurements were analyzed using the STATISTICA 13.0 package (Version 13.0, StatSoft Inc., Tulsa, OK, USA).



Figure 3. Test stand for the evaluations of the bending strength and modulus of elasticity.

### 3. Results and Discussion

The mean values of the modulus of elasticity are shown in Table 2. The values shown therein indicate that the prepared beams, with the exception of grade GL32c, exhibited a low variability of the modulus of elasticity in bending. Moreover, the obtained values were close to or only slightly higher than the assumed ones (negative value of  $\delta$ ). Since the moisture of the beams during the test differed considerably from 12% (the average moisture for all the beams was 8.83%), the outcomes were recalculated using Bauschinger's Equation (2). With the exception of grade GL32c beams, the calculated values of the modulus of elasticity were only slightly lower than the assumed ones. For GL32c, the relative difference was 5.1%. Assuming that the values of the modulus of elasticity calculated for 12% MC are appropriate, it should be expected that the beams satisfy the assumptions in this regard.

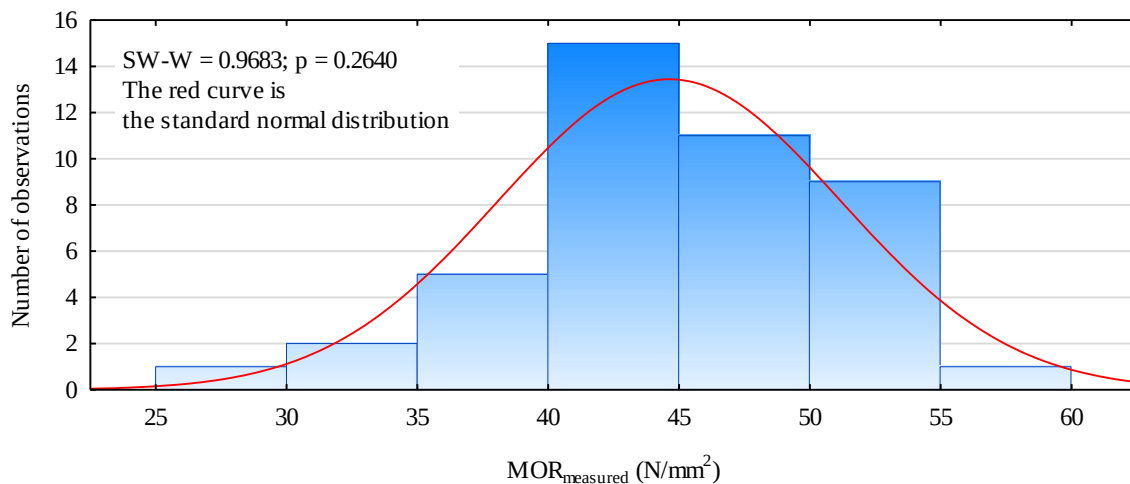
Table 2. Elastic properties of the designed beams.

| Beam Type | Assumed Values                           |         | Determined Values                        |         | $\delta$ * (%) | $E_{\text{mean per 12\%MC}}$ (kN/mm <sup>2</sup> ) | $E_{5\text{percentyl per 12\%MC}}$ (kN/mm <sup>2</sup> ) |
|-----------|------------------------------------------|---------|------------------------------------------|---------|----------------|----------------------------------------------------|----------------------------------------------------------|
|           | $E_{\text{meanZ}}$ (kN/mm <sup>2</sup> ) | CoV (%) | $E_{\text{meanP}}$ (kN/mm <sup>2</sup> ) | CoV (%) |                |                                                    |                                                          |
| GL24c     | 11.71                                    | 1.81    | 12.79                                    | 6.42    | −9.21          | 11.45                                              | 10.43                                                    |
| GL28c     | 12.82                                    | 3.83    | 13.63                                    | 6.84    | −6.31          | 12.78                                              | 11.78                                                    |
| GL32c     | 14.84                                    | 4.00    | 14.94                                    | 14.1    | −0.68          | 14.08                                              | 11.68                                                    |

\*—Relative change:  $\delta = (E_{\text{meanZ}} - E_{\text{meanP}})/E_{\text{meanZ}} \times 100\%$ .

It is assumed that the prepared beams should have a static bending strength that is not lower than 24 N/mm<sup>2</sup>, 28 N/mm<sup>2</sup> and 32 N/mm<sup>2</sup>, respectively, for beam types GL24c, GL28c and GL32c. The lowest strength for all the prepared beams was 29.97 N/mm<sup>2</sup>, and the highest was 55.38 N/mm<sup>2</sup>. However, the static bending strength of the beams had a normal distribution (Figure 4), and, importantly, its standard deviation was only 6.45 N/mm<sup>2</sup> and its variation coefficient was 14.5%, even though they were designed for different values of the modulus of elasticity. This means that the strength of

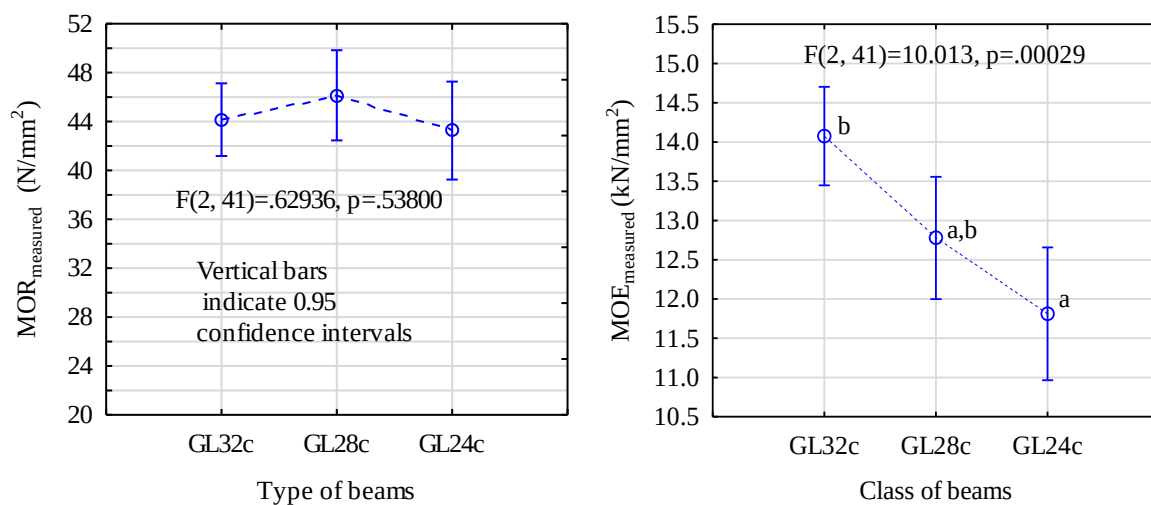
the obtained beams was characterized by a low variability and was not strongly correlated with the designed system.



**Figure 4.** A histogram of the static bending strength for the glued beams made of mechanically graded timber.

Hence, the static bending strength is not correlated with the grade of the designed beams.

The data in Figure 5 show that all the models are characterized by a similar strength of around 44.5 N/mm<sup>2</sup>, regardless of the assumed timber grade, whereas an analysis of the modulus of elasticity shows the presence of two clearly different groups.

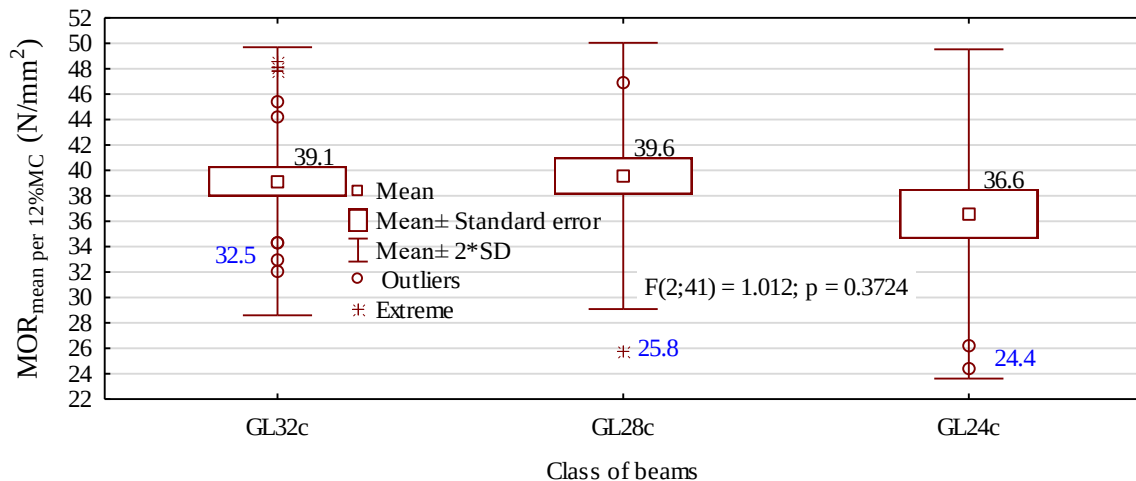


**Figure 5.** A one-factor ANOVA for the system: glued beam's grade—static bending strength; and beam's grade—modulus of elasticity. The letters denote uniform groups for Tukey's test.

The values of strength obtained in the bending test were also recalculated with Bauschinger's formula, using a factor of  $\alpha = 0.04$  this time. The results obtained with that factor are shown in Figure 5. The mean values calculated for all the beams were thus reduced from 44.5 N/mm<sup>2</sup> to 38.6 N/mm<sup>2</sup>, which is still rather high. However, the assignment to the specific grade GL is based on a 5-percentile value of strength. For the represented number of samples, this value is the lowest or close to the lowest.

The values shown in Figure 6 indicate that the beams assigned to the groups GL32c and GL24c satisfied the strength requirement, reaching the following values: 32.5 N/mm<sup>2</sup> for grade GL32c beams and 24.4 N/mm<sup>2</sup> for grade GL24c beams. The batch of beams modeled to be assigned to grade GL28c did not satisfy requirements and should have been assigned to grade GL24c, even though it had the

highest mean value. What is important, in the case of that group, is that its assignment to the specific grade was attributed to a value regarded as being a statistical extreme. Moreover, the second lowest value of the static bending strength reached in that group was as high as  $36.8 \text{ N/mm}^2$ . Without taking into account the strength of the three beams with the lowest values, the 5-percentile value would be  $32.5 \text{ N/mm}^2$ .



**Figure 6.** Characteristic values of the static bending strength for the prepared beam (samples). The numbers in blue denote the 5-percentile value.

It is hard to predict the exact point of failure and the potential strength in some cases. For Beam 41 (Figure 7a), the cause of destruction was found, as expected, in the second and third lamellas and was due to the presence of large rotten knots in the pure bending zone. On the other hand, the beam demonstrated a strength that was nearly twice as high as expected. In the second case, failure occurred in the middle zone, for the lamellas 3/4/5 from the top, in a practically knotless zone, at a strength of about 98 kN (Figure 7b).



**Figure 7.** Beam failure images: (a) GL24c—MOR(MOR<sub>12%</sub>)—48.5(43.4)  $\text{N/mm}^2$ —the strongest in the group, (b) GL28c—MOR(MOR<sub>12%</sub>)—30.4(25.8)  $\text{N/mm}^2$ —the weakest in the group.

Obviously, the presence of knots is the main cause of the beams' destruction. On the other hand, nearly 60% of the beams failed because of damage of the outer lamellas, and some 34% failed because of damage of the middle lamellas. For three beams, the exact starting point of destruction could not be identified (Figure 8).

The type of destruction propagating from the beam's middle zone was only dominant for grade GL32c beams. In the other cases, more than 70% involved destruction in the outer layer. It would be unjustified to reject the zero hypothesis that states that the strength of the prepared beams depends on the starting point of the propagation of the destruction (Figure 9). The average static bending strength for the beams destroyed as a consequence of damage to the outer lamellas was  $39.6 \text{ N/mm}^2$ , and the value was  $37.3 \text{ N/mm}^2$  for those where the destruction originated in the middle layer. A different

situation was observed for the modulus of elasticity. In this case, the differences were statistically significant and beams with a higher MOE value were destroyed mainly in the middle layer. This is probably attributable to the fact that the beams with higher moduli of elasticity had higher-quality outer lamellas and were capable of withstanding the arising stress, whereas lower-grade timber, though located deeper, was exposed to critical/damaging stress.

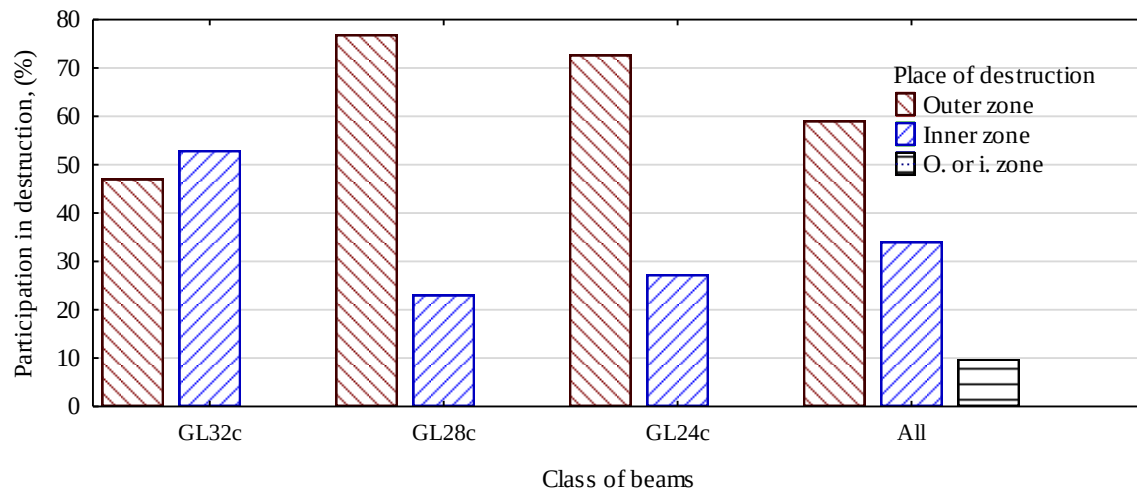


Figure 8. Impact of the point of destruction for various beam grades.

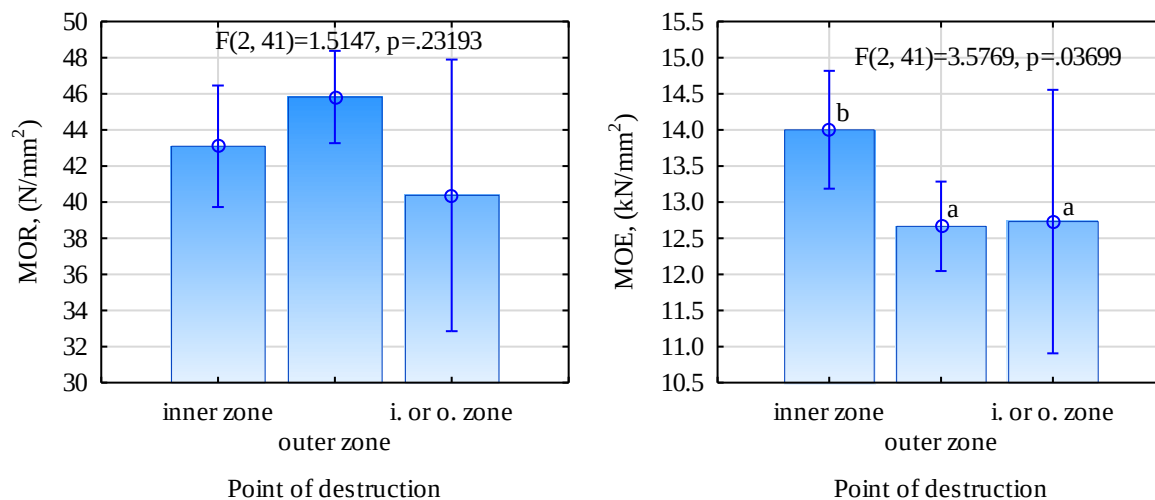
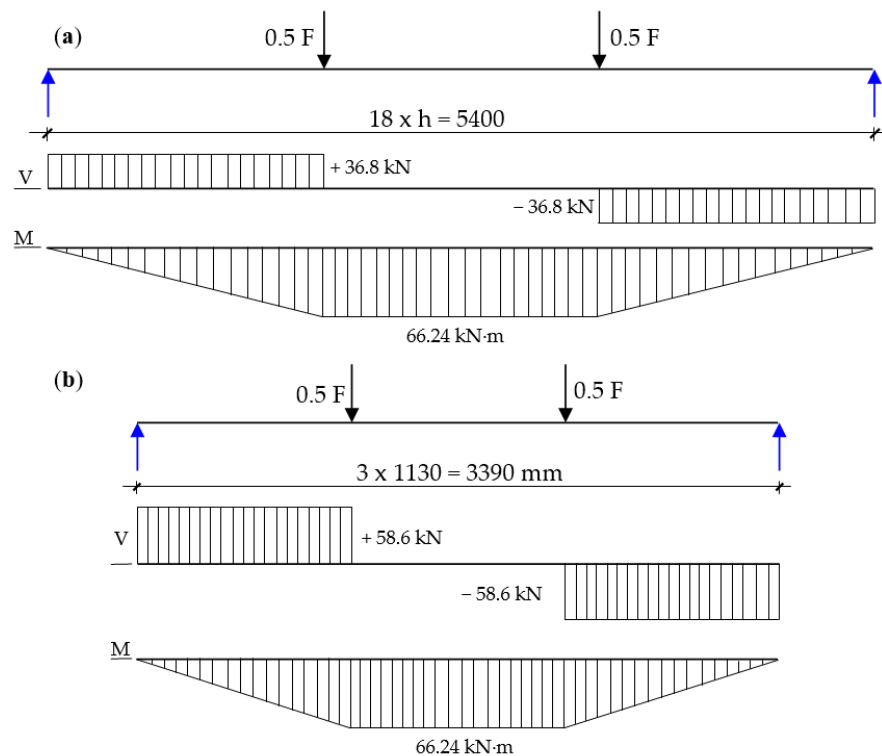


Figure 9. ANOVA of the assessment of the static bending strength and modulus of elasticity relative to the point of destruction (Letters mark uniform groups determined with the Tukey HSD test).

In order to determine the effect of the relation between the supports' spacing ( $l$ ) and the height of the manufactured beams ( $h$ ), a model system with the cross-sections' dimensions of  $138 \times 300$  mm and a strength of 32 MPa was adopted. The  $J_y$  value for the adopted system was  $31,050 \text{ cm}^4$ . According to EN 408 [59], the  $l/h$  relation should be  $18 \pm 3$ ; however, in the conducted research, the beams were characterized by a relation of 13.3. The shear forces diagrams and bending moments diagrams of the beams, with a support spacing of  $18 \times h = 5400$  mm (in compliance with the standard) and with a support spacing of 3390 mm for experimental beams, are presented in Figure 10. Moreover, the significant physical quantities' characteristics for the bend test are included in Table 3.

On the basis of the results presented in Figure 10 and Table 3, it can be concluded that the significant reduction in the beams' length in comparison with the regulations of EN 408 [59] showed an increase in the shear stresses by 60%. The considerable increase in the shear force value can lead to the beams' destruction in the inner zone, more precisely in the inner lamellas. The assumed timber length

(and consequently also the beam length) derived from the most efficient breakdown of the 14-m long logs into 3.5-m long sections. This type of division ensured less material wastes and made it easier to move the research materials; however, this length can influence the obtained results. The average shear strength of pine wood is around  $10 \text{ N/mm}^2$  (it ranges between  $6$  and  $14 \text{ N/mm}^2$ ). However, our observations show that this did not have a significant impact on the obtained research results. Most of the beams were destroyed between the pressures. In exceptional cases, the beams were damaged outside the pressures, but mainly in the tension zone.



**Figure 10.** Shear forces diagrams and bending moments diagrams for (a) beams consistent with the dimensional requirements of EN 408 and (b) experimental beams used in the conducted research.

**Table 3.** Physical quantities for the bend test—No. 1 and 2: theoretical beams, No. 3: a beam with the maximum strength obtained during the tests.

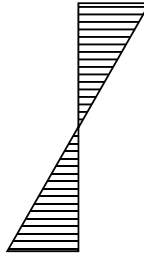
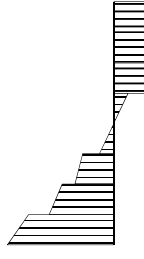
| No. | Type of Beam (mm)      | Class of MOR ( $\text{N/mm}^2$ ) | F (N)   | V (kN) | M (kN·m) | $\tau_{xz}$ ( $\text{N/mm}^2$ ) |
|-----|------------------------|----------------------------------|---------|--------|----------|---------------------------------|
| 1   | $18 \times h = 5400$   | 32                               | 73,600  | 36.8   | 66.2     | 1.3                             |
| 2   | $11.3 \times h = 3390$ | 32                               | 117,240 | 58.6   | 66.2     | 2.1                             |
| 3   | $11.3 \times h = 3390$ | 48.6                             | 154,770 | 77.4   | 66.2     | 2.8                             |

For solid structures or homogeneous glued laminated timber, the stress distribution will be linear over the entire height of the section (GL32h—Table 4). Composite beams are constructed from more than one type of material so as to increase stiffness or strength (or to reduce cost). In the analyzed case (e.g., GL32c—Table 4), the layers are glued together. Therefore, it should be assumed that the deformations at the interface of the layers are the same. In the elastic range at the height of each layer, the stress distribution will be linear. However, due to the variable E modulus for each layer, we observe stress jumps at the layers' borders.

It appears that stress jumps at the layers' borders, although not large, may contribute to the destruction of the beams in the deeper lamellas. Deeper lamellas were clearly damaged where there were wood defects. In the case of very high-quality external lamellas, the second and third layers were

responsible for the quality of the beam. It should be remembered that the lamellas of these layers were only assessed in terms of the linear elasticity modulus.

**Table 4.** Modules of elasticity of individual layers for beams of the GL32h (homogeneous) and GL32c (combined) type and their stress diagrams.

| Beams                                                                             | GL32h                       |                                                                                   | GL32c                         |                                                                                    |
|-----------------------------------------------------------------------------------|-----------------------------|-----------------------------------------------------------------------------------|-------------------------------|------------------------------------------------------------------------------------|
|                                                                                   | $E$<br>(N/mm <sup>2</sup> ) | $\sigma_x$ (N/mm <sup>2</sup> )                                                   | $E^*$<br>(N/mm <sup>2</sup> ) | $\sigma_x$ (N/mm <sup>2</sup> )                                                    |
|  | 14,200                      |  | 16,450                        |  |
|                                                                                   | 14,200                      |                                                                                   | 13,270                        |                                                                                    |
|                                                                                   | 14,200                      |                                                                                   | 11,420                        |                                                                                    |
|                                                                                   | 14,200                      |                                                                                   | 8580                          |                                                                                    |
|                                                                                   | 14,200                      |                                                                                   | 8580                          |                                                                                    |
|                                                                                   | 14,200                      |                                                                                   | 11,420                        |                                                                                    |
|                                                                                   | 14,200                      |                                                                                   | 13,270                        |                                                                                    |
|                                                                                   | 14,200                      |                                                                                   | 16,450                        |                                                                                    |
|                                                                                   | 14,200                      |                                                                                   |                               |                                                                                    |
|                                                                                   |                             | 32.2                                                                              |                               | 35.7                                                                               |
|                                                                                   |                             |                                                                                   |                               | 21.6 26.8                                                                          |
|                                                                                   |                             |                                                                                   |                               | 12.4 14.4                                                                          |
|                                                                                   |                             |                                                                                   |                               | 4.66 6.20                                                                          |
|                                                                                   |                             |                                                                                   |                               | 0                                                                                  |
|                                                                                   |                             |                                                                                   |                               | 0                                                                                  |
|                                                                                   |                             |                                                                                   |                               | 6.20 4.66                                                                          |
|                                                                                   |                             |                                                                                   |                               | 14.4 12.4                                                                          |
|                                                                                   |                             |                                                                                   |                               | 26.8 21.6                                                                          |
|                                                                                   |                             |                                                                                   |                               | 35.7                                                                               |

\*—laboratory beam GL32c.

#### 4. Conclusions

For eight-layered beams made of grade GL24c, GL28c and GL32c timber, the modulus of elasticity was only slightly different from its assumed values, and the obtained beams satisfied the requirements of the standard EN-14080 [57] in this regard.

The static bending strength obtained from the 4-point bending test was not related to the class of the designed beam models. Regardless of the assumed class, the average beam strength was above 36.6 N/mm<sup>2</sup>.

We adopted a procedure for preparing timber before making glued components, which provided the designed systems with satisfactory modulus of elasticity values and a static bending strength that was essentially higher than its assumed value. However, the scope of the study needs to be extended to include beams with other cross-sections so that the objective of this research work can be fully met. Nonetheless, at this point in our research, it seems that the visual grading of timber can be limited to only the timber items that are intended for use as outer layers.

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#### References

1. Borysiuk, P. Veneer Laminated Wood LVL meets the global markets for wood-based construction materials. *Biul. Inf. OBRPPD* **2007**, *1–2*, 63–71. (In Polish)
2. Borysiuk, P.; Kowaluk, G. Types and examples of applications of wood-based construction materials. *Biul. Inf. OBRPPD* **2007**, *3–4*, 115–119. (In Polish)
3. Sterr, R. Untersuchungen zur Dauerfestigkeit von Schichtholzbalken. Mitteilung aus dem Institut für Holzforschung und Holztechnik der Universität München (Investigations on the fatigue resistance of laminated wood beams). *Holz Roh Werkstoff* **1963**, *21*, 7–61. [[CrossRef](#)]
4. Gerhards, C.C. Effect of early wood and latewood on stress-wave measurements parallel to the grain. *Wood Sci. Technol.* **1975**, *11*, 69–72.

5. Krzosek, S. *Strength Grading of Polish Pine Structural Sawn Timber*; Wydawnictwo SGGW: Warsaw, Poland, 2009. (In Polish)
6. Wieruszewski, M.; Gołuński, G.; Hruzik, G.J.; Gotych, V. Glued elements for construction. *Ann. Warsaw Univ. Life Sci. SGGW For. Wood Technol.* **2010**, *72*, 453–458.
7. Serrano, E. Glued-in rods for timber structures—A 3D model and finite element parameter studies. *Int. J. Adh. Adhesiv.* **2001**, *21*, 115–127. [[CrossRef](#)]
8. Kawalerczyk, J.; Siuda, J.; Mirski, R.; Dziurka, D. Hemp flour as a formaldehyde scavenger for melamine-urea-formaldehyde in plywood production. *BioResources* **2020**, *15*, 4052–4064.
9. Kägi, A.; Niemz, P.; Mandallaz, D. Einfluss der Holzfeuchte und ausgewählter technologischer Parameter auf die Verklebung mit 1K-PUR Klebstoffen unter extremen klimatischen Bedingungen. *Holz Roh Werkstoff* **2006**, *64*, 261–268. [[CrossRef](#)]
10. Krystofiak, T.; Proszczyk, S.; Lis, B. Adhesives for large-scale wooden construction elements for buildings. *Drewno Wood* **2008**, *51*, 61–79. (In Polish)
11. Krystofiak, T.; Proszczyk, S.; Lis, B.; Wieruszewski, M.; Gotych, V. Studies upon durability of glue lines in production of laminated wood for skeleton building prepared in industrial conditions. In Proceedings of the XXth Symposium Adhesives in Woodworking Industry, Zvolen, Slovakia, 29 June–1 July 2011; pp. 169–176.
12. Bos, H. The Potential of Flax Fibres as Reinforcement for Composite Materials. Ph.D. Thesis, Technische Universiteit Eindhoven, Eindhoven, The Netherlands, 2004. [[CrossRef](#)]
13. Brol, J. Effectiveness of reinforcing wooden beams with CFRP bands. In Proceedings of the VII Konferencja Naukowa “Drewno i Materiały Drewnopochodne w Konstrukcjach Budowlanych”, Międzyzdroje, Poland, 12–13 May 2006. (In Polish).
14. Burawska, I. Studies on Changes in Strength of Weakened Wooden Bending Beams When Reinforced with Carbon Fibre. Master’s Thesis, Szkoła Główna Gospodarstwa Wiejskiego w Warszawie, Warsaw, Poland, 2012. (In Polish).
15. Burawska-Kupniewska, I.; Krzosek, S.; Mankowski, P.; Grzeskiewicz, M.; Mazurek, A. The influence of pine logs (*Pinus sylvestris* L.) quality class on the mechanical properties of timber. *BioResources* **2019**, *14*, 9287–9297.
16. Burawska, I.; Tomusiak, A.; Beer, P. Influence of the length of CFRP tape reinforcement adhered to the bottom part of the bent element on the distribution of normal stresses and on the elastic curve. *Ann. Warsaw Univ. Life Sci. SGGW. For. Wood Technol.* **2011**, *73*, 186–191.
17. Burawska, I.; Zbieć, M.; Beer, P. Study of peel and shear strength of adhesive joint between pine wood and CFRP tape. Chip and chipless woodworking processes. In Proceedings of the 8th International Science Conference, Technical University in Zvolen, Zvolen, Slovakia, 6–8 September 2012; pp. 35–40.
18. Burawska, I.; Zbieć, M.; Tomusiak, A.; Beer, P. Local reinforcement of timber with composite and lignocellulosic materials. *BioResources* **2015**, *10*, 457–468. [[CrossRef](#)]
19. Orłowicz, R.; Gil, Z.; Fanderejska, E. Extension capacity of spiral bars used in joints of wooden structures. In Proceedings of the VII Konferencja Naukowa: Drewno i Materiały Drewnopochodne w Konstrukcjach Budowlanych, Szczecin-Międzyzdroje, Poland, 27–29 May 2004; pp. 161–167. (In Polish).
20. Ritter, M.A.; Williamson, T.G.; Moody, R.C. Innovations in glulam timber bridge design. In *Structures Congress 12: Proceedings of Structures Congress '94, Atlanta, GA, USA, 24–28 April 1994*; Baker, N.C., Goodno, B.J., Eds.; American Society of Civil Engineers: New York, NY, USA, 1994; Volume 2, pp. 1298–1303.
21. Rapp, P.; Lis, Z. Testing of wooden beams reinforced with carbon fibre bands. *Inżynieria Budownictwo* **2001**, *7*, 390–392. (in Polish).
22. Czuczelo, K. Testing of Glued Laminated Timber from Strength Sorted Pine Wood. Ph.D. Thesis, Katedra Nauki o Drewnie i Ochrony Drewna, Wydział Technologii Drewna SGGW w Warszawie, Warsaw, Poland, 2005. (In Polish).
23. Brandner, R. Production and technology of cross laminated timber (CLT): State-of-the-art report. In *Focus Solid Timber Solutions, European Conference on Cross Laminated Timber, Graz, Austria, 21–22 May 2013*, 2nd ed.; COST Action: Graz, Austria, 2014; pp. 3–36.
24. Bejder, A.K.; Kirkegaard, P.H.; Wraber, I.K.; Falk, A. The Materiality of Novel Timber Architecture—Developing a Model for Analysing and Evaluating Materials in Architecture. 2016. Available online: <https://vbn.aau.dk/en/publications/the-materiality-of-novel-timber-architecture-developing-a-model-f> (accessed on 6 July 2020).

25. Bejder, A.K.; Kirkegaard, P.H.; Wraber, I.K.; Falk, A. The Materiality of Novel Timber Architecture—Based on a Case Study Analysis of Cross-Laminated Timber. 2011. Available online: <https://vbn.aau.dk/en/publications/the-materiality-of-novel-timber-architecture-based-on-a-casestudy> (accessed on 6 July 2020).
26. Bejder, A.K.; Kirkegaard, P.H.; Fisker, A.M. *On the Architectural Qualities of Cross Laminated Timber*; Cruz, P.J.S., Ed.; Taylor & Francis Group: London, UK, 2010; pp. 119–121. [CrossRef]
27. Augustin, M.; Blaß, H.J.; Bogensperger, T.; Ebner, H.; Ferk, H.; Fontana, M.; Frangi, A.; Hamm, P.; Jöbstl, R.A.; Moosbrugger, T.; et al. *BSP Handbuch. Holz-Massivbauweise in Brettspertholz—Nachweise auf Basis des Neuen Europäischen Normenkonzepts*; Verlag der Technischen Universität Graz: Graz, Austria, 2010.
28. Falk, A. Cross-laminated timber plate tensegrity and folded roofs. In Proceedings of the Wood for Good: Symposium on Innovation in Timber Design and Research, Copenhagen, Denmark, 20 September 2010.
29. Espinoza, O.; Trujillo, V.R.; Laguarda, M.F.; Buehlmann, U. Cross-laminated timber: Status and research needs in Europe. *BioResources* **2016**, *11*, 281–295. [CrossRef]
30. Krauss, A.; Fabisiak, E.; Szymański, W. The ultrastructural determinant of radial variability of compressive strength among the grain of Scots pine wood. *Ann. Warsaw Univ. Life Sci. SGGW For. Wood Techno.* **2009**, *68*, 431–435.
31. Alfred Franklin, V.; Christopher, T. Fracture energy estimation of DCB specimens made of glass/epoxy: An experimental study. *Adv. Mater. Sci. Eng.* **2013**, *2013*, 7. [CrossRef]
32. Kumar, K.; Rao, S.; Gopikrishna, N. Evaluation of strain energy release rate of epoxy glass fibre laminate (mode—I). *Int. Educ. Res. J.* **2017**, *3*, 44–46.
33. Blackman, B.R.K.; Kinloch, A.J.; Paraschi, M. The determination of the mode II adhesive fracture resistance, GIIC, of structural adhesive joints: An effective crack length approach. *Eng. Fract. Mech.* **2005**, *72*, 877–897. [CrossRef]
34. De Moura, M.; Campilho, R.; Gonçalves, J.P.M. Pure mode II fracture characterization of composite bonded joints. *Int. J. Solids Struct.* **2009**, *46*, 1589–1595. [CrossRef]
35. Hu, Q.; Gao, Y.; Meng, X.; Diao, Y. Axial compression of steel-timber composite column consisting of H-shaped steel and glulam. *Eng. Struct.* **2020**, *216*, 110561. [CrossRef]
36. Le, T.D.H.; Tsai, M.-T. Experimental assessment of the fire resistance mechanisms of timber–steel composites. *Materials* **2019**, *12*, 4003. [CrossRef] [PubMed]
37. Gonzales, E.; Tannert, T.; Vallee, T. The impact of defects on the capacity of timber joints with glued-in rods. *Int. J. Adhes. Adhes.* **2016**, *65*, 33–40. [CrossRef]
38. Otero-Chans, D.; Estévez-Cimadevila, J.; Suárez-Riestra, F.; Martín-Gutiérrez, E. Experimental analysis of glued-in steel plates used as shear connectors in Timber-Concrete-Composites. *Eng. Struct.* **2018**, *170*, 1–10. [CrossRef]
39. Schänzlin, J.; Fragiocomo, M. Analytical derivation of the effective creep coefficients for timber-concrete composite structures. *Eng. Struct.* **2018**, *172*, 432–439. [CrossRef]
40. Estévez-Cimadevila, J.; Otero-Chans, D.; Martín-Gutiérrez, E.; Suárez-Riestra, F. Testing of different non-adherent tendon solutions to reduce short-term deflection in full-scale timber-concrete-composite T-section beams. *J. Build. Eng.* **2020**, *31*, 101437. [CrossRef]
41. Toratti, T.; Schnabl, S.; Turk, G. Reliability analysis of aglulam beam. *Struct. Saf.* **2007**, *29*, 279–293. [CrossRef]
42. Falk, R.H.; Colling, F. Laminating effects in glued-laminated timber beams. *J. Struct. Eng.* **1995**, *121*, 1857–1863. [CrossRef]
43. Tomasi, R.; Parisi, M.A.; Piazza, M. Ductile design of glued-laminated timber beams. *Pract. Period. Struct. Design Construct.* **2009**, *14*, 113–122. [CrossRef]
44. Hiramatsu, Y.; Fujimoto, K.; Miyatake, A.; Shindo, K.; Nagao, H.; Kato, H.; Ido, H. Strength properties of glued laminated timber made from edge-glued laminae II: Bending, tensile, and compressive strength of glued laminated timber. *J. Wood Sci.* **2011**, *57*, 66–70. [CrossRef]
45. Fujimoto, K.; Hiramatsu, Y.; Miyatake, A.; Shindo, K.; Karube, M.; Harada, M.; Ukyo, S. Strength properties of glued laminated timber made from edge-glued laminae I: Strength properties of edge-glued karamatsu (*Larix kaempferi*) laminae. *J. Wood Sci.* **2010**, *56*, 444–451. [CrossRef]
46. Castro, G.; Paganini, F. Mixed glued-laminated timber of Poplar and Eucalyptus grandis clones. *Holz Roh Werkst.* **2003**, *61*, 291–298. [CrossRef]

47. Teles, R.F.; Cláudio, H.S.; Menezzi, D.; De Souza, F.; De Souza, M.R. Theoretical and experimental deflections of glued laminated timber beams made from a tropical hardwood. *Wood Mater. Sci. Eng.* **2013**, *8*, 89–94. [[CrossRef](#)]
48. Fink, G.; Frangi, A.; Kohler, J. Probabilistic approach formodelling the load-bearing capacity of glued laminatedtimber. *Eng. Struct.* **2015**, *100*, 751–762. [[CrossRef](#)]
49. Foschi, R.O.; Barrett, J.D. Glued-laminated beam strength. *J. Struct. Div. ASCE* **1980**, *106*, 1735–1754.
50. Hernandez, R.; Bender, D.; Richburg, B.; Kline, K. Probabilistic modeling of gluedlaminated timber beams. *Wood Fiber Sci.* **1992**, *24*, 294–306.
51. Jöbstl, R.A.; Schickhofer, G. Comparative examination of creep of GLT and CLT slabs in bending. In Proceedings of the 40th Meeting of CIB-W18, Bled, Slovenia, 28–31 August 2007.
52. Thiel, A. ULS and SLS Design of CLT and its implementation in the CLT designer. In *Solid Timber Solutions, European Conference on Cross Laminated Timber, Graz, Austria, 21–22 May 2013*, 2nd ed.; COST Action: Graz, Austria, 2014; pp. 77–102.
53. Fragiocomo, M. Seismic behavior of cross-laminated timber buildings: Numerical modeling and design provisions. In *Solid Timber Solutions, European Conference on Cross Laminated Timber, Graz, Austria, 21–22 May 2013*, 2nd ed.; COST Action: Graz, Austria, 2014; pp. 3–36.
54. European Committee for Standardization. *Structural Timber—Strength Classes*; EN 338; European Committee for Standardization: Brussels, Belgium, 2016.
55. European Committee for Standardization. *Structural Timber—Determination of Characteristic Values of Mechanical Properties and Density*; EN 384; European Committee for Standardization: Brussels, Belgium, 2018.
56. Pereira, M.C. de M.; Calil Neto, C.; Icimoto, F.H.; Calil Junior, C. Evaluation of tensile strength of a *Eucalyptus grandis* and *Eucalyptus urophylla* hybrid in wood beams bonded together by means of finger Joints and polyurethane-based glue. *Mater. Res.* **2016**, *19*, 1270–1275. [[CrossRef](#)]
57. European Committee for Standardization. *Timber Structures—Glued Laminated Timber and Glued Solid Timber—Requirements*; EN 14080; European Committee for Standardization: Brussels, Belgium, 2013.
58. Bodig, J.; Jayne, B.A. *Mechanics of Wood and Wood Composites*; Van Nostrand Reinhold: Hoboken, NJ, USA, 1982; p. 376.
59. European Committee for Standardization. *Timber Structures—Structural Timber and Glued Laminated Timber—Determination of Some Physical and Mechanical Properties*; EN 408; European Committee for Standardization: Brussels, Belgium, 2012.



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