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EXPERIMENTAL INVESTIGATION OF THE EMBEDMENT STRENGTH OF LAMINATED VENEER LUMBER (LVL)

ABSTRACT

Connections in timber structures play a vital role in the stiffness, strength and overall performance of the structure. Embedment properties are of paramount to the overall performance of bolted connections. This study experimentally investigates the performance of embedment strength of LVL manufactured from Nordic Spruce (Picea Abies), utilising 10mm steel dowels. A total of 50 embedment tests were conducted following the half-hole method, as specified in ASTM:D5764−97a. The tests had been performed considering 0°, 45°, and 90° load-to-grain angles, on edgewise orientation of the embedment properties and failure modes were analysed. The experimental embedment strengths were then compared to the respective characteristic embedment strengths proposed in Eurocode 5. While the characteristic embedment strength was 11% lower than the mean embedment strength for load parallel to grain, it overestimated the embedment strength by 9.2% and 7.2% for load-to-grain angles of 45°, and 90°, respectively.

Keywords

Embedment strength; Laminated Veneer Lumber (LVL); Half Hole Test; Fasteners; Eurocode 5

INTRODUCTION

Engineered Wood Products (EWP) have proven to have a great potential and an immense impact on the construction industry. They have lesser carbon footprint compared to steel and concrete, with sustainable and reusable characteristics addressing the current concerns rising in building design and construction (ARUP, 2019). EWP are innovative construction materials that have brought advantages over traditional wood, reducing cost and construction time on site, while provide improved quality with less waste and predictable structural performance (Porteous, 2007).

Laminated Veneer Lumber (LVL) is one of the finest EWP prominently used in a wide range of applications in building and bridge construction. Because of the rigorous quality control measures in place during the automated manufacturing process, the natural defects in the wood have little to no structural impact on the final product. Thus, its high strength properties compared to its weight and the excellent dimension stability make it a popular choice for extensive range of structural applications (Stark et al., 2010, Industries, 2020).

The performance of timber joints affects directly the design, appearance and structural response of timber structures (Smith and Foliente, 2002). Metal dowel-type joints with dowels, bolts, screws or nails, are commonly used in timber structures (Bader et al., 2015b). The yield load of metal dowel-type joints can be predicted by the European Yield Model (EYM) which is based on the Johansen's equations (Johansen, 1949). The EYM assumes that both the metallic fastener and wood exhibit an elastic-plastic behaviour and considers the embedment of the fastener into the wood. The embedment is characterised by the embedment strength of the wood, and the yielding of the fastener, which are the key parameters for the design of metal dowel-type joints (Hu et al., 2022, Nguyen et al., 2018, Sandhaas et al., 2018). Thus, the embedment strength plays a significant role in determining the yield load of the joint (Mouka and Dimitrakopoulos, 2022), while the embedment stiffness governs the stiffness of the joint (Tao et al., 2021). For timber members, the embedment properties are determined considering key parameters such as the fastener diameter, the density of the wood and the angle where the load is applied in terms of its grain direction (Smith and Foliente, 2002). Experimentally, the embedment properties can be determined by two test methods: (i) half-hole (HH) and (ii) full-hole (FH) tests. HH tests are performed under compression resulting a uniform stress distribution along the fastener (ASTM:D5764−97a, 2007). In contrast, FH tests are performed under both compression and tension utilising two side plates resulting a parabolic stress distribution (ASTM:D5764−97a, 2007, EN383, 2007).

There is a comprehensive literature on embedment strength properties for timber and several Engineered Wood Products, such as Glued Laminated Timber (GLT) and Cross laminated Timber (CLT). However, studies that report embedment properties for LVL are relatively limited, especially given the material properties' variability, as LVL can be made from different types of timber, and manufacturers may customise the composition and properties of LVL to suit specific requirements. Schweigler (2016) investigated the load-to-grain dependence of the embedment properties, such as embedment strength, embedment moduli and slip behaviour for dowel-type fasteners, with a diameter of 12 mm and 16 mm. Similarly, Bader et al. (2015a) have shown that the dowels forced parallel to the grain demonstrated higher bending deformation compared to the dowels forced perpendicular to the grain. Experiments on embedment behaviour of both solid timber and LVL from Radiata Pine were conducted by Quenneville (2011) to examine the ductile joint performance. The embedment tests were conducted under various load to grain angles considering bolts with diameter of 6mm up to 30mm. In addition to the embedment strength, many studies investigate the influence of the load-to-grain angle as well as the bolt size on the embedment slip modulus, which regardless of the dowel diameter, both the slip modulus and the embedment strength decrease as the load to grain angle increases (Nguyen et al., 2020, Wang et al., 2023, Sandhaas et al., 2013).

Regarding the effect of the density on the embedment strength, Sandhaas et al. (2013) and Xu et al. (2022) stated that there is no significant correlation between them. However, Van Blokland et al. (2021) and Yurrita and Cabrero (2018) have explained that the characteristic embedment strength can increase over the density on both parallel and perpendicular grain load conditions. A notable reduction in the embedment strength was identified when moisture content is increased (Sandhaas et al., 2013, Van Blokland et al., 2021).

When determining the embedment behaviour, the influence of fastener diameter is vital. It has been shown that when the dowel diameter increases, the embedment strength decreases, while dowels with larger diameters demonstrate high stiffness in both loading and preloading conditions, therefore have less slip deformation (Wang et al., 2023, Quenneville, 2011, Nguyen et al., 2020). However, after evaluating matched pairs of HH and FH samples that were taken from Radiata Pine and Southern Pine under a constant density, Ottenhaus et al. (2022) identified that only the FH test data exhibited a considerable negative correlation between the diameter of the fastener and the embedment strength whereas the results of HH test did not show any significant correlation. In that comprehensive literature review on the embedment strength properties on LVL, Ottenhaus et al. (2022) concluded that further investigation should be carried out for LVL to find out the influence of both FH and HH test methods under different load to grain angles and fastener diameters.

This present study pertains to the broaden investigation on the embedment properties of LVL. The scope is to contribute to a more comprehensive database of experimental results and enhance the existing knowledge on this matter. This paper examines the effect of the load-to-grain angle on the embedment properties, such as embedment strength, slip modulus, and embedment elastic modulus, for a specific type of LVL considering a 10mm diameter fastener. It analyses the failure mechanisms and crack development. Lastly, the study compares the experimental findings with the characteristic embedment strength obtained from the Eurocode 5 for LVL and provides findings to enhance the knowledge on the embedment properties for LVL with the HH method.

MATERIAL AND EXPERIMENTAL SETUP

The examined specimens were manufactured by European engineered wood that utilises Nordic spruce and pine. They consisted of 3 mm thick strength graded softwood veneer. All veneers had the same grain direction. The veneers were bonded with weather and boil-resistant phenol formaldehyde adhesive (Kerto-S®, 2022). The material was treated to provide a safety against the undesirable influences of the moisture content changes. The specimens were conditioned at room temperature conditions (i.e., 18^0C -22^0C and 65% relative humidity) before testing. Selected samples were measured and weighted to determine the moisture content, wet density and dry density. The moisture content and wet density were determined according to the Australian Standards (2098.1, 2006, 2098.7, 2006) for veneers and plywood, considering 15 specimens. The average value for the wet density was 512.9 kg/m^3 (with a standard deviation (SD) of 7.47 kg/m^3) and the average dry density was 485.3 kg/m^3 (SD = 11 kg/m^3). The mean moisture content was 9.98% (SD= 0.13%).

The specimens were manufactured as 75mm x 75mm x 75mm cubes, with a 10 mm diameter half-hole on the top surface considering edgewise orientation of the veneers (Figure 1a, 1b). The size of the specimens is based on the recommended minimum dimensions in the ASTM:D5764−97a (2007) to resist splitting during the test. The utilisation of the edgewise orientation is common in structural applications because it allows the member to attain its highest levels of strength and stiffness.

A total of 50 embedment tests were performed, using 10 mm steel dowel and load-to-grain angles of (i) 0° (load parallel to grain), (ii) 45°(load at 45° to grain), and (iii) 90° (load perpendicular to grain) (Figure 1c). The embedment behaviour was determined following the half-hole test set up in ASTM:D5764−97a (2007) as illustrated in Figure 2(a). The specimens were labelled considering the grain orientation (F_E), load-to-grain angle (i.e. 0°, 45°, and 90°), dowel diameter (10mm), half-hole configuration (H/H) and the sample number (Y_1), e.g. FE0_10mm_H/H_Y_1 stands for the Edgewise orientation, load-to-grain angle of 0°, 10 mm dowel, half-hole test, sample Y_1. The tests were conducted in the Structural Engineering Laboratory of the Edith Cowan University, employing an Instron 8801 universal testing machine of 100 kN capacity. The tests were conducted in a displacement-control constant rate of 1 mm/min. To avoid bending of the fastener during the test, a rigid steel plate with a curved edge of 10 mm was utilised, which was clamped to the movable crosshead of the testing machine. The dowel displacement was measured by a linear variable differential transformer (LVDT) on the movable crosshead of the Instron machine. The tests were concluded when either (i) an embedment of 5 mm displacement was reached, or (ii) the load was dropped more than 20% of the maximum load.

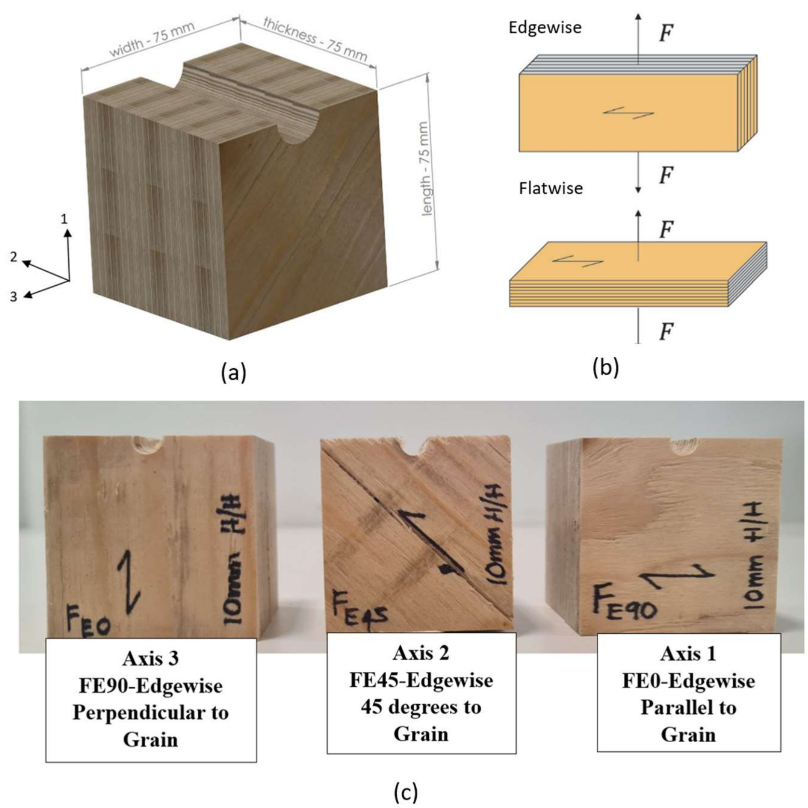

Figure 1:(a) Examined specimens with dimensions; (b) edgewise and flatwise orientation perpendicular to the grain of veneers; (c) specimens under the load-to-grain angles of 0°, 45°, and 90° with 10 mm half-hole set up before testing.

RESULTS AND DISCUSSION

Figure 3, Figure *4* and Figure *5*, present the experimental embedment stress-displacement curves for 0°, 45°, and 90° load-to grain angles with 10 mm dowel diameter, respectively. The embedment stress values σ_{emb} (MPa) were obtained from the respective force values F normalised with the assumed bolt-specimen projected area (ASTM:D5764−97a, 2007), as:

$$\sigma_{emb} = \frac{F}{td} \qquad (1)$$

where, t is the thickness of the specimen and d is the dowel diameter (both in mm).

The curves exhibit an initial linear elastic stage, followed (in most cases) by a plastic stage. The failure modes vary among the specimens at different load-to-grain angles. The FE0 specimens had undergone a limited plastic deformation before failing from splitting parallel to the grain direction (Figure 6(a)). The failure was brittle, as the splitting occurred at around 1 mm embedment displacement in most of the specimens. The FE45 specimens had undergone a larger plastic deformation and a post-elastic hardening behaviour, due to the combined crushing of the fibres underneath the dowels and the splitting of the fibres at an angle parallel to the load direction (Figure 6(b)). The FE90 specimens had exhibited a similar behaviour as the FE45 specimens, with a higher post-elastic hardening behaviour, and failed due to fibre crushing and splitting perpendicular to the grain (Figure 6(c)). These results are in agreement with findings observed by Khoshbakht et al. (2018), Quenneville (2011) , Nguyen et al. (2020) and Shi et al. (2023).

Table 1 summarises the embedment test results. The slip (or foundation) modulus K_{emb} is the slope of the experimental force- displacement curves in the elastic region (determined as the region between 10% and 40% of the maximum force as indicated in Figure 2(a)). The embedment strength $\sigma_{emb,y}$ is determined based on the *yield* load $f_{h.0.05d}$, which is derived as 5% of the dowel diameter to the offset that is intersecting with the stress- displacement curve (Figure 2(a)) (ASTM:D5764−97a, 2007). The embedment elastic modulus E_{emb} occurs as:

$$E_{emb} = \frac{K_{emb}}{t} \quad (2)$$

In addition, the ultimate embedment strength $\sigma_{emb,u}$ is determined based on the ultimate load, instead of the yielding load. The ultimate load is determined as either (i) the maximum load for specimens that fail before the full embedment of the bolt, or (ii) the load at 5 mm embedment displacement (i.e. when the bolt embeds into specimen). The average value of the ultimate embedment strength is 2.3%, 18% and 28% higher than the average embedment strength obtained using the yield load, for a load-to-grain angle of 0^0, 45^0 and 90^0, respectively. This can be easily explained from the gradual increase of the stress after the yield load, with the increase of the load-to-grain angle, in Figure 3, Figure *4*, and Figure *5*.

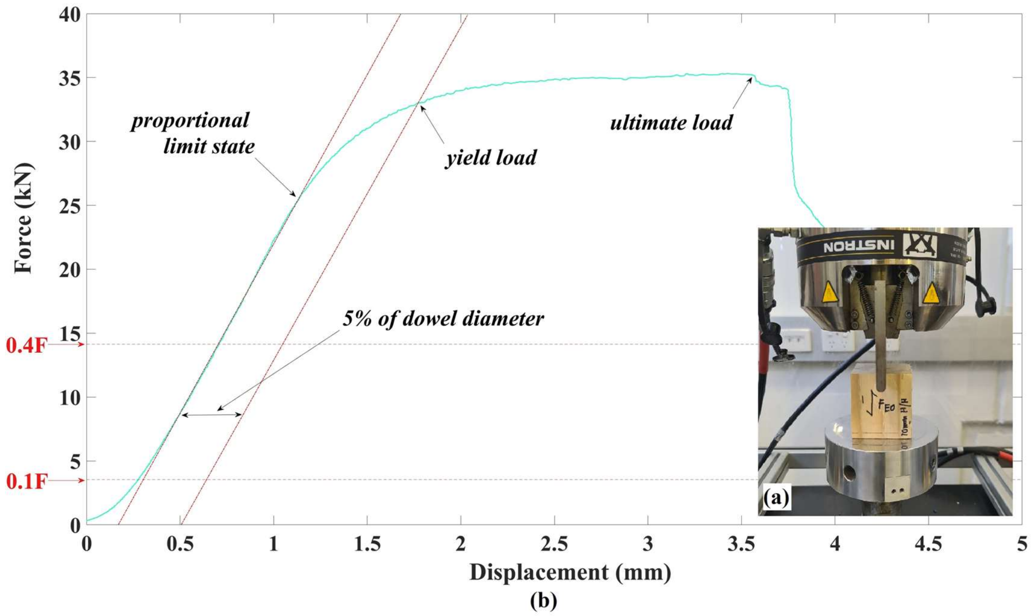

Figure 2: a) Test picture of half-hole 10mm dowel embedment test in load parallel to the grain b) schematic illustration of the 5% offset method.

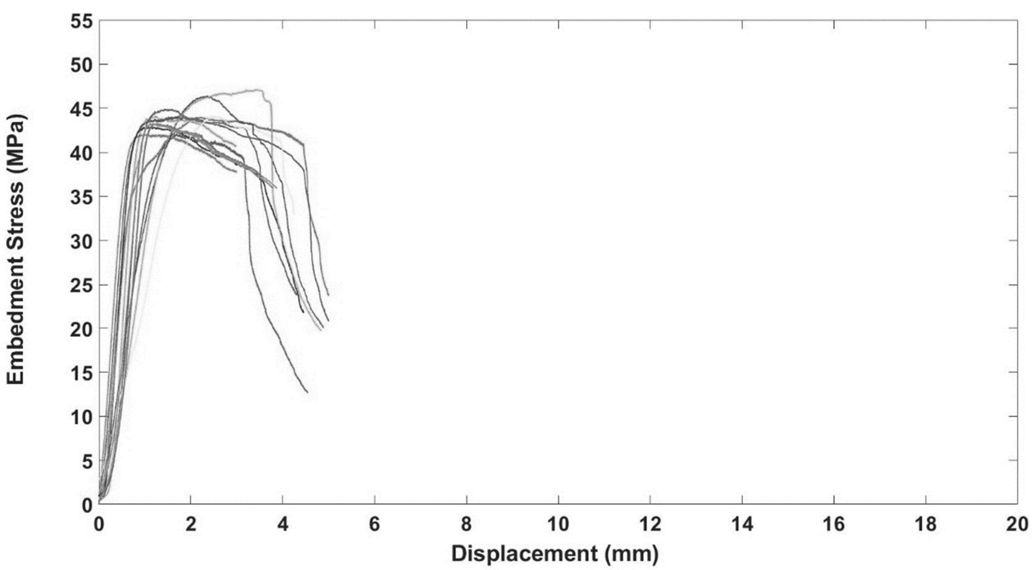

Figure 3: (a) Embedment stress vs displacement diagram for a load-to-grain angle of 0^0 (load parallel to grain); (b) Failure mode (splitting) of FE0 specimens.

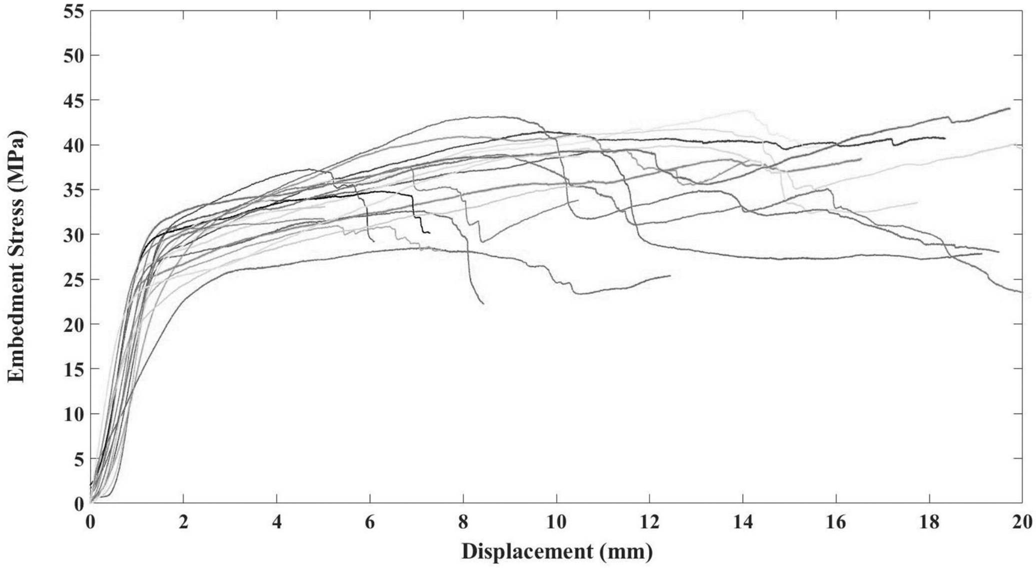

Figure 4:(a) Embedment stress vs displacement diagram for a load-to-grain angle of 45^0 (load at 45^0 to grain); (b) Failure mode (crushing and splitting) of FE45 specimens.

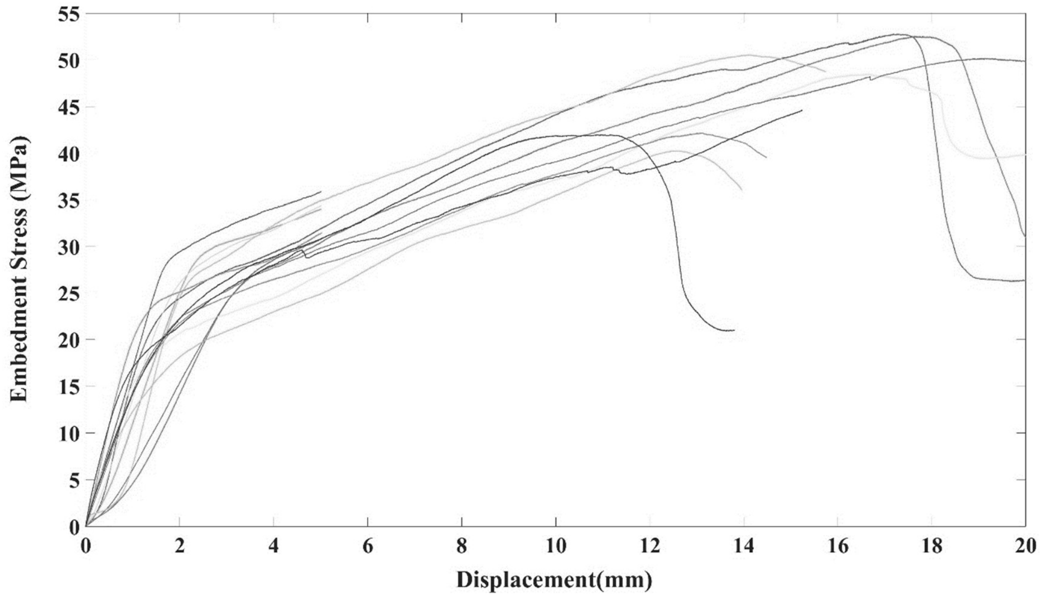

Figure 5: (a) Embedment stress vs displacement diagram for a load-to-grain angle of 90^0 (load perpendicular to grain); (b) Failure mode (crushing and splitting) of FE90 specimens.

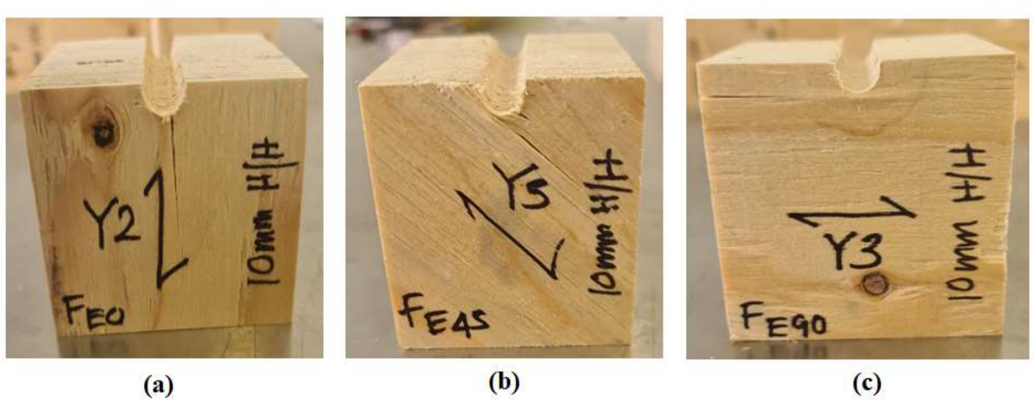

Figure 6: (a) Failure mode (splitting) of FE0 specimens, (b) Failure mode (crushing and splitting) of FE45, (c) Failure mode (crushing and splitting) of FE90 specimens.

Table *1* shows that the average values of slip modulus K_{emb} and embedment elastic modulus E_{emb} decrease as the load-to-grain angles increase (roughly a 50% decrease for every 45^0 increase of the load-to-grain angle). Both the embedment strengths $\sigma_{emb,y}$ and $\sigma_{emb,u}$ follow a similar trend, i.e. they decrease as the load-to-grain angle increases. These results are in agreement with findings obtained by Schweigler et al. (2016), Wang et al. (2023) and Quenneville (2011).

Analytical estimation of the embedment strength of LVL

The experimental embedment values will be compared with the characteristic embedment strength values for LVL obtained according to Eurocode 5 (EN1995.1.1, 2004). The characteristics embedment strength $f_{h,\alpha,k}$ at an angle α to the grain, for bolts up to 30 mm diameter, can be calculated as:

$$f_{h,\alpha,k} = \frac{f_{h,0,k}}{(1.30+0.015d)sin^2\alpha+cos^2\alpha} \quad (3)$$

where $f_{h,0,k}$ .is the characteristics embedment strength at a load-to-gain angle $\alpha = 0°$, which is calculated as:

$$f_{h,0,k} = 0.082(1-0.01d)\rho_k \quad (4)$$

where ρ_k is the characteristic timber density at 12% moisture content (in kg/m^3). Since the moisture content of the examined specimens was less than 12%, the specimen density at 12% moisture content ρ_{12}, is obtained as follows:

$$p_{12} = \frac{1.12p}{1+MC} \quad (5)$$

where p is the specimen density, and MC is the respective moisture content of the specimen. The average value for p_{12} for the examined specimens is p_{12m} = 522.3 kg/m^3 (EN:384, 2004). The corresponding 5%- characteristic density value, assuming a normal distribution is p_k= 508.95 kg/m^3. Table *1* presents the characteristic embedment strength for the examined LVL specimens for load-to-grain angles of 0°, 45° and 90°.

Table 1: Average embedment properties for load-to-grain angles of 0°, 45° and 90° (mean ± SD (CoV)).

Number of specimens	Load-to grain angle	Slip modulus K_{emb} *(N/mm)*	Embedment Strength $\sigma_{emb,y}$ *(MPa)*	Ultimate Embedment Strength $\sigma_{emb,u}$ *(MPa)*	Embedment Elastic Modulus E_{emb} *(MPa)*	Characteristic embedment strength (Eurocode5) *(MPa)*
15	0°	38709.78 ± 10415.34 (0.27)	42.20 ± 2.08 (0.05)	43.70 ± 1.67 (0.04)	516.13 ± 138.87 (0.27)	37.56
20	45°	19190.41 ± 3983.23 (0.21)	28.08 ± 3.94 (0.14)	33.14 ± 2.31 (0.07)	255.87 ± 53.11 (0.21)	30.66
15	90°	11772.92 ± 3135.94 (0.27)	24.16 ± 4.91 (0.20)	31.13 ± 3.01 (0.10)	156.97 ± 41.81 (0.27)	25.90

The values of the characteristic embedment strength are obtained by Eurocode 5 follow similar trend with the experimental values as the load-to-grain angle changes. The characteristic embedment strength decreases as the load-to-grain angle increases. For load parallel to grains, the characteristic embedment strength is 11% lower than the respective experimental value. However, for load-to-grain angles of 45° and 90° the characteristic embedment strength overestimates the average experimental values by 9.2% and 7.2% respectively.

CONCLUSION

The embedment strength plays a significant role deciding the structural capacity of timber connections which directly influence the structural integrity of timber structures. This paper focused on the embedment properties of dowel connections in Laminated Veneer Lumber (LVL). The tests were conducted referring to ASTM:D5764‒97a (2007), the half-hole test method was followed on 0°, 45°, and 90° load-to-grain angles using 10 mm steel dowel. In total of 50 specimens were tested to determine the embedment properties, such as slip modulus, embedment elastic modulus, and embedment strength. It is shown that the embedment properties decrease significantly when the load-to-grain angle increases. When subjected to a load parallel to grain the specimens display greater embedment values, yet they exhibit a brittle failure due to splitting parallel to grains. When the load-to-grain angle increases the failure mode is a combination of fibre crushing under the area of the bolt and splitting parallel to the direction of load. The experimental mean values of embedment strength are compared with the respective characteristic embedment strength obtained by Eurocode 5. While the characteristic embedment strength is 11% lower than the mean embedment strength for load parallel to grain, it overestimates the embedment strength by 9.2% and 7.2% for load-to-grain angles of 45°, and 90°, respectively. Further research should be conducted to explore all parameters that effect the embedment strength of LVL members.

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