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STRUCTURAL PERFORMANCE ANALYSIS OF HOLLOW GLUE-LAMINATED TIMBER

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ABSTRACT: Recently, innovative systems for the construction of prefabricated timber houses have been developed worldwide. The aim of most manufacturers is to develop elements that simplify construction, i.e. achieve maximum speed and economy. The cavities significantly reduce the weight of the GLT elements, making them easy to transport, which not only eliminates the need for cranes and machinery, but also makes construction cheaper. Another advantage is a better thermal insulation. An experimental and numerical analysis of the effects of perforation on the behavior of the GLT elements (softwood and hardwood) under ambient conditions was carried out. In addition, a parametric FEM analysis was carried out by varying the number and arrangement of holes in the cross-section of the timber element. Hollow GLT elements made of softwood (degree of perforation 28%), achieved 69.65% of the load-bearing capacity of the solid cross-section specimens. Hollow GLT elements made of hardwood achieved an average of 72.63% of the load-bearing capacity of the solid cross-section samples. Furthermore, it was shown that the degree of cavity formation is proportional to the CSPG regardless of the type of wood. The experimental investigations (bending and compression perpendicular to the grain) were confirmed by the FEM analysis.

KEYWORDS: timber, hollow, FEM, glulam, prefabricated

1 – INTRODUCTION

Over the past decade, there has been a marked increase in the quantity of large-scale timber edifices conceptualized and erected utilizing cross-laminated timber (CLT) and glue-laminated timber (GLT). The predominant benefits are particularly evident in low-rise timber construction, which has the potential to contribute significantly to the sequestration of carbon in the global endeavor against climate change and global warming [1]. Carbon sequestration within forest ecosystems transpires through the accumulation of biomass in arboreal species during the process of photosynthesis. At the conclusion of this natural cycle, wood liberates its stored carbon back into the atmosphere through mechanisms such as decomposition or combustion. The utilization of wood in the construction of edifices (and its subsequent recycling into furniture, panels, or other products post-demolition) can optimize the carbon sequestration effect [2].

A reduction in carbon dioxide emissions by 25% could be achieved if merely 10% of new residential structures were constructed from wood [3]. Arboreal species exhibit a heightened capacity for carbon dioxide absorption during their growth phase. Consequently, by planting two new trees for every one that is harvested, the carbon dioxide absorption rate would exceed twofold [2]. In addition to the implications for carbon dioxide emissions, it is imperative to evaluate the energy requisite for processing the building materials. The tree remains central in this context. Approximately 30% to 40% of the tree trunk is utilized for timber components, while the remaining portions are not discarded. Instead, these materials are repurposed for the production of heating pellets, and sawdust is effectively employed as an excellent insulating medium.

Moreover, timber constructions have the potential to fulfill architectural ambitions and may ultimately yield reduced costs and enhanced construction efficiencies when juxtaposed with conventional, more prevalent construction methodologies. To fully exploit the advantages of timber, various wood-based products, in the form of diverse iterations of glue-laminated timber, have been developed alongside traditional sawn timber. These innovations allow for a myriad of shapes and cross-sectional configurations tailored to specific requirements, with minimal constraints. It is feasible to incorporate curved elements that substantially enhance the aesthetic appeal [4].

Another salient advantage of wood is its exceptionally favorable weight-to-strength ratio. This characteristic facilitates the construction of timber structures on suboptimal soil conditions or on steeper gradients, where the establishment of conventional concrete frameworks would prove considerably more complex. Wood possesses two additional, notable properties. One is its

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capacity to exchange air with its surroundings and filter it through the building, while the other is its ability to regulate ambient humidity levels. Consequently, wood as a construction material fosters a highly conducive living environment, a quality that is markedly amplified by the presence of natural materials on the exposed surfaces within the structure [3].

1.1 Available prefabricated systems of timber construction

Currently, there are several available prefabricated systems of timber structures. „LUXHOME“ [5] has developed a prefabricated system of timber houses from “timber bricks” (*Figure 1*a). The production itself is automated so that by defining the dimensions of individual parts, the quantities of materials and costs are obtained immediately, which can significantly reduce the amount of waste material.

The next system is „ECOCELL“ [6]. This is a SIP system (structural insulated panels) that consists of an insulating material that is placed between two boards, most often OSBs (*Figure 1*b). The system is solid, energy efficient, and very affordable. Most SIP systems use oil-based foam insulation, while „ECOCELL“ has developed an innovative insulation system, the first that is non-oil based. Insulation makes up 75 % of the volume of the element. The insulating material is in the shape of a honeycomb and is made of 100 % recycled paper, in the form of corrugated cardboard, which is covered with a mineral coating.

Fabric Workshop [7] is a company that designs a system of hollow-core, solid timber panels (*Figure 1*c), columns, and walls, for which 50 % fewer wood fibers are being used, and the total cost is 10–35 % lower compared to CLT. Due to the cavities and box shape, this system has a better strength/weight ratio than comparable steel and concrete systems. Although the material is expensive, there are significant savings in execution speed and error prevention due to this design method.

„BRIKAWOOD“ [8] is a timber brick-building system, developed by the French company Catharhome, which allows one to quickly build a house without the use of nails, screws, or adhesive. Each unit consists of four parts: two side elements and two transverse spacers that fit into each other with the help of a classic dovetail joint (*Figure 1*d).

Another modular system is „GABLOK“ (*Figure 1*e), which represents insulated timber blocks, designed from recyclable materials [9]. Gablok has been using expanded polystyrene with a graphite additive (EPS) for its building system. An insulated timber block of 60 cm weighs only 7.5 kg, which makes it very easy to handle, with no cranes needed on the construction site. The combination of timber and EPS provides significant insulation value, which can be further increased by the use of insulating materials on the outside of the blocks.

Finally, STEKO is a modular building system developed in Switzerland [10]. It is easy to install, even without the use of adhesive, nails, or similar mechanical fasteners. It consists of five parts that are glued together with non-toxic adhesive (*Figure 1*f). STEKO modular system is suitable for residential buildings, as well as for communal, agricultural, industrial, or business buildings up to 10 storeys high.

Figure 1. Prefabricated systems: (a) Luxhome; (b)Ecocell;(c) Fabric; (d) Brikawood; (e) Gablock; (f) Steko.

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2 – BACKGROUND

According to the preceding section, there is a growing global trend towards the development of innovative systems for the construction of modular timber housing. The primary objective of the majority of manufacturers is to design components that will facilitate the construction process, specifically to attain the maximum construction velocity at the minimal feasible expense. In accordance with analogous principles, a novel hollow glue-laminated timber component has been conceived.

2.1 Hollow Glued-Laminated Timber Elements

The novelty and scientific contribution is articulated in the following manner:

- The innovative characteristics of the timber elements exemplify a new generation of timber products that promote enhanced construction efficiency, assembly proficiency, material conservation, and overarching environmental sustainability on a global scale.
- Experimental investigations of hollow timber elements were conducted to explore the various possibilities of cavity types and configurations that influence the load-bearing capacity and serviceability of these innovative hollow components.
- The creation of a numerical model aimed at simulating the behavior of hollow timber elements has been executed. The simulation outcomes will be juxtaposed with the experimental findings, and the model will be calibrated as necessary to facilitate a more comprehensive parametric analysis.
- The dimensions of individual lamellae and the materials from which they are fabricated can significantly influence the stress and displacement metrics, thereby allowing for the adjustment of cross-sectional shapes based on the requisite characteristics.
- The potential to attain diverse cross-sectional attributes is contingent upon the intended purpose of the element (refer to the discussion paragraph).

- The elements are made of waste material from doors and windows production of the factory and as such contributes to sustainability and circular economy. Also unused botanical species were used such as hornbeam for better exploitation of the wood resources.

Cavities substantially diminish the mass of individual elements, enabling transportation by one or two individuals, which obviates the necessity for cranes and concurrently reduces construction costs. The weight per meter for such hollow elements is approximately 6.5 kg. The elements are composed of 20 mm-thick lamellae, in which elliptical or circular cavities are intricately incised (*Figure 2*). Within each lamella, the grain orientation is aligned along its length, interconnected through adhesive bonding. The lamellae are derived from recycled waste materials, and the sawdust generated from the cavity incisions can be repurposed as insulating material or processed into pellets.

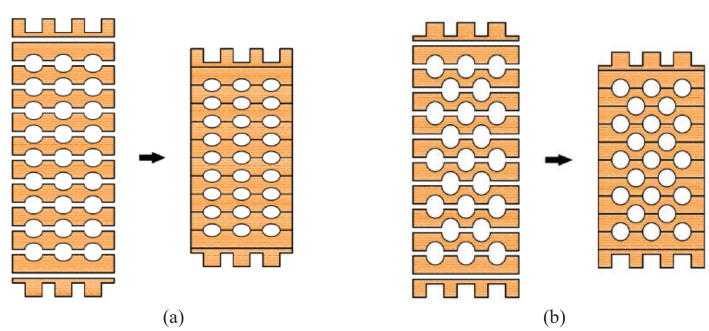

Figure 2. Images should be full width and print quality. Combine smaller images into a single item.

The initial and terminal lamellae are designed such that, when stacked vertically, the elements interlock seamlessly. This configuration promotes rapid and efficient construction without the requirement for fasteners. In the remaining lamellae, semi-elliptical or semi-circular profiles are cut and subsequently adhered together to achieve the desired cross-section featuring elliptical or circular cavities. The percentage of the cavity part varies from 0% to 40% of the whole cross section. As the samples with elliptical cavities exhibited superior performance during experimental evaluations, the validity of the assumptions embedded in the numerical calculations—that the elements operate as mechanically assembled beams, in accordance with standard EN 1995-1-1 [11] was scrutinized in the context of a singular example, alongside numerical modeling. For elements with circular cavities, the principle remains analogous, with the equations for the circle utilized in the formulas in lieu of those for the ellipses

3 – PROJECT DESCRIPTION

Before the medium and large-scale testing of the samples, the basic material properties were tested according to EN 408 [12]. The density, the elastic moduli parallel and perpendicular to the grain, the bending strength, the tensile strength parallel to the grain, and the shear strength of the bond line were determined.

In order to determine the elastic moduli parallel to the grain and the bending strength, two types of samples were made, with dimensions of 20 × 20 mm (solid wood) and 60 × 60 mm (laminated wood). Furthermore, the samples were reproduced for both soft and hard wood. The 20 mm samples were made for the purpose of testing the material properties of the material, i.e. solid wood (one lamella), while the 60 mm samples are composed of 3 interconnected lamellas and form a laminated wood sample. Therefore, it is necessary to test the laminated samples for the orthogonal and parallel position of the lamellas, in relation to the direction of loading. All samples were tested by 4-point bending to failure according to EN 408:2012 [12]. The experimental setup for the samples can be seen in *Figure 3*. A universal testing machine Z600E with a capacity of 600 kN was used for the test. According to EN 408 [12], the load is applied at a constant speed. The speed of movement of the piston head must not exceed (0.003 h) mm/s, where h is the height of the specimen. The testing was carried out until the samples failure. The failure occurred in the lower zone of the cross-section reaching its strength.

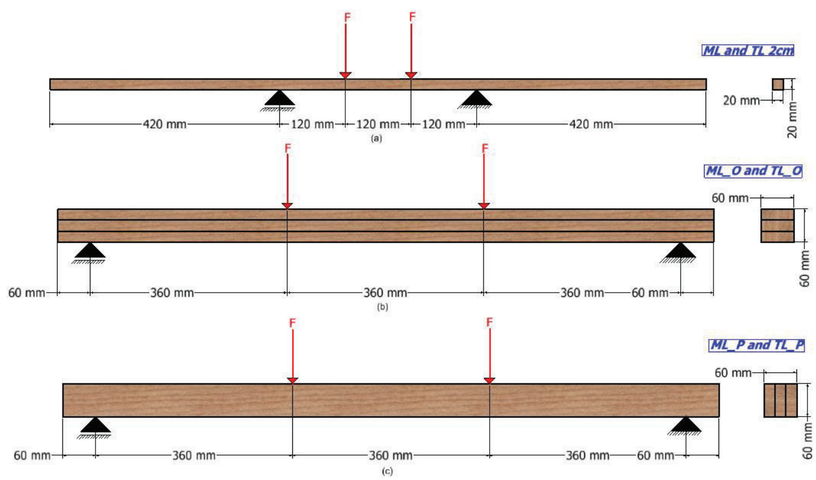

Figure 3. Material characteristics - experiment setup

4 – EXPERIMENTAL SETUP

BENDING

A dynamic-static universal testing apparatus, provided by Zwick Roell GmbH & Co. KG, Germany, was employed for the execution of experimental bending assessments. The apparatus possesses a load capacity of 250 kN, categorized as class 1, signifying a permissible deviation of 1 %. This apparatus facilitates the acquisition of data pertaining to force magnitude, displacement, acceleration, relative deformation, temperature, and stress parameters. The system is adept for both short-term and long-term static high-resolution measurement applications. The data acquisition system utilized is the MGC plus, manufactured by HBM—Hottinger Baldwin Messtechnik, Germany. The load application was governed by displacement control, with a specified rate of 6 *mm/min*. The load was administered across a steel beam integrated with an additional *I* profile, thereby simulating a four-point bending configuration. A total of six measurement channels were employed, encompassing time, deflection at the supports and midspan, piston displacement, and load. Linear variable differential transformers with precision specifications of 10 mm (supports) and 100 mm (midspan) nominal values were implemented for the measurement of deflections. In light of the presence of notches in the terminal lamellae of the specimens, supplementary timber elements were fabricated and positioned at the load input region. These substitute elements are constructed from hardwood and are geometrically congruent to the specimen's configuration, taking the form of notched connections.

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The surface of the element in contact with the load cell is entirely flat, thereby facilitating appropriate load input. Given the objectives of this investigation, it became imperative to establish a system aimed at mitigating lateral-torsional buckling of the element at the designated positions. Slender bending beams characterized by a substantial height-to-width ratio, when subjected to loading parallel to their weaker axis, exhibit potential stability challenges. This phenomenon is attributable to the deflection encountered in the compression chord. The beam experiences lateral displacement accompanied by concurrent rotation. As a result, steel clamps were affixed to the supports, encompassing a minimum of two-thirds of the sample height. Concerning the consistency of the experiment, the load-midspan displacement exhibited anticipated responses, with all beams displaying analogous stiffness up to a specific load threshold corresponding to the elastic range. Upon exceeding higher load levels, a significant reduction in stiffness was observed, attributed to localized defects within the timber, cracking, and the behavior of the adhesive. Failure was precipitated by the pressure achieving the tensile strength in the lower region of the specimen. To ascertain the mechanical properties of the wood, four-point bending tests on the timber elements were conducted in accordance with EN 408 [12] (*Figure 4*). The samples were simply supported with a span of 18h, where h denotes the height of the specimen. The distance from the support to the point of force application as well as the separation between the forces was established at 6h. To mitigate local stress concentrations at the force application sites, small steel plates were installed, thereby enhancing force distribution and achieving a more uniform spread across each sample. The maximum force was attained after a duration of (300 ± 120) seconds. Displacements were recorded at the midpoint of the span and at the supports.

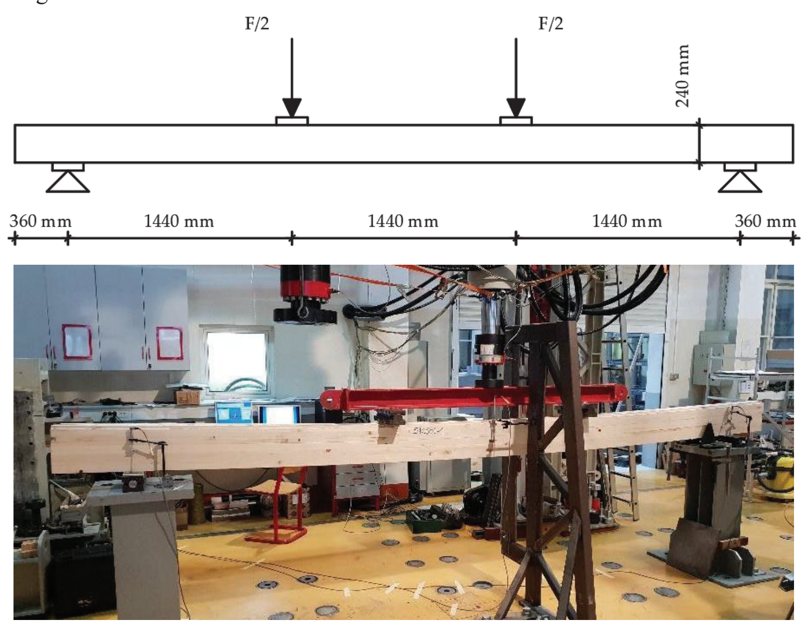

Figure 4. Four-point bending test setup.

COMPRESSION PERPENDICULAR TO THE GRAIN

The structural design is often determined by the wood's compressive strength in the direction perpendicular to the grain, $f_{c,90,k}$ (CSPG). It goes without saying that CSPG varies tangentially and radially and is dependent on the type of wood. [13–15]. As a special issue, it should be highlighted the compression strength perpendicular to the grain in cross-laminated timber (CLT), where significant conclusions are given in [16–19]. The Z600E Universal Static Testing Machine, manufactured by Zwick Roell GmbH & Co. KG (Ulm, Germany), served as the apparatus for conducting this particular experimental investigation. The Z600E is characterized as a versatile pressure-tensile testing device with a maximum capacity of 600 kN, which operates via electric drive and is specifically engineered for conducting highly accurate static and low-cycle assessments of relatively small specimens. The apparatus is capable of achieving a crosshead velocity ranging from 0.01 to 200 mm/min. The highest frequency permissible during testing is 0.5 Hz, with a velocity setting accuracy of 2.5 %. The transmission rate of measured values to the connected PC is recorded at 500 Hz. This machine features an upper testing zone designated for tensile assessments (including materials such as reinforcing steel, prestressing wood, plastics, composites, etc.) and a lower testing zone intended for compressive and bending evaluations of smaller specimens. Control of the machine is facilitated through a PC utilizing the "test expert" software, which governs the force or displacement applied throughout the testing protocol. Specimens featuring elliptical and circular cavities were subjected to testing along both the strong and weak axes. The loading velocity was calibrated to ensure that the maximum force, which corresponds to the failure threshold of the specimen, was attained within a specified duration (300 ± 120 s). The gauge length was prescribed to be approximately 0.6 h, positioned centrally within the test specimen, while maintaining a minimum distance from the b/3 edges of the sample. An illustrative example of a laminated specimen, complete with annotated dimensions, is presented in *Figure 5*.

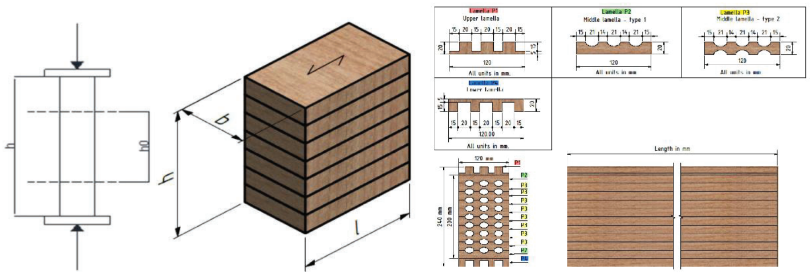

Figure 5. Load and gauge position, specimen dimensions.

To comprehensively analyze the behavior of innovative hollow glue-laminated timber elements, a thorough investigation was conducted encompassing all permutations of specimen orientations and applied loads. This pertains to the arrangement and loading of specimens in both the strong-axis and weak-axis directions, as well as the positioning of the applied force in relation to the boundary conditions (whether loaded at the edge or centrally). A comparative analysis was executed for both full and hollow-timber cross sections fabricated from softwood (fir). In addition, the examination incorporated hollow-timber cross-section components derived from hardwood (hornbeam). To ascertain the baseline value of the CSPG for full-timber cross sections constructed from hardwood, samples of solid hardwood were also subjected to analysis, albeit solely for the foundational configuration, without investigating the effects of load positioning relative to the boundary conditions.

Concerning the geometric specifications (*Figure 5*), the cross-sectional dimensions for all specimens were standardized at 120 × 240 mm, while the lengths varied as follows: 105, 209, 400, 440, 520, and 640 mm. In total, 120 specimens were manufactured, with six samples produced for each of the 20 distinct groups. Each specific group of specimens is distinguished by the wood type, cross-sectional design, and specimen length, where the length signifies whether the specimen is subjected to loading in the strong or weak axis direction. While the hollow timber elements are observable in the Figure x, the full normal counterparts exhibit the same design but are devoid of the elliptical voids. As illustrated in*Figure 6*, the first and last lamellae possess serrated edges, necessitating the insertion of supplementary elements to ensure flat outer surfaces; the inferior surface for support, and the superior surface for force application. These additional elements are precisely shaped like lamellas P1 and P4 (*Figure 5*), yet they are constructed from a more resilient timber to mitigate local embossing. Steel plates were affixed atop these supplementary elements, through which the load was subsequently applied (*Figure 6*).

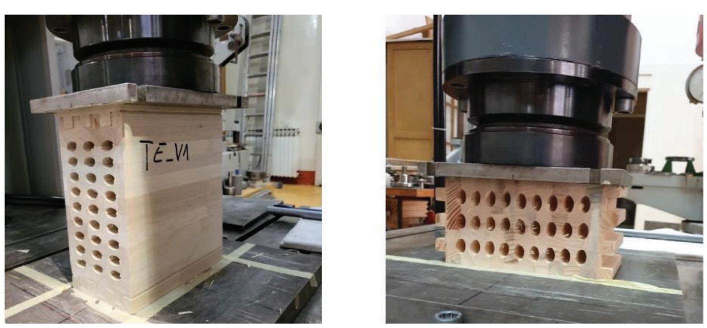

Figure 6. Loading of specimens.

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5 – RESULTS

BENDING

Specimens with ellipse-shaped cavities, marked SE(0)-n, and circular cavities, marked SK(0)-n, were tested. The notation (0) represents strong-axis bending, while "n" represents the number of the tested sample. In Figure 13, Figure 14 and Figure 15, the results, according to the data obtained from the tests, are shown.

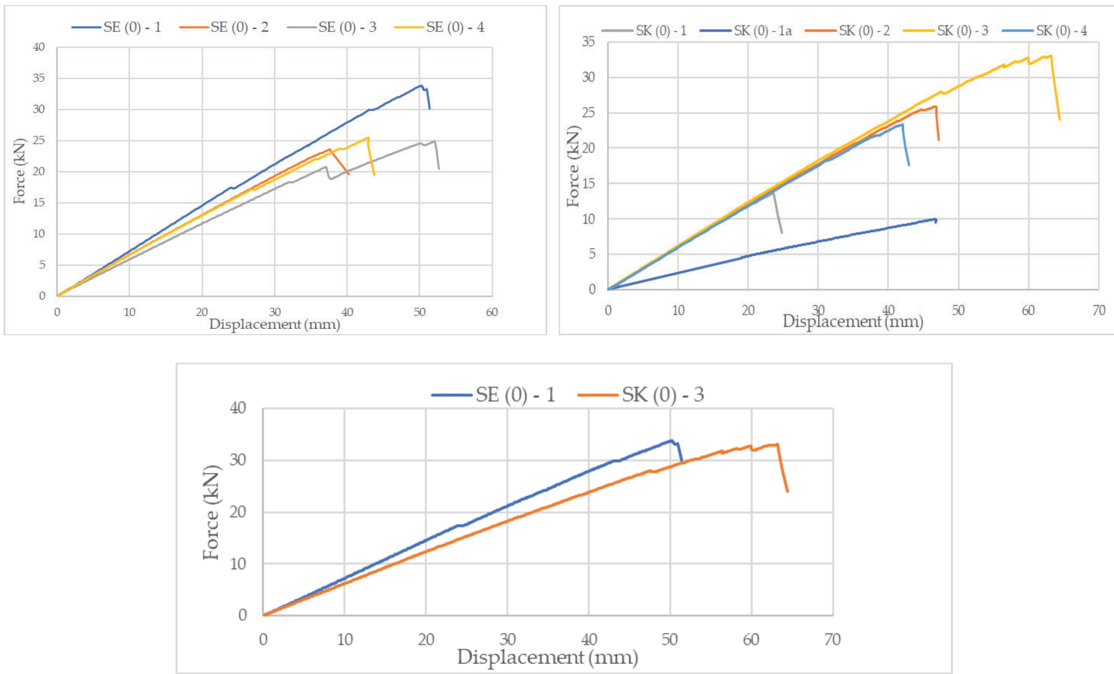

Figure 7 Force-displacement curve

The brittle nature of the wood in the tension zone is the primary mechanism of failure, as indicated by the linearity of the force-displacement curve for the samples of both types of cavities. Due to the failure of grains at the maximum stress, regions of force reduction at constant displacement are seen on the curve toward the end of the test. Then there was the sound of wood shattering. After then, the force increases until the subsequent grain fails, and so on, until the sample fails completely when it reaches its tensile strength (*Figure 8*).

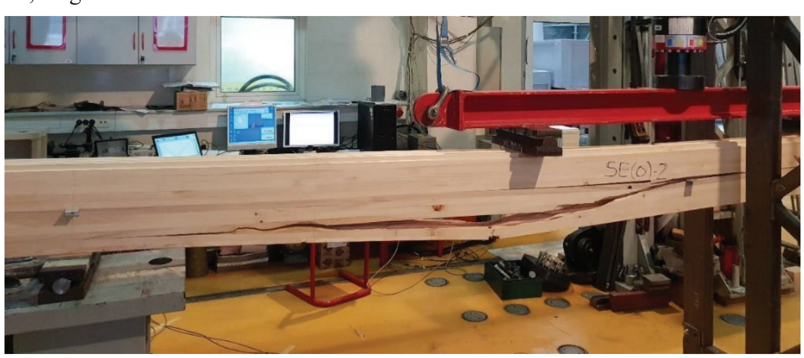

Figure 8 Specimen failure

The higher slope of the force-displacement curve for samples with elliptical cavities can be seen in Figure 15, which indicates their greater stiffness. The percentage of samples with elliptical cavities that have perforations is the first explanation. The second is that, unlike examples with circular cavities, the elliptical cavities are arranged one below the other, allowing for proper force transmission along with the wooden web. The value of the force at which the maximum deflection (l/250) is reached, as established by the serviceability limit state, further demonstrates the greater stiffness of samples with elliptical cavities. The force value is 37% of the failure force for samples with elliptical cavities and 32% of the

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failure force for samples with circular cavities. In *Figure 7*, It is evident that samples with identical cavity types do not fail at the same load level. Natural wood flaws such knots, shakes, cross-grain, crookedness, rind galls, burr, and curl are the main culprits.

Finally, with a 3.01% variation for the strong-axis bending, the deformations derived from the FEM model (Ansys) closely resemble those from the experimental measurements. The experimental tests showed 50.266 mm deflection, while FEM calculated is 61.824 mm. The difference in stresses between the manual calculation and the model in ANSYS is very small, less than 1%, which is a very good match of the results.

COMPRESSION PERPENDICULAR TO THE GRAIN

Considering the large number of specimens and tests, it is not reasonable to accommodate all the graphs in this section. As a result, Figure 9 only displays the typical results for each sample group in the form of load-displacement curves; all other values are shown in a tabular comparison. Comparing the behavior and load-carrying capacity of novel hollow GL timber elements with those of conventional GL timber elements was the ultimate goal for all groups of specimens. As a raw material that is more frequently employed in practice, softwood specimens were the main subject of this reference. Nonetheless, comparing the properties of hollow softwood and hardwood specimens and figuring out the hardwood material's base CSPG value were crucial goals.

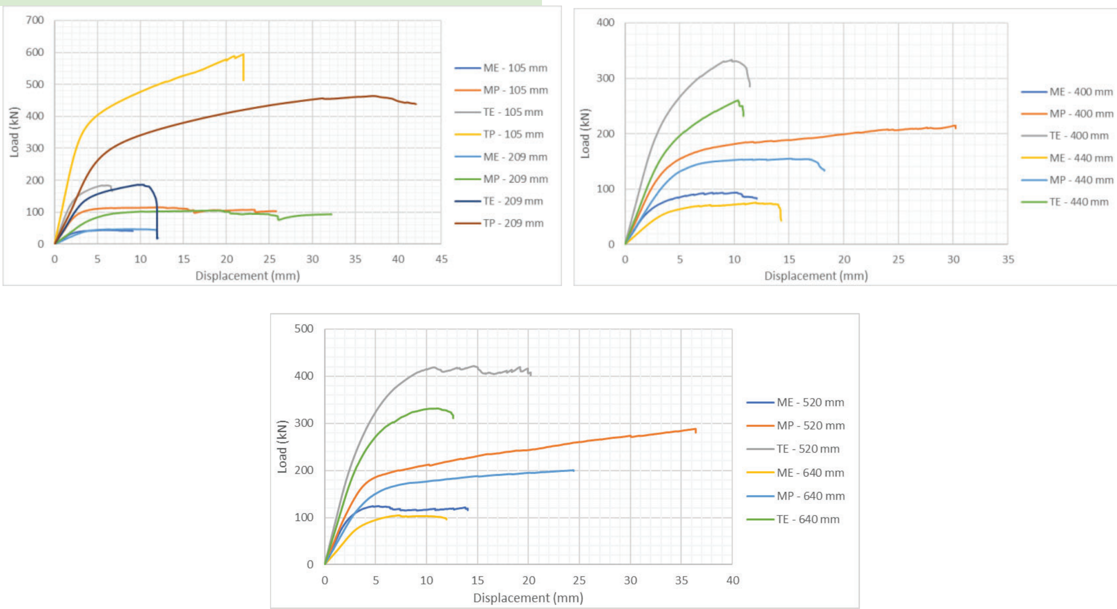

Figure 9 Characteristic load-displacement curves for each group of specimens

Figure 9 illustrates the specimens' nearly linear behavior up to the yielding point, where the timber fails when the displacement increases without an increase in force as the curve's slope lowers. Although all specimen types exhibited this tendency, individual specimen types have distinct failure modes. The weakest or thinnest portion of the cross-section between the two elliptical cavities has been the site of failure in hollow timber specimens. When the compressive strength of typical GL timber specimens was attained, the timber began to crack. Additionally, the slope of the curve indicates that softwood specimens with elliptical cavities (ME) should have the lowest stiffness. The stiffness and strength attained by ME specimens are noticeably less than those of regular softwood specimens without perforations (MP). Furthermore, the horizontal portion of the curve that represents MP specimens shows increased compression ductility because of the entire cross-section. The imprinting of the load cell into the timber element is the physical embodiment of this. Finally, hardwood specimens had the maximum failure force and stiffness, which can be attributed to their higher timber density, or compressive strength. However, a brittle fracture is an unwanted result of this. Although the principles leading to the failure of hardwood specimens with elliptical cavities (TE) or without holes (TP) are like those made of softwood, another difference could be seen. The hardwood specimens cracked at the finger joint due to the high strength of the timber, greater than glue. It was especially noticed on specimens loaded at the edge and in the middle. The failure modes of the specimens were

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examined and contrasted in addition to the load-displacement curve comparison (*Figure 10*).

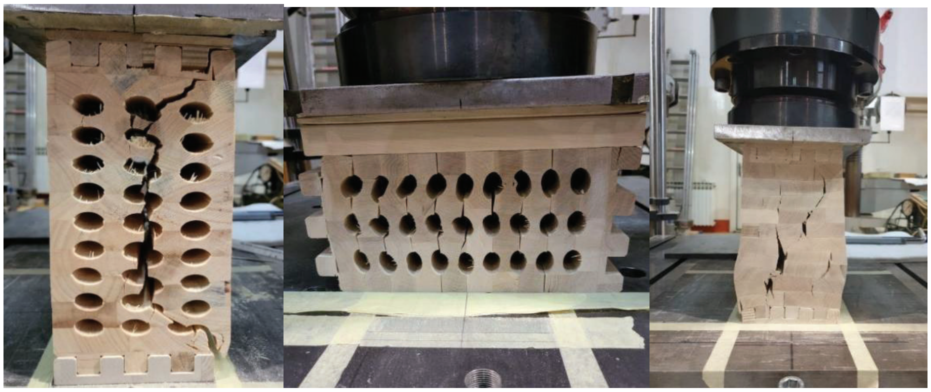

Figure 10 Failure modes

Depending on whether the failure modes represent a full-timber or hollow-timber cross-section, they can be categorized into two characteristic groups. The wood failure of the space between the holes, in the direction of the applied stress, was the primary mode of failure for the novel hollow GL timber elements. The load transmission over the solid wood ridges is straightforward due to the arrangement of elliptical cavities in columns. The cracks primarily form a straight line joining the ellipses' top arcs. This shows that the failure happened during crushing in the cavity area and that the load transfer path was appropriate. When the compressive strength perpendicular to the grains was attained, the normal GL wood elements failed, and fracture followed the stress trajectory. Compressive strength tests conducted perpendicular to the grain for specimens loaded in the stronger axis direction showed that these specimens behaved similarly to specimens loaded in the weaker axis direction. Once more, a nearly linear pattern was seen, which eventually transformed into a curve that shows the material's yielding. It was also evident in this instance that the hollow timber specimens' cracks were primarily vertical and connected the cavities in the force's direction. Finally, the FEM analysis confirmed the experimental research. The results of the comparative numerical analysis showed how the arrangement and layout of the cavities affect the stress distribution.

6 – CONCLUSION

This paper provides data from experimental tests on innovative timber elements with arbitrary percent of the cavities . Cavities affect the behavior of glued laminated timber elements. The limit state of load-bearing capacity and serviceability is reached earlier, compared to standard glued laminated timber elements. Hollow glued laminated timber elements made of softwood, with the application of alternating cross-sectional hollowing of 28%, reached 69.65% of the load-bearing capacity of specimens with a solid cross-section. Hollow glued laminated timber elements made of hardwood, reached an average of 72.63% of the load-bearing capacity of specimens with a solid cross-section. By combining different lamella thicknesses, the wood class of individual lamellas, and ultimately, the arrangement of lamellas, positive effects on deformation and/or stress within the elements can be achieved. By increasing the thickness of the edge lamellas, a positive effect can be achieved in the form of a reduction in vertical deformations and stresses in a glued laminated timber element. By increasing the class of the inner lamellas, the vertical deformation of hollow glued laminated timber elements is reduced. Furthermore, when investigating pressure perpendicular to the grain, hollow hardwood samples have a higher load-bearing capacity than softwood samples without holes, due to approximately three times the CSPG. The CSPG of softwood, for hollow specimens loaded in the direction of the stronger axis, decreases by an average of 55%, and in the case of hardwood specimens, by an average of 50%. The degree of hollowness is proportional to the CSPG regardless of the type of wood. Furthermore, the hollowness does not affect the force transmission with respect to the boundary conditions and load position, i.e. the coefficients kc,90 have similar values for hollow and solid glued laminated timber elements. Based on the review of the state of the art and the conclusions drawn from experimental and numerical research in this paper, the main questions that could be addressed in further research have been formulated, primarily relating to the development of parametric analysis, testing new types of adhesives and their compatibility for hollow wooden elements made of hard and soft wood, and studying in more detail the stress distribution and force paths using the DIC measurement method.

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