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EXPERIMENTAL STUDY OF TIMBER COMPOSITE 1D ELEMENTS USING DENSIFIED WOOD AND HARDWOOD WELDED DOWELS

Jure Barbalić[1], Nikola Perković[2], Bruno Zadravec[3], Vlatka Rajčić[4]

ABSTRACT: This paper is a part of an extensive research of multi-layered timber structural elements made without glue or metal fasteners. The paper focuses on the research of beam real dimension elements. The elements are formed in different designs, from timber lamellas connected by densified wood dowels as well as by dowels that are welded on the basis of friction between wooden parts. This method of connection, which provides inter-layer shear resistance, was tested for beams in bending, with different arrangement of dowels and lamellas. Before the beams testing, a study was made on the embedment strength and the slip modulus of the wooden dowels for different grain directions. The main originality of this study is defining the optimal way of joining, considering the practical difficulties encountered in constructing deeper multi-layer beams. The significance of this research is the demonstrated ability to produce multi-layer timber 1D elements that are structurally efficient and, at the same time, completely favorable for reuse or recycling.

KEYWORDS: dowel laminated timber (DLT), densified wood, wood welding, timber-timber composite, DLT beam

1 – INTRODUCTION

Although from a technical point of view, wood has a number of advantages, as a natural material, it however, has many inherent characteristics which impede its application in constructional situations. To overcome these problems, as well as to enable broader applications in construction, engineered wood products such as glued-laminated timber (GLT), cross-laminated timber (CLT) laminated veneer lumber (LVL), plywood or nail-laminated timber (NLT), have been developed and widely implemented. Nevertheless, assembling of this products is highly energy intensive in production. Using adhesively bonding or mechanical joining of timber blocks to form large structural elements and, therefore, has a large environmental footprint. So, there is still a need for a "greener" alternative to join the timber components in muti-layer elements. [1] One of the adhesive-free technique which have been proposed in recent years is dowel laminated timber (DLT). Connecting hardwood dowels to softwood boards started in Switzerland in the 1990s as a structurally efficient and economic mass timber structural material which can be used for floor, wall, and roof structures. Traditional construction techniques of dowel laminated timber was combined with advanced research on highly densified wood materials, to manufacture adhesive free EWPs. Replacing traditional structural systems, these prefabricated solid timber elements create a construction method that is fast, clean, and sustainable, not to mention aesthetically pleasing. However, there is a lack of statutory structural design standard in this area. Furthermore, there is a limited number of studies that have dealt with the development and characterisation of dowel laminated timber members mechanical properties which dependent on different factors such as lamella/dowel species and size, dowel arrangement, loading orientation. [2]

The objective of this research is to investigate and compare different assembly variations for dowel joining lamellae in multi-layer load-bearing beam elements. In addition to a review of the literature and related research projects, tests was made for five beam specimens with four different arrangements of dowels. The aim of the research is to determine the optimal way of connecting the lamellas, depending on whether the element is in bending.

[1] Jure Barbalić, Faculty of Civil Engineering, University of Zagreb, Zagreb, Croatia, jure.barbalic@grad.unizg.hr

[2] Nikola Perković, Faculty of Civil Engineering, University of Zagreb, Zagreb, Croatia, nikola.perkovic@grad.unizg.hr

[3] Bruno Zadravec, Faculty of Civil Engineering, University of Zagreb, Zagreb, Croatia, bruno.zadravec@grad.unizg.hr

[4] Vlatka Rajčić, Faculty of Civil Engineering, University of Zagreb, Zagreb, Croatia, vlatka.rajcic@grad.unizg.hr

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Also, in order to investigate the behavior of dowels, tests were done by varying the dowel diameter (10 and 12 mm), the direction of the fibers in relation to the force (0, 45 and 90 degrees), as well as the type of dowel (densified or welded). This should contribute to the future development of adhesive-free joining techniques as well as improve competitiveness and sustainability of such load-bearing components.

2 – ASSESSMENT OF EFFICIENCY

Over the past decade, research efforts have increased to develop more environmentally friendly building materials, mainly due to the large contribution of the construction sector to material consumption and energy consumption. Life Cycle Inventory (LCI) studies [3], examining the energy requirements, and resulting emissions to the environment, associated with the production of glulam and other structural timber products, have identified the need to optimise the utilisation of natural materials, and particularly the manner in which they are used [4] so as to maximise the environmental accruing from them. To address this challenge, the application of wood and engineered wood products (EWP) has become a major focus. [5,6] Additional environmental benefits can also be achieved by enabling the reuse of EWPs. [5,7] The use of dowel lamination technology has been the subject of numerous studies in recent years as an alternative to glue lamination technology to further improve the environmental performance of EWPs. There have been significant advances in this technology and numerous commercial products are available and used in several large timber structures worldwide as presented in [1,2,8,9].

In contrast to standardized methods, the use of dowels made of densified wood, as well as hardwood welded dowels, enables the production of high-quality laminated timber elements without using adhesives or metal fasteners. In wood densification, the base material achieves better properties by applying a temporary increase in pressure, which permanently densifies the void between the cellulars. In welded wooden dowels, high frequency rubbing of the two surfaces causes friction and heat that soften and then bond the lignin, mechanically joining the cellular material. If the economic cost and mechanical performance of this type of structural joints can be shown to be at least comparable to that achieved by nailing or adhesives, then limits of the durability and fire resistance, completely disassemble and recycle of the structure, as well as problem of the strong carbon footprint can be avoided in construction of multi-storey buildings. In this regard, there are many studies [1,2] on the technical characteristics and load-bearing capacity of wooden beams, floor panels and walls laminated with wooden dowels, welded wooden dowels, wooden inserts or wooden nails. All of these works concluded that joint systems made with wooden dowels perform well with good initial stiffness and load carrying capacity compared to traditional joining methods using bonded wooden dowels or metallic fasteners.

The use of timber dowels to transfer shear forces between the timber layers leads to partial composite action, between the individual layers, and hence to a composite beam with semi-rigid connections. The structural response of such a beam will be bound between that of a layered beam with no inter connectivity and a layered beam with fully rigid interfaces between the individual layers. Suggested in [10], the efficiency of the dowel connection can be evaluated as:

$$Eff = (D_n - D_i / (D_n - D_c)) \cdot 100 \qquad (1)$$

where D_n is the theoretical composite beam deflection with fully composite connections, D_c is the theoretical composite beam deflection without interlayer connections, D_i is the theoretical composite beam deflection with semi-rigid interlayer connections. Using the "γ-method", which can be found in Eurocode 5 [11], it is possible to approximate the effective bending stiffness of a simply supported composite beam, composed of n layers, as follows:

$$EI_{eff} = \Sigma(E_iI_i + \gamma E_iI_ie_i^2) + (E_rI_r + E_rI_re_r^2) \qquad (2)$$

where I_i, A_i and E_i represent the second moment of inertia, area and modulus of elasticity of the timber layers, e_i represent distance of the center of gravity of the cross-section of an individual layer to the neutral axis of the cross-section of the entire element and where the index r is used for the reference layer.

The shear coefficient γ, of the semi-rigid connexion, is given by:

$$\gamma = 1 / (1 + (\pi^2 E_iI_is_i) / (kL^2)) \qquad (3)$$

where s is the regular spacing between dowels, L represents the length of the beam and k is the slip modulus of the dowel. In the (3), $\gamma = 1$ indicates a fully composite connections, while $\gamma = 0$ indicates no shear transfer between layers. Based on these input parameters, it is easy to determine the normal stresses in the composite section for each timber layer, the load on each timber dowel, or the total deflection of the beam.

3 – DETERMINATION OF WOODEN DOWELS CHARACTERISTICS

This study describes in detail the process of determining the embedment strength and the slip modulus of joints with densified hardwood dowels, i.e., joints with welded hardwood dowels, loaded at different angle to the lamella fibers. The use of hardwood for dowels is gaining increasing attention due to its sustainability and aesthetic as well as mechanical properties. However, traditional joining and processing methods often limit the full potential of this material.

The specimens preparation was carried out in accordance with the EN 1380 standard [12]. Twelve series of six specimens were produced, i.e. a total of 72 specimens of joints that differ in fiber orientation (loading parallel, at an angle of 45° or perpendicular to the fiber direction), dowel diameter (from Ø 10 mm and Ø 12 mm) and the method of installation of the dowel (densified dowels or welded dowels). The specimens have different dimensions, determined in accordance with the recommendations of the standard, depending on the dowel diameter and the direction of loading. In order to ensure proper failure mode, the capacity force was previously determined analytically according to the expressions given in Eurocode 5 [11] for dowel type fasteners.

The first phase was the selection of materials. European spruce as softwood was selected for the base material, while beech as hardwood was used for the dowels, due to its higher density, strength and easier availability. Before the specimens were made, the material was conditioned to achieve the desired equilibrium moisture content. This step allows the wood to adapt to new conditions, thereby reducing internal stress and increasing dimensional stability. The duration of this process depended on the type of wood and the initial moisture content and usually lasted to several weeks.

After conditioning, the density of the wood of the base material was determined, as an essential parameter. All tests were carried out in accordance with ISO 3129 [13] and ISO 13061 [14] standards and EN 384 [15] and EN 408 [16]. The test results indicate a mean wood density of ρ_{mean} = 415 kg/m^3 with an equilibrium moisture content of 12% (with a standard deviation of 59.48 and a coefficient of variation of 14.33%), where the wood density is given as the ratio of the mass to the volume of the test prisms. Although efforts were made to make specimens from the same piece of wood, the density of the wood still varies somewhat higher.

After conditioning, the specimens were made. The final dimensions of the specimens are shown in Tab. 1. The wood was cut and shaped into elements of smaller dimensions, while the dowels were made by precision machining to enable their stamping, or welding. The one dowel are installed in the middle of the each lamela. Densification process included exposing the wood to high temperatures and pressures, which resulted in a decrease in porosity and an increase in density. Both types of dowels were finally made with grooves for better adhesion and easier assembly. The dowels were pressed using a machine press. The welding of the dowels was carried out in such a way that the dowel were connected to a drill and during installation, heat was generated between the elements by rotation due to friction, which dissolved the lignin in the wood and enabled the formation of a bond. During the welding, it was important to immediately stop the rotation after the desired level of penetration of the dowel, in order not to neutralize the effect of the melted layer of lignin.

Table 1: Dimensions of specimens

Type of specimen		Dimensions		
Dowel diameter [mm]	***Force angle [°]***	***Length [mm]***	***Heigh [mm]***	***Thickness [mm]***
10	0	100	140	15
	45	140(198)	140	15
	90	400	100	15
12	0	100	168	18
	45	168(238)	168	18
	90	480	100	18

During the test, the specimen was continuously supported by one edge on the press stand, while the load was applied via a steel stirrup that was supported on a wooden dowel right next to the lamella itself (as shown in Fig. 1). The width of the lamellas, as well as the width of the steel stirrup plates, which is equal to the width of the lamella, was defined so that the specimen failed in the desired way, that is, to fail by reaching embedment strength. This provides insight into the yield point in the joint, which is important for calculating the stiffness and load-bearing capacity of laminated elements with dowels. The load was applied at a constant rate of 0.50 mm/min for specimens loaded parallel to the grain, at a rate of 0.45 mm/min for specimens loaded at an angle of 45° to the grain, and at a rate of 0.40 mm/min for specimens loaded perpendicular to the grain. The rate of load application was determined according to the maximum force obtained for the test specimen, in order to comply with the rule on the time duration of the load on the specimen.

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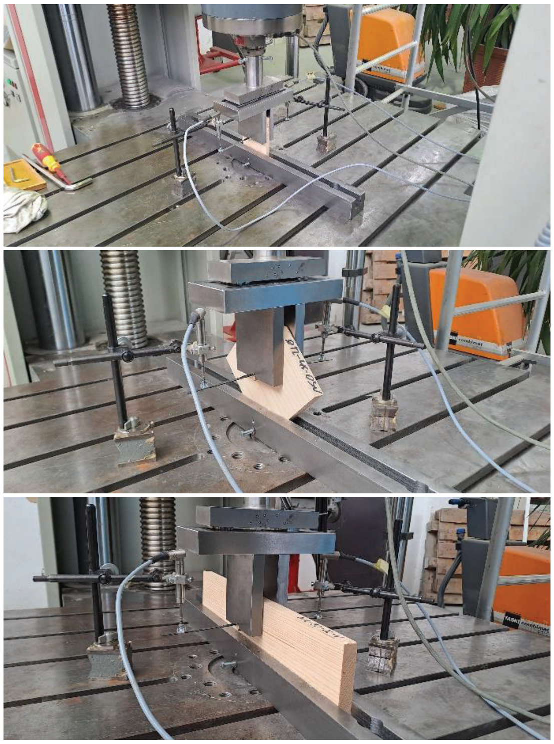

Figure 1: Specimens loaded parallel to the grain (above), at an angle of 45° to the grain (middle), and perpendicular to the grain (below)

The device used to apply force to the specimens had an accuracy of within 1% for determining the force in the system for loads less than 10% of the load capacity and 0.1% for the failure load. The vertical deformations of the dowel were measured on both sides of the lamella by LVDT sensors and were ultimately taken as the average value of the specimen deformation in the area of force application. The measuring instruments meet the accuracy requirements of 1%. Each specimen was loaded to approximately 40% of the load capacity in a period of approximately 120 seconds, then the load was maintained at this level for an additional 30 seconds, after which the specimen was unloaded to approximately 10% of the load capacity in a period of approximately 90 seconds and the load was again maintained at this level for an additional 30 seconds, and then the specimen was loaded again to failure in a period of up to approximately 300±120 seconds. The specimen was loaded to a maximum displacement of 5 mm or to failure.

By processing the data generated during the tests, force – displacement curves were obtained. The curves are shown in Fig. 2. The test showed the typical behavior of dowel joints according to Johansen's theory. But, in relation to theoretical assumptions, there are certain deviations and the tested values are not on the safe side. So, in case of the wooden dowels, there is a need for correction of expressions for the embedment strength given in Eurocode 5 [11]. Finally, the stiffness of the joints, i.e. the value of the slip modulus K_{ser}, was obtained. Data are given in Tab. 2 and compared to values calculated according to the Eurocode 5 [11] (where the diameter of the fastener and the characteristic density of the wood are taken into account). This data will be the basis for further calculations, whether it is the calculation of the load-bearing capacity and deflection of the DLT beams or the load-bearing capacity of the dowels in the beam itself.

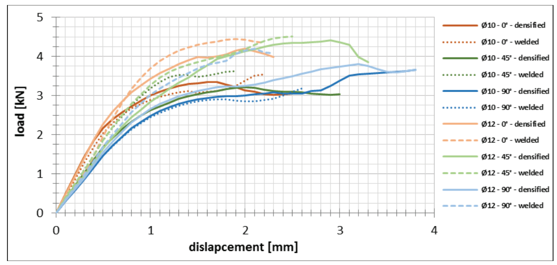

Figure 2: Averaged force – displacement curves for tested specimens

The difference in the behavior of welded and pressed dowels is more significant for smaller dowel diameters, where failure occurs more quickly in joints with welded dowels. The reason for this may be the wear of the drilled hole in the wood during welding the dowel. However, the smaller difference, even more favorable in favor of the welded dowel, is for joints with larger dowel diameters. It can be concluded that with an increase in diameter and a better bond formed during welding due to a larger contact surface, the influence of lignin that binds the dowel to the basic ancient material would be much more effective.

Table 2: Comparison of theoretical and tested data

Type of specimen			Theoretical data / Tested data	
Dowel diameter [mm]	***Force angle [°]***	***Dowel installation type***	$f_{h,\alpha,mean}$ [N/mm²]	$K_{ser,mean}$ [N/mm]
10	0	impress	29.52 / 22.27	3479 / 4789
		welded	31.75 / 23.62	3881 / 4260
	45	impress	27.72 / 21.37	4423 /3389
		welded	33.39 / 24.11	5846 / 3698
	90	impress	21.20 / 24.34	3888 / 2949
		welded	21.44 / 21.21	3956 / 2927
12	0	impress	26.34 / 19.46	3639 / 4674
		welded	26.09 / 20.59	3588 / 3797
	45	impress	22.31 / 20.45	3901 / 3285
		welded	22.46 / 20.8	3941 / 3741
	90	impress	16.74 / 17.58	3489 / 3106
		welded	18.92 / 19.44	4190 / 3393

4 – BEHAVIOR OF DOWEL LAMINATED TIMBER BEAMS

In order to investigate the behaviour and efficiency of the DLT timber beams, it was decided to carry out an experimental four-point bending test of the beams in accordance with the EN 408 standard [16]. All beams had cross-sectional dimensions of 100 mm width and 120 mm height, and were composed of four 30 mm thick laminations. Four series of five specimens were formed to study the influence of the type, position and length of the dowel. All used dowels had the same diameter of 10 mm. In the first series (marked as "90°*-densified"), densified wooden dowels of 60 mm length were installed between two lamellas, perpendicular to the longitudinal axis of the beam. Care was taken to ensure that the dowels in adjacent rows of lamellas were installed in a staggered manner to avoid splitting. The same principle was used in the second series (marked as "90°*-welded"), where welded dowels were used. In the third series (marked as "90°-densified"), densified wooden dowels of 120 mm length were used, which were installed through all four lamellas, perpendicular to the longitudinal axis of the beam. In the fourth series (marked as "45°-densified"), densified wooden dowels of 170 mm length were used, which were installed through all four lamellas, at an angle of 45° to the longitudinal axis of the beam. For the last two series, a counterpart series with welded dowels was not made because the welding depth was not suitable for this type of connection. The dowel body is worn out by welding and at depths greater than 80 mm it is not wide enough to touch the base wood, and thus creating friction. This problem could be solved by forming conical dowels and holes. However, such a process would require the production of special tools and milling cutters. The test standard specifies four-point bending over a test span of 18 times the height of the specimen. As a result, the specimen was intended to be supported over a test span of 2160 mm with point loads at 720 mm from each support. The total length of each specimen was slightly longer, at 21 times the height of the specimen, or 2520 mm.

The first phase was the selection of materials. European spruce as softwood was selected for the base material. This species usually achieves structural grade C24 due to the climatic conditions in which it grows. The standard EN 338 [17] gives an average value of 11000 MPa for the modulus of elasticity of C24 wood in the longitudinal direction, which is used as the primary substrate for the DLT elements in this study. Before the specimens were made, the material was conditioned to achieve the desired equilibrium moisture content. After conditioning, the density of the wood of the base material was determined according to the [13-16]. The test results indicate a mean wood density of ρ_{mean} = 427 kg/m3 with an equilibrium moisture content of 12% (with a standard deviation of 13.57 and a coefficient of variation of 3.18%). It can be seen from the above data that the uniformity of wood quality has been achieved.

Typically, hardwood dowels have been used in the production of DLT products, however, in this study densified and welded dowels are used, as defined in the previous chapter. Densified dowels have shown good properties in shear testing compared to other standard hardwood dowels. They also have the property of shape recovery or elasticity, which means that they will expand over time, resulting in a strong bond that can be useful a characteristic in many applications in wood structural engineering. Such proven superior structural properties compared to natural wood are also environmentally friendly, making them a good alternative to metal fasteners. [8] On the other hand, welded dowels are effective due to the temperature-induced softening and flowing of some amorphous, cells interconnecting wood material. The consequence is high densification of the bonded interface. Wood species, relative diameter, difference between the dowel and the receiving hole, and dowel insertion are the parameters that yield significant strength differences.

The wood was cut and shaped into lamellas, while the dowels previously made (for determination of its characteristics). The dowels are installed in the same way as mentioned in the previous chapter. The arrangement of dowels in each specimen is shown in Fig. 3.

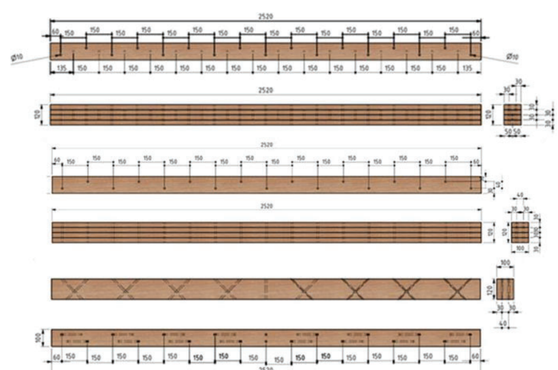

Figure 3: Specimens type for DLT beams experimental investigation

During the test, steel plates are positioned at the support points and load points as specified by EN 408 [16]. The

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load was applied at a constant rate of 15 mm/min for for all specimens. The speed of load application is set at a value slightly lower than the maximum load speed allowed by the standard. The device used to apply force to the specimens had an accuracy of within 1% for determining the force in the system for loads less than 10% of the load capacity and 0.1% for the failure load. Each specimen was loaded to approximately 10% of the load capacity, then the load was maintained at this level for an additional 30 seconds, after which the specimen was unloaded to start position, and then the specimen was loaded again to failure. The deformation at the mid-span, i.e., at the bottom of the beam cross-section was measured by LVDT sensors, as well as horizontal displacement on a sliding bearing at the middle of the cross section. In order to gain insight into the coupling efficiency, the horizontal displacement of the edge lamellas (upper and lower) on a fixed bearing was measured. The measuring instruments meet the accuracy requirements of 1%. Test settings are shown in Fig. 4.

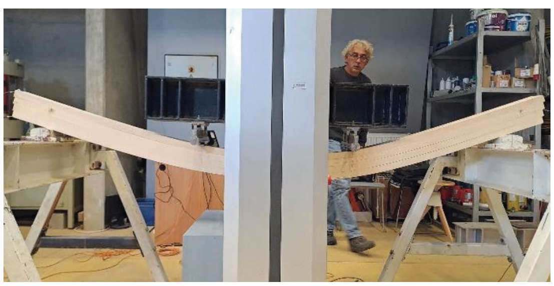

Figure 4: Characteristic failure of beam pecimen with densified dowels with dowels installed alternately through the lamellas

All specimens failed equally, due to the fracture of the lowest lamella at the moment when the stress exceeded the bending strength of the wood. There is no significant difference in the achieved load-bearing capacity or behavior between the samples with densified and welded dowels when they were installed alternately through pairs of lamellas. However, it is important to note that tensile failure of the welded dowels occurred at the ends of some samples. The cause of this is probably the weakening of the section due to welding. A slightly larger increase of 8% in load-bearing capacity was achieved in the case when the dowels were installed vertically through all lamellas. As expected, a more significant increase of 18% was achieved in the case when the dowels were installed at 45 degrees. In both cases, sliding of the dowel along the hole was observed in the case of large deformations, which is to be expected given that the dowels do not deform axially, but only transmit shear force between the lamellas. The characteristic failure modes are shown in Fig. 5. Looking at the images of the tested beams, there is an impression that the deformation as well as relative displacements between the lamellas is too large for the achieved failure load. However, it should be emphasized that the goal of this research was not to obtain a beam stiff enough for classical use in construction, but to examine the behavior of the beam with different dowel settings. Therefore, the arrangement of dowels along the beam is somewhat less frequent to ensure that the wood does not split during installation or loading. It is logical that for larger diameters and a denser arrangement of dowels, the beam would certainly be stiffer.

Figure 5: Characteristic failure of beam pecimen with densified dowels installed alternately through the lamellas (A), welded dowels installed alternately through the lamellas (B), densified dowels installed vertically through the all lamellas (C) and densified dowels with dowels installed at a 45° angle through the all lamellas (D)

By processing the data generated during the tests, force – displacement curves were obtained. The curves are shown in Fig. 6. In the same picture, the diagrams of displacement forces according to theoretical calculations based on the "γ-method" are given. The elastic modulus $E_{0,mean}$ with a value of 11000 MPa was used, while the force in relation to the displacement was calculated using the expression for the deformation of the beam loaded with a pair of forces symmetrically placed in relation to the center of the beam:

$$\Delta = (Fa / 24EI) \cdot (4a^2 - 3L^2) \quad (4)$$

where Δ is the vertical deformation, F the total force, L is the span of the beam, and a is the distance of the force input from the support.

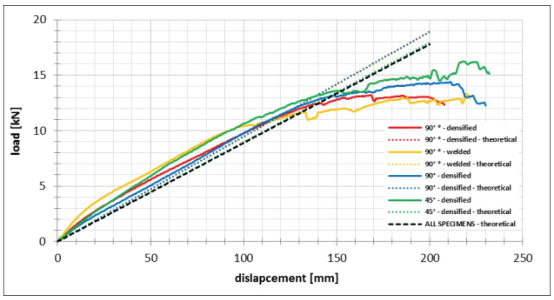

Figure 6: Averaged force – displacement curves for tested specimens with curves for theoretical behaviour of DLT beams

The theoretical value of the stiffness EI required for the deflection calculation was calculated for two cases. In the first case, the slip modulus value was defined with respect to the values obtained in the dowels experimental study. Values obtained from dowels testing were adjusted with respect to the beam wood density. In the second case, the slip modulus was used according to the expression given in Eurocode 5 [11]. This expression for K_{ser} does not distinguish between the angle of force application or the type of dowel. Therefore, the value of the slip modulus as well as the beam stiffness is the same for all types of samples. All data are shown in Tab. 3.

Table 3: Comparison of theoretical and tested data

Type of specimen	Tested data		Theoretical data	
	F_{max} [kN]	EI_{mean} [Nmm^2 x 10^{10}]	$K_{ser,mean}$ [N/mm]	EI_{mean} [Nmm^2 x 10^{10}]
90°*-densified	13.32	4.045	4342 / 3836	3.384 / 3.180
90°*-welded	13.31	4.853	4309 / 3836	3.371 / 3.180
90°-densified	14.38	3.783	4342 / 3836	3.384 / 3.180
45°-densified	16.21	4.197	3907 / 3836	3.209 / 3.180

From data in Tab. 3. it is evident that the analytically obtained stiffness is the same for all types of samples, while there are certain deviations between the samples in the experimental values. However, these differences are not that significant. The stiffness of beams with diagonally installed dowels and beams with welded dowels is slightly higher, which indicates the positive influence of the type of dowel and the method of installation. Theoretical values are on the safe side, so it can be said that the standardized "γ-method" method is acceptable for the calculation of DLT beams. However, it should be noted that it is important to accurately determine the slip modulus as a parameter that significantly affects both the load-bearing capacity and deformability of beams.

5 – CONCLUSION

The experimental results demonstrate that it is possible to achieve a high degree of composite action using dowel laminated timber for the beams. This degree of efficiency could be further enhanced for even more competitive performance by using more dowels in multiple rows in case of larger cross section elements. The contribution of wood welding is presented, and it is concluded that there is no difference for smaller dowel diameters. Influence of melted lignin film is only evident for larger diameters, where the friction between the wood parts when pressed dowel is used is less than the cohesive force created by welding the dowel. The positioning of the wooden dowel inside the beam does not significantly affect its load-bearing capacity and deformability. Therefore, for assembly simplicity, dowels can be used between individual lamellas, rather than through the entire cross-section. This is especially important for beams with large cross-sections. The standardized "γ-method" proved to be satisfactory for calculation of deflection and stresses in beam. However, for final application which also includes the calculation of load-bearing capacity, it is necessary to adapt the standardized expressions for metal fasteners, especially regarding the embedment strength and the slip modulus where tests showed lower values than theoretical. Optimisation of dowels distance, as well as further investigation of their hydro-thermomechanical and creep/relaxation behavior deserves attention.

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