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UNDERSTANDING THE EFFECT OF LAMINATION THICKNESS VARIATIONS ON BOND INTEGRITY IN CROSS LAMINATED TIMBER (CLT)

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ABSTRACT: Integrity of the adhesive bond is an imperative criterion for qualifying layered engineered wood-based composites (EWP) for structural use. In cross laminated timber (CLT) even moderate variations in lamination thickness within the same layer can significantly affect the pressure distribution at the intersections of laminations, this study aims to address the strict criteria set by the North American CLT product performance standard ANS I/APA PRG320, which are not yet supported by theoretical or experimental data. By employing Digital Image Correlation (DIC) techniques, the goal of this study is to determine the effect of thickness variation in CLT laminations on bond formation and the resulting integrity in CLT lay-up while also addressing a critical knowledge gap regarding the fundamental aspects of cross-laminated panel construction, ultimately providing valuable insights for CLT manufacturers. The specific objectives were to (1) determine the effect of thickness variation in adjacent lamination on pressure transfer and adhesive bond formation between layers (2) measurement of adhesive bond integrity distribution in lab specimens with known thickness variation, (3) determination of structural performance in panels fabricated with lamella of known thickness tolerance. The research expects that CLT with tight thickness tolerance has a better pressure transfer and bond integrity.

KEYWORDS: CLT, Thickness tolerance, bond integrity, clamping pressure, DIC

1 – INTRODUCTION & BACKGROUND

Cross-laminated timber (CLT), first introduced in commercial construction in Germany and Austria in the late 1990s, is a wood-based composite made by gluing together structural grade lumber in alternating grain directions. In 1970, solid wood construction contributed to the building culture of the forested Alpine and European regions, but it did not suit the architectural requirements and development well and it was gradually pushed to the side. Before the eventual breakthrough in 1980s and 1990s with the introduction of cross laminated timber, development trends in solid wood construction were quiet. The need to find a more valuable application for the side boards during the 1990s by the sawmill industry led to the introduction of CLT in the 1990s [1]. The word CLT was first translated into English from the German word "Brettsperrholz" by [2]. The German word "Brettsperrholz" (BSP), however, was initially coined by [3] to designate materials that are mostly used for the solid vertical central plate that connects the top and bottom flanges of a girder while [4] further uses the same word in connection to timber bridge decks. The first translation of the term "Brettsperrholz" into CLT was used to designate products that are used for web of solid girders. Also, [5] in his work, used the term "Brettlagenholz" to portray specific subgroup within the broader classification of "laminar laminated timber products. Interestingly, they are often associated and linked to shells, grid-shells, or three-dimensional spatial grid structure.

Historically, the development and use of laminar laminated timber products began in the 19th century, with notable contributions from Schuchow (1896) and Kalep (1908) [6]. Research in laminated timber products continued in the 1960s and advanced further with Cziesielski (1974) and others. The first residential buildings using solid wood panels as primary load-bearing elements were pioneered by Schuler and Guyer in 1993 [7]. Moser pioneered the first residential buildings reflecting the current state-of-the-art in Germany in 1995, as noted by other authors.

For proper understanding and connection of the concept of CLT, there is a need to journey to uncover the origins of CLT as this takes us through Switzerland, Germany,

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and Austria, where several scientists delve into archives and interview pioneering architects, engineers, and industrial owners. Their investigation reveals how collaboration and innovation transformed surplus timber into a groundbreaking building material.

In Switzerland, the historical development of Cross-Laminated Timber (CLT) began in the early 1990s in Rothenthurm, driven by the need to utilize surplus wood from sawmills. Pioneered by Pius Schuler, the process initially involved producing high-quality veneered wood panels "*Tischlerplatten*" (blockboards), later scaling up to larger laminated building materials [8]. Schuler's innovations included using a band saw to cut glulam beams or single-layer panels and improving the "*Blockholz"* (log wood) process with three-layer cross-laminated panels for enhanced stability and moisture resistance. The advantage of Schuler's method was the reduction in both the number and size of construction and expansion joints, achieving nearly seamless connections with gaps measured in millimeters rather than centimeters. Furthermore, the single-layer member of the Schuler's "massiver laminierter Block" (massive laminated block) bending strength was confirmed in Biel by Heinz Koster and Fritz Maeder (both Schulers academic partners) to be 36MPa, a value that is similar to glulam of high-grade. [8]. Early projects, like the Wiki House, demonstrated CLT's potential for low-cost, sustainable construction, combining industrial efficiency with craftsmanship and influencing the evolution of timber engineering in Switzerland.

German timber engineering, on the other hand, has its share of the journey. In the early 1990s, alongside Schuler's *Blockholz* developments, Karl Moser in Aichach, Germany, was working on creating cross-laminated "*Dickholz"* (thick wood) panels using side boards from local sawmills. Moser, inspired by Kerto laminated veneer lumber (LVL) panels from Finland, used vacuum press technology to laminate these panels [8] [9]. By 1994, Moser successfully produced a prototype, later patenting the vacuum-glued process. The process further witnessed continuous refining, leading to the emergence of innovations like robotic arms for automated cutting and larger vacuum presses for bigger panels. In 1995, Moser's company completed the Aichach Kreisgut Housing project, a major pilot for cross-laminated *Dickholz* panels, demonstrating the potential for wood in multi-story, affordable housing. Despite the panels not being officially approved yet, the project received special approval. [10]. The buildings used a mix of solid cross-laminated *Dickholz* panels for exterior walls and Filigree concrete slabs for floors. This project helped generate interest in large-scale CLT construction and influenced later developments in the field.

In Austria, its contribution to the development of CLT began as that of its Swiss and German counterpart in the early 1990s. when compared to Germany and Switzerland seems uncleared due to limited documented information in the public domain. The Austrian timber industry integrated engineering advancements and sustainability, optimizing CLT from local resources. Close collaboration between researchers and industry drove innovation, establishing Austria as a global CLT leader.

The concept of CLT as a product was developed back in the 1970s – 1980s, but not until 1998 that it received technical approval, which marks a significant milestone sparking a decade of research, development, application, and production between 2000 – 2009 [11].

Its demand as an engineered wood product (EWP) over lumber has increased with the advances in technology and environmental awareness. The distribution of natural wood defects in engineered wood products (EWPs), according to [12], contributes to greater uniformity in their mechanical and physical properties when compared with lumber. Consequently, [13] opined that the structural efficiency of wood frame construction is enhanced, the performance of buildings is improved, and costs are also reduced. CLT can support loads both in and out of plane and is utilized as a floor element, full-size wall, bridge deck, and linear timber parts. According to [14], the principal advantages of utilizing CLT above other conventional engineered wood products (EWP) are increased in-plane compressive strength and stiffness, improved acoustic and thermal performance, and enhanced integrity. Extensive research resulted in creation of design guidelines and product standards [12] [13] [15] [16]. Ever since the first commercial introduction of CLT over the past three decades, the global production volume has continuously witnessed a significant increase [17] [18] [19] with an estimated annual global output of just over 2,000,000 m^3 in 2023. The CLT global output witnessed a thirtheen percent increase accounting for about 2,300,000 m^3 and was estimated to reach 2,800,000 m^3 – 3,400,000 m^3 at the end of 2025 [19] about 90% of the world CLT productions comes from Europe (includes Austria, Germany, Italy, Switzerland and Czechia e.t.c) [19] [20] [21] [22] [23].

In the production of CLT, one of the principal concerns is the integrity and performance of adhesive bonds as it significantly impacts the panel quality and structural application. Since the production of CLT entails gluing together structural grade lumber in perpendicular

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directions to each other, the strength properties of the CLT would be affected by the stress distributed across the adjacent layers of the laminar when used in load-bearing applications.

Bond integrity can be affected by several factors and one of them is clamping pressure, which in CLT may depend on the thickness variation in all layers. The [16] has adopted the world's strictest criteria on the performance of the adhesive bonds and thickness tolerance criteria that requires a 0.20mm threshold for CLT but does not provide much empirical evidence of how they came about it. Thus, necessitates understanding how thickness variations influence bond integrity, and this knowledge would empower manufacturers to produce CLT with acceptable adhesive bonds, fostering wide products acceptances. In a parallel project 3-layer and 5-layer CLT panels of dimension 243.84 cm by 304.8 cm were fabricated in OSU pilot plant with three replicates each. Two panels were used for bending test using [24] and was dissected into blocks after failure. 7.62 cm x 7.62 cm specimens were obtained from the panel and subjected to block shear and cyclic delamination test using PRG320-2019.

The result show widespread delaminations in these panels despite "passing" performance when standard sampling was applied.

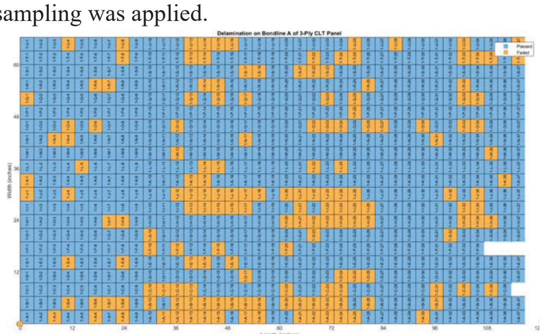

Figure 1: Distribution of specimens failing PRG320-2019 delamination criterion in 3-ply prototype panels with possible sampling areas marked as solid and dashed red rectangles

The hypothesis of this study is that the effect of thickness variation in laminations on local bonding conditions at clamping pressures used in the industry, and consequently on the structural performance of structural panels can be determined empirically. The specific objectives of this study were to (1) determine the effect of thickness variation in adjacent lamination on pressure transfer and adhesive bond formation between layers (2) measurement of adhesive bond integrity distribution in lab specimens with known thickness variation, (3) determination of structural performance in panels fabricated with lamella of known thickness tolerance. This presentation will focus on Objective 1.

3 – MATRIALS & METHODS

The approach in this study involves the use of empirical tests and coupled with numerical modelling. DIC was used to measure the strain displacement.

3.1 – EXPERIMENTAL SETUP

In this study, three boards of white fir (*Abies concolor*) wood with a dimension of 12.7 cm x 243.84 cm were selected. The thickness of each board was measured at 15.24 cm, at both sides along the grain. Then based on the average thickness obtained from both sides of the board, the boards were cut into pieces for three-layered and five-layered CLT, core, and face layers. Three pieces of nominal 2 x 6 lumber were cut into sections and processed into 10.16 cm x 10.16 cm x 3.81 cm blocks for the core layer and 30.48 cm x 10.16 cm in blocks for the longitudinal layer of the scaled-down test layup. The thickness of each block was measured at 6 points along the side along the grain. The left and right sample blocks at the core were kept at the same thickness tolerances, and that of the centre varied. Specimen layups with known thickness tolerances were then subjected to clamping pressure using the Instron universal testing machine (UTM).

3.2 – Digital image correlation (DIC)

The qualitative and quantitative study of the mechanical behavior of materials under certain loading conditions is provided by Digital Image Correlation (DIC). DIC (Correlated Solutions, Columbia, SC, USA) was used to track the deformation of CLT cross-layers under compression load. A subset of 29 and a set size of 1 were used, and a precision value of 3.41×10^{-3} and 1.32×10^{-3} macrostrain was achieved.

A uniform surface with one color cannot be recognized by DIC. All pixels have the same color, and then the same value of gray scale. Hence, the speckled pattern on the CLT layup was created by black spray (Figure 2).

Figure 2. The surface of CLT layup with and without applying black spray.

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The DIC was calibrated before the commencement of the test to enable the system to recognize the target in a couple of different positions. With the camera, DIC software triangulates the camera position accurately and cracks or calculates any lens distortion. The calibration target was focused on both cameras. A metal grit (calibration target or plate) with three reference markers was placed in front of the camera. Several positions for the metal grit were defined (tiled edge on right and left, push back the bottom line of the metal grit push forward the bottom line of metal plate) Figure 3. Shots were taken from each position of the metal grit (twenty shots) for the calibration. The resulted value of calibration was below 0.02 (standard deviation of the residual after model created by triangular camera position; in other words, the residual of the bundle adjustment optimization process used to calibrate a DIC system).

The deformation on the face of the test layup was then measured using optical system based on the digital image correlation (DIC) principle. The test layups were subjected to nominal stress of 1 MPa at ramp rates of 3 mm/min and 4 mm/min for 3-layered and 5-layered dry CLT respectively. Examples of 3-layer setups are shown (Figure 4). The DIC tracks the deformation of CLT cross-layers under compression load. The elastic modulus for individual blocks was calculated using the stress and strain displacement obtained from UTM and DIC.

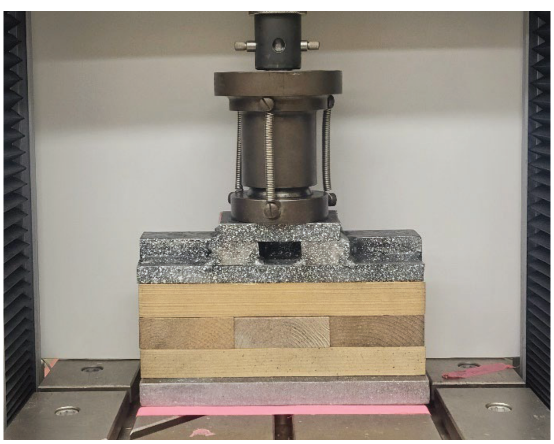

Figure 3: Dry CLT layup under clamping pressure

5 – PRELIMINARY RESULTS

The thickness distribution of the samples is shown in Figure 4. The preliminary results for the vertical displacement map for the transverse dry blocks of 3ply and 5ply CLT layup were presented in Figure 5. The pressure transfer in the transverse blocks of dry CLT layup is presented in Figure 6, while the results for the stress distribution for both 3ply and 5ply CLT are presented in Figure 7. Based on the result from the preliminary study, the outcome of this study is expected to show that thickness tolerance of the three-layered and five-layered CLT layup above 0.20 mm will have a negative impact on the distribution of local pressure across the CLT and bond formation.

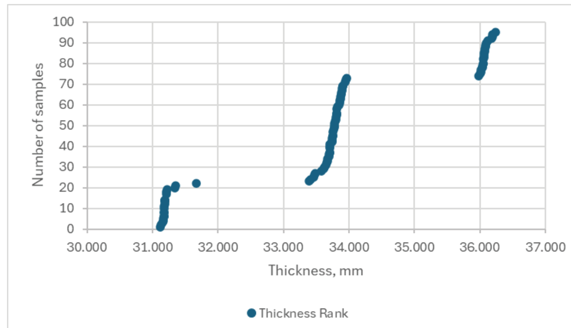

Figure 4: Distribution of sample thickness

As revealed in Figure 4, the average thickness of the samples selected for the lies between 33.00 mm – 34.00 mm. The strain deformation map, as revealed in Figure 5 shows that all three pieces at the core of the 3-ply CLT layup with tight thickness experience equal deformation as there is a better pressure transfer compared to the samples with a 2.00 mm gap thickness variation where the least deformation was observed at the center piece.
In Figure 6, it is observed that pressure was transferred in all the pieces in the dry CLT layup with a tight tolerance, where the centerpieces had the better average stress value of 0.0015 MPa compared to the sample with a 2.00 mm gap thickness, where the centre piece had the lowest average stress value, as there was no visible form of transferred pressure. As revealed, a similar trend was also observed in the 5-ply CLT layup. Furthermore, the average stress distribution, as reported in Figure 7, equally followed a similar pattern for the 3-ply and 5-ply layups; however, it was observed that the first left piece had the highest average stress value. This could be attributed to the difference in stiffness (elastic moduli) of individual pieces. A different average stress distribution trend was observed for the 5-ply CLT layup.

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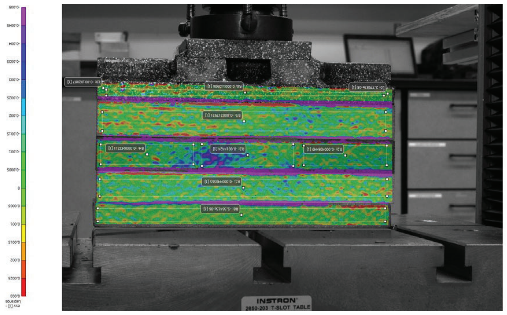

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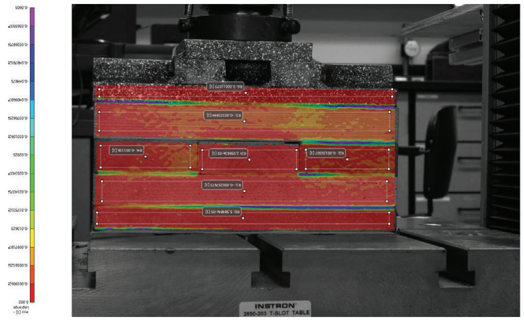

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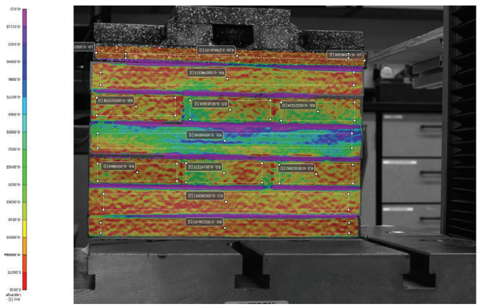

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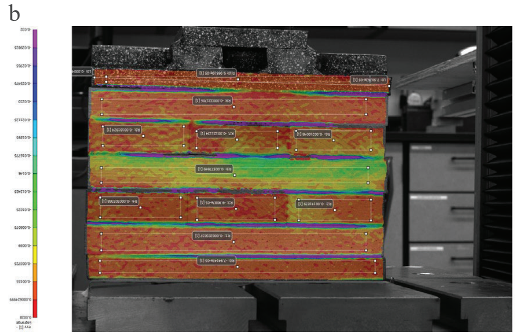

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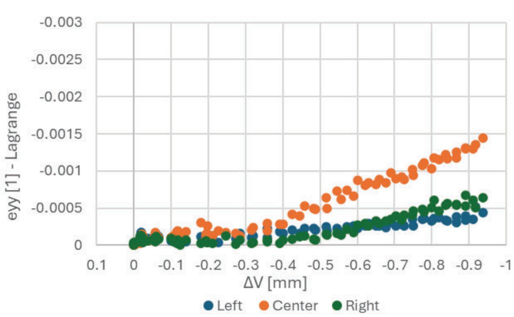
Figure 5: a) and b Vertical displacement map in 3ply CLT with tight thickness tolerance while c) and d) displacement map for 5ply in transverse block of dry CLT layup



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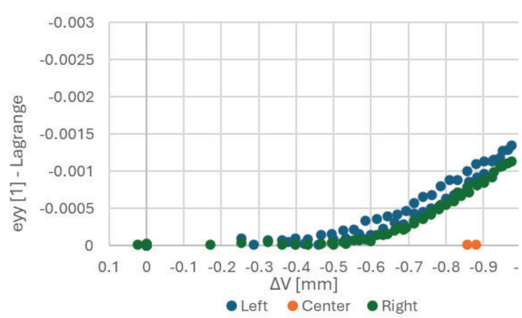

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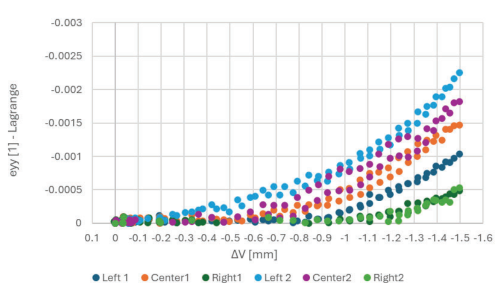

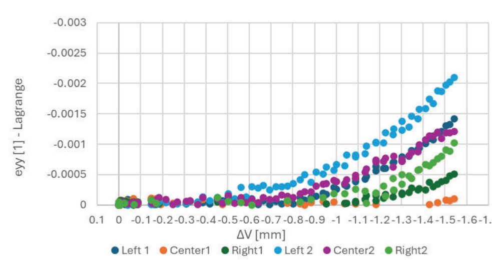

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c

Figure 6: a) average stress in 3Ply CLT with tight thickness b) with 2.0 mm gap c) 5Ply with 0.01 mm thickness tolerance d) with 0.20 mm average displacement

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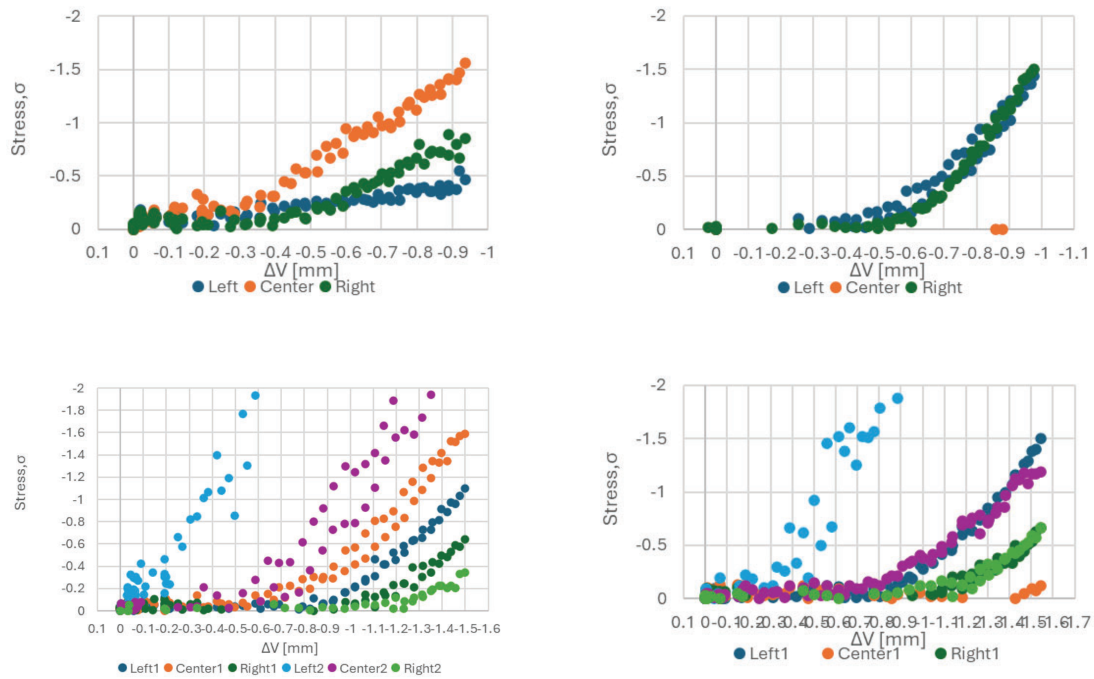

Figure 7: a) and b) average stress distribution of 3Ply CLT with tight thickness and 2.0 mm gap c) and d) average stress distribution of 5ply CLT with 5Ply 0.01 mm and 0.20 mm thickness tolerance

6 – PRELIMINARY CONCLUSIONS

CLT with a tight thickness has better pressure transfer and integrity when compared to CLT with exaggerated gap. The method developed was able to demonstrate that thickness tolerance can influence the pressure distribution in CLT layup.

7 – REFERENCES

[1] Guttmann E (2008) Brettsperrholz: Ein Produktportra¨t [Cross laminated timber: a product profile]. Zuschnitt 31:12–14 (in German)

[2] Schickhofer G, Hasewend B (2000) Solid timber construction: a construction system for residential houses, offices and industrial buildings. In: Ceccotti A, Thelandersson S (eds) Cost Action E5—proceedings of timber frame building systems: Seismic behavior of timber buildings, timber construction in the new millennium, Venice

[3] Droge G, Stoy KH (1981): Grundzu¨ge des neuzeitlichen Holzbaues: Konstruktionselemente, Berechnung und Ausfu¨hrung [Basics of contemporary timber engineering: construction elements, design and execution], vol 1. Ernst & Sohn, Berlin (in German)

[4] Steurer A (1989) Entwurfsgrundlagen und Konstruktionsprinzipien von Holzstegen [Design pronciples and construction pronciples of pedestrian timber bridges]. 21. Fortbildungskurs der Schweizerische Arbeitsgemeinschaft fu¨r Holzforschung (SAH) ‘‘Bru¨cken und Stege aus Holz’’, Zurich (in German)

[5] Lischke N (1985) Zur Anisotropie von Verbundwerkstoffen am Beispiel von Brettlagenholz [Regarding the anisotropy of composite products exemplarily for laminar laminated timber]. VDI, ISBN 978-3181498057 (in German)

[6] Rattasepp T, Mang HA (1989) Zur Stabilita¨t flacher eckgestu¨tzter Hyparschalen aus Holz mit geradlinigen Randtra¨gern [Regarding stability of flat edge supported hyper shells in timber with straight lined edge girders]. Bauingenieur 64:255–266 (in German)

[7] Schickhofer G (1994) Starrer und nachgiebiger Verbund bei geschichteten, fla¨chenhaften Holzstrukturen [Rigid and Flexible Composite Action of Laminated Timber Structures]. Dissertation, Graz University of Technology (in German)

[8] Fleming, P. H. (2021). Genealogy of Cross-Laminated Timber (CLT). In *Cross-Laminated Timber: Pioneering innovation in massive wood*

construction (pp. 15-44). Takenaka Carpentry Tools Museum; ETH Zurich.

[9] Abrahamsen RB (2013) Bergen im Holzbaufieber–der wohl erste 14 Geschosser [Bergen in timber fever—the first 14 story building]. In: 19. Internationales Holzbau-Forum IHF 2013, Garmisch- Partenkirchen (in German)

[10] Karl Moser, (1997) "*Dickholz: die andere Holzbauweise,*" in *Holzbausysteme im Wohnungsbau*, ed. Peter Schreibmayer, (Graz: Technische Universität Graz, 1997), 74‑89.

[11] Schickhofer G, Bogensperger T, Moosbrugger T (eds., 2010) BSPhandbuch: Holz-Massivbauweise in Brettsperrholz—Nachweise auf Basis des neuen europa¨ischen Normenkonzepts [CLThandbook: solid timber construction technique with cross laminated timber—verification based on the new European standardization concept]. Verlag der Technischen Universita¨t Graz, Graz (in German)

[12] Lam, F. (2001). Modern structural wood products. *Progress in structural engineering and materials*, *3*(3), 238-245

[13] Lam, F., & Prion, H. G. (2003). Engineered wood products for structural purposes. *Timber engineering*, 81-102.

[14] He, M., Sun, X., Li, Z., & Feng, W. (2020). Bending, shear, and compressive properties of three-and five-layer cross-laminated timber fabricated with black spruce. *Journal of Wood Science*, *66*(1), 1-17.

[15] Lech Muszynski, Pipiet Larasatie, Jose Erlin Martinez Guerrero, Raquel Albee, Eric N. Hansen1(2020). Global CLT industry in 2020: Growth beyond the Alpine Region Proceedings of the 63rd International Convention of Society of Wood Science and Technology July 12-17, 2020 – Virtual Conference

[16] ANSI/APA (2019). ANSI/APA PRG 320-2018: North American standard for performance-rated cross-laminated timber. Tacoma, W.A: APA-The Engineered Wood Association. 23 pp

[17] Dugmore, M., Nocetti, M., Brunetti, M., Naghizadeh, Z., & Wessels, C. B. (2019). Bonding quality of cross-laminated timber: Evaluation of test methods on Eucalyptus grandis panels. *Construction and Building Materials*, *211*, 217-227.

[18] United Nations, Forest products annual market review 2014-2015. United Nations Economic Commission for Europe (2015). https://issuu.com/unpublications/docs/9789210575607

[19] Lech Muszynski (2024): Chapter 10: The Global Mass TimberPanel Industry 2024 International Mass Timber Report Chapter 10, Pg 252 - 275

[20] G. Schickhofer, Starrer und nachgiebiger verbund bei geschichteten, flächenhaften Holzstrukturen (Ph.D thesis), Graz University of Technology, Austria, 1994. (In German).

[21] R. Brandner, G. Flatscher, A. Ringhofer, G. Schickhofer, A. Thiel, Cross laminated timber (CLT): overview and development, Eur. J. Wood Wood Prod. 74 (2016) 331–351

[22] L. Muszynski, E. Hansen, S. Fernando, G. Schwarzmann, J. Rainer, Insights into the global cross-laminated timber industry, Bio Products Business. 2 (2017) 77–92.

[23] H. Plackner, Brettsperrholz wächst global. https://www.holzkurier.com/schnittholz/2015/02/brettsperrholz_waechstglobal.html, 2015 (last accessed 11/09/2018).

[24] ASTM D4761-19. Standard Test methods for mechanical properties of lumber and wood-based structural materials.

 https://doi.org/10.52202/080513-0039