WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA

Advancing Timber for the Future Built Environment

INFLUENCE OF KNOTS ON STRAIN DISTRIBUTIONS IN GLUED LAMINATED TIMBER BEAMS

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ABSTRACT: Glued laminated timber (GLT) beams are engineered wood products made by gluing finger-jointed timber boards to create structural elements for various construction applications. The mechanical properties of GLT beams depend significantly on the mechanical properties of the timber boards and local defects, such as knots. This paper examines the influence of knots on the mechanical behavior, particularly strain distributions of GLT beams. In total 22 GLT beams, each five meters long, were tested in four-point bending. Strain distributions were measured in the constant bending moment region of the beams using a digital image correlation method. The effects of growth irregularities, finger joints, and particularly knots, as well as their interaction within bonded lamellae, on the longitudinal and transversal strain distributions, were investigated. The results show that knots induce significant strain concentration in longitudinal and transversal directions. Also, the digital image correlation method was found to be suitable for investigating the influence of local defects on the mechanical behavior of large-scale GLT beams.

KEYWORDS: GLT beams, Bending tests, Knots, Strain distributions, Digital image correlation

1 – INTRODUCTION

Glued laminated timber (GLT) beams are engineered wood products extensively used in construction applications. To fabricate the GLT beams, timber boards are strength graded to ensure consistent quality and mechanical properties. The strength-graded timber boards are then joined end-to-end using a finger-jointing technique to manufacture endless lamellae. Once the endless lamellae are fabricated, they are cut to the required length. These lamellae are then layered and bonded with adhesives under controlled pressure to fabricate the GLT beams. After this stage, the GLT beams are planned to achieve their specified dimensions. For a more detailed explanation of the GLT beam fabrication process, it is referred to [1].

Mechanical properties of the GLT beams depend significantly on the mechanical, morphological, and geometrical characteristics of the timber boards used for fabrication [2, 3]. Additionally, the geometrical arrangement of the timber boards, including the placement of local defects such as knots and finger joints (FJs), plays a crucial role in determining the structural performance of the beams [4]. Previous studies have explored the effect of timber board arrangements on the mechanical properties of GLT beams and highlighted the importance of understanding the mechanical behavior of local defects within the GLT beams (e.g., see [5–7]). Among the local defects, knots are distinctively critical as they influence stress distribution, strain concentrations, and load-bearing capacity of the beams. Therefore, to understand the mechanical performance of GLT beams, it is essential to investigate the mechanical behavior of knots, particularly strain distributions, and their interaction within bonded lamellae.

The mechanical behavior of knots has predominantly been investigated on individual timber boards using a digital image correlation (DIC) method. In [8], the effect of knots on strain concentrations in small-scale timber specimens under tensile loading was examined. The study described that knots induce substantial strain concentrations in longitudinal and transversal directions. Previous studies [9, 10] similarly explored the strain distributions around knots in spruce timber specimens subjected to tensile loads and focused on capturing detailed strain fields. They demonstrated that knots are the primary source of strain concentration in timber boards. Moreover, in [11], strain distributions in spruce timber boards under tensile loading were investigated across longitudinal, transversal, and shear directions. The study included various types of knots and examined the interaction effects between multiple knots on strain distributions. In summary, these studies underline that knots significantly disrupt strain distributions in multiple directions and highlight the DIC method as a suitable tool for analyzing the mechanical behavior of timber boards containing knots. However, studies on the influence of the knots on the strain distributions within GLT beams are lacking.

This paper investigates the impact of knots on strain distributions of GLT beams in the longitudinal and transversal directions. The study is a part of the research presented in [4] in which the stiffness properties of FJs within the GLT beams were evaluated using a DIC method.

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https://doi.org/10.52202/080513-0041

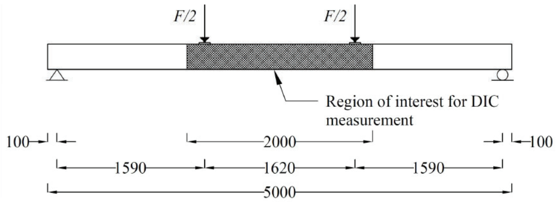

Figure 1: Four-point bending test setup of GLT beams. Dimensions are in mm.

2 – MATERIAL AND METHOD

The experimental investigations were performed on 22 GLT beams with the dimensions of $b \times h \times l = 115 \times 270 \times 5000\ \text{mm}^3$. This section summarizes the fabrication process of the GLT beams, experimental setup, and procedure. For more detailed information about the material and method, see [4].

Spruce timber boards with cross-section dimensions $w \times t = 125 \times 50\ \text{mm}^2$ and lengths between $3800\ \text{mm} < l < 4700\ \text{mm}$ from southern Finland were used to fabricate the GLT beams. The timber boards were scanned using the commercial grading device Finscan [12] to measure the knots' coordinates and dimensions. The grading information of each timber board from the grading device was stored and tracked throughout the GLT beam fabrication process to identify the local material properties within the beams. Based on the knot measurements, a knot parameter (KAR_{10}) was calculated. This parameter represents the ratio of the projected cross-sectional areas of knots within a 10 mm length (overlapping knots were accounted for only once) to the cross-sectional area of the timber board.

The experimental study on GLT beams was conducted in the structural laboratory of the Department of Civil Engineering at Aalto University. The beams were conditioned in a climate chamber at 20°C, with a relative humidity of 65%. Four-point bending tests were performed on the GLT beams according to European standard EN 408 [13]; the test setup is illustrated in Figure 1. The loading protocol was force-controlled with a 10 kN/min loading rate. The loading was continued until the beams failed.

The stereo DIC method was used to measure the strain distributions in the region of interest (with constant bending moments) of the GLT beams, highlighted in Figure 1. A special speckle pattern was applied to the surface of the region of interest. The pattern ensured evenly spaced features of varying shapes within the desired size range, providing consistent information across the entire region of interest. For more detailed information about the pattern features, it is referred to [14].

3 – INFLUENCE OF KNOTS

3.1 GENERAL

The strain distributions in the region of interest within the GLT beams are analyzed in longitudinal and transversal directions. The results show significant variability across the GLT beams due to inherent differences in material properties and lamella arrangements. Figure 2 exemplifies KAR_{10} value map and longitudinal strain (ε_{xx}) distribution for one of the beams. A compilation of the GLT beams' local material properties maps and test results is provided in [4].

Approximately the lower half of the beam experiences tensile stress, while the upper half is under compressive stress, leading to corresponding tensile and compressive strains. Knots experience relatively significant strain concentrations. Strain distribution is most pronounced in the outermost lamellae, where stress levels are highest. Knots in these regions show greater strain concentrations than those in the middle of the height of the beam. In general, it can be seen that areas with notable KAR_{10} values correspond to the area of strain concentrations. This highlights the critical role of knots, particularly in high-stress areas, in influencing the overall strain distribution in GLT beams. However, it can also be seen that not all the knots result in strain concentration due to their visibility on the measurement surface. Because of that and significant variation in knot characteristics such as type, dimension, and location within timber board, statistical methods did not yield meaningful quantitative results between the knot characteristics and strain distributions. Therefore, this paper presents a qualitative investigation of the influence of knots on strain distribution.

3.2 INFLUENCE ON LONGITUDINAL AND TRANSVERSAL STRAIN DISTRIBUTIONS

The study examines the influence of knots on strain distributions, focusing on ε_{xx} and transversal strain (ε_{yy}) in the GLT beams. The investigation specifically considers edge, splay, and narrow side knots due to their visibility on the measurement surface. Knots in the high-stress zones are analyzed to understand their impact. According to the DIC measurements, knots consistently cause strain concentrations compared to the surrounding clear wood, affecting both ε_{xx} and ε_{yy} over the beam height and along the lamellae.

To demonstrate the effect of knots on strain distributions over the beam height, the ε_{xx} in two sections, A-A and B-B, are shown in Figure 3 (left). Both sections are derived from the same timber boards glued in the GLT beam and contain no FJs between them. The sections are 70 mm apart, with Section A-A free of knots or FJs in all the lamellae and Section B-B containing two knots: one in Lamella 2 (tension zone) and the other in Lamella 6 (compression zone).

In Section A-A, the strains are approximately linearly distributed with minor variations. In contrast, Section B-B exhibits significant variation in strain distributions, with strains concentrated in Lamellae 2 and 6 associated with the knots. At a load of $0.8F_u$, in the utmost fibers in tension zones, the strain values are nearly the same in both sections. In compression zones, the maximum strain in Section B-B is nearly twice as high as in Section A-A. These differences become more pronounced at higher load levels.

For the transversal direction, the ε_{yy} over the beam height is demonstrated in Figure 3 (right). In the compression zone, $\varepsilon_{yy} > 0$, indicating expansion, whereas in the tension zone, $\varepsilon_{yy} < 0$, indicating contraction in the lamella. In Section A-A, ε_{yy} distributions are nearly linear with minor variations over the beam height, with maximum strains in the outermost fibers. However, in Section B-B, knots in

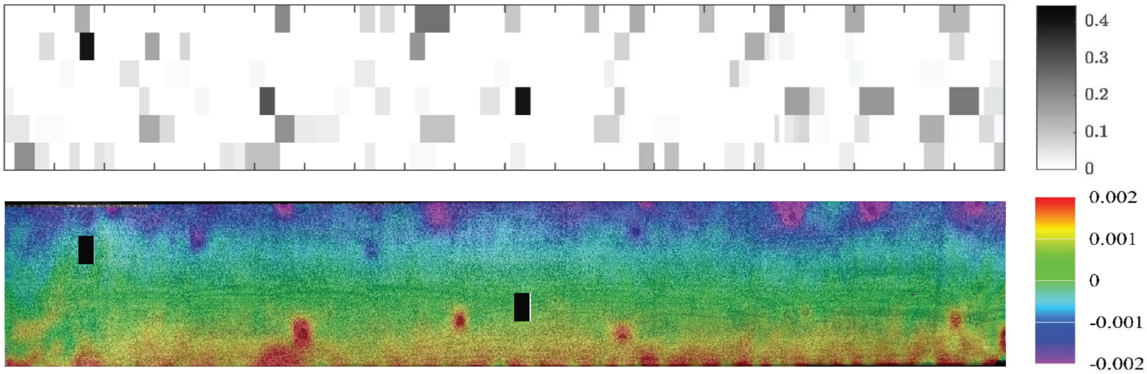

Figure 2: The region of interest in one of the GLT beams. Top: KAR_{10} *values and bottom: longitudinal strain distributions at* $0.6F_u$. *Thick vertical black lines indicate finger joints.*

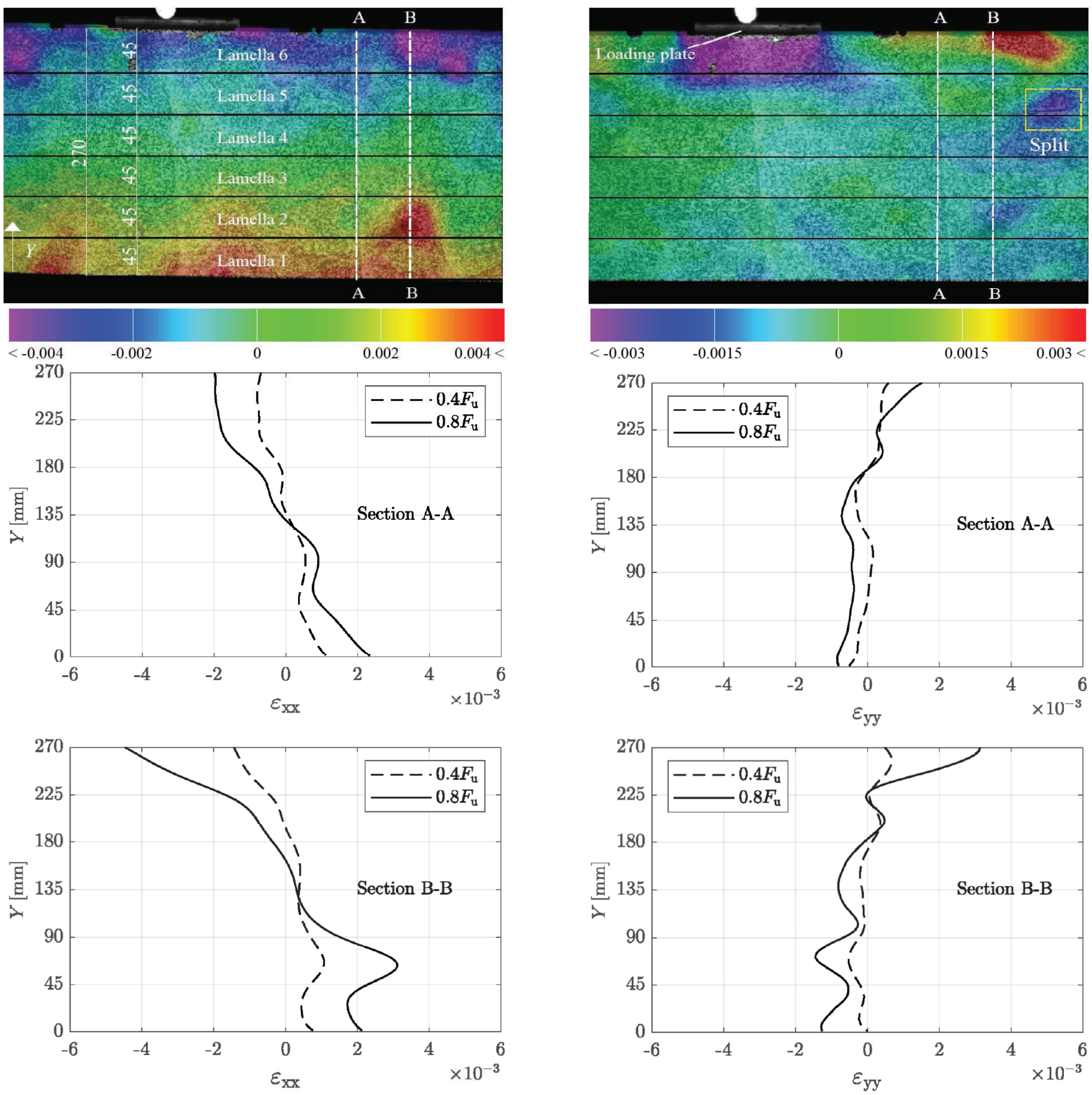

Figure 3: Strain distribution over the beam height of beam no. 1 between the length of 1500-2000 mm*; see [4] for illustration of strains in the whole region of interest of the GLT beam and coordinate of the length. Left: longitudinal strain* (ε_{xx}) *and right: transversal strain* (ε_{yy}). *The DIC measurements indicate strains at* $0.8F_u$.

https://doi.org/10.52202/080513-0041

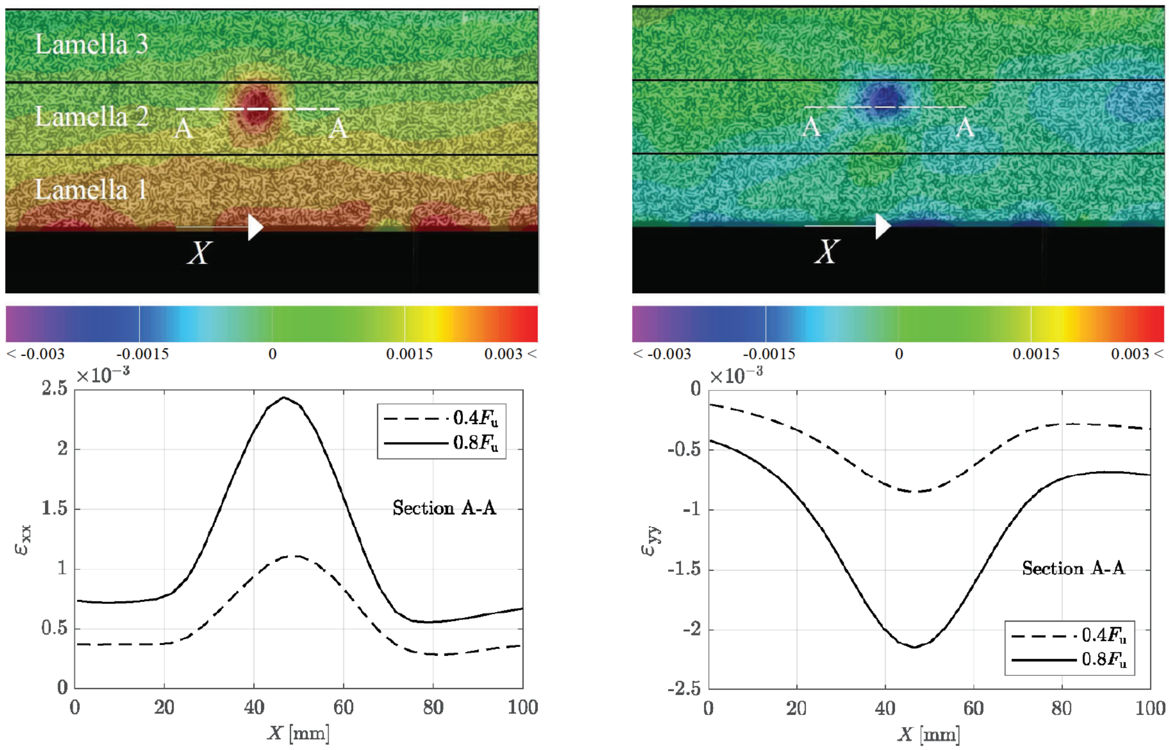

Figure 4: Strain distribution along the lamella and across the knot in beam no. 19 between the length of 2300-2600 mm*; see [4] for illustration of strains in the whole region of interest of the GLT beam and coordinate of the length. Left: longitudinal strain (ε_{xx}) and right: transversal strain (ε_{yy}). The DIC measurements indicate strains at* $0.8F_u$.

Lamellae 2 and 6 cause fluctuations in strain distribution, shifting the locations of maximum strains to these lamellae.

Moreover, a split is identified in Lamella 5 near Section B-B, generating localized ε_{yy} concentrations. However, it does not significantly influence ε_{xx} due to the parallel orientation of the split to the longitudinal direction. Also, under the loading plates, compression strain concentrations are observed in the transversal direction; see Figure 3 (right).

Knots also influence strain distributions along the lamellae for both ε_{xx} and ε_{yy} distributions, as demonstrated in Figure 4. The figure shows the strain distribution around a single knot and clear wood regions. In tension zones $\varepsilon_{xx} > 0$ indicating elongation in longitudinal direction and $\varepsilon_{yy} < 0$ standing on contraction in transversal direction in the knot area. While in compression zones being $\varepsilon_{xx} < 0$ and $\varepsilon_{yy} > 0$ indicate compression and expansion in longitudinal and transversal directions accordingly. In all cases, maximum strains occur at the knot area, while regions before and after the knot show uniform strain distributions with smaller magnitudes.

3.3 INFLUENCE ON ADJACENT LAMELLAE

The strain concentrations due to the knots in specific lamella may also cause significant variations in strain distributions in neighboring lamellae. The effect on the strain distribution in the neighboring lamellae depends on the knot's size relative to the lamella thickness, its proximity to adjacent lamellae, and the local properties of the surrounding material. Larger knots tend to have a more significant influence, particularly near the edges of adjacent lamellae. Furthermore, structural features such as FJs or pre-existing defects in neighboring lamellae can amplify the strain distribution. The strain distributions around single knots are illustrated in more detail in three examples:

- Knot in the outmost lamella (Lamella 1) in the tension zone (Figure 5 Section A). The knot's major diameter is 13 mm, and the distance from the center of the knot to the outer edge and the edge of the Lamella 2 is 15 mm and 30 mm, respectively.
- Knot in the compression zone (Lamella 5) shown in Figure 5 Section B. The major diameter is 20 mm, and the distance between the center of the knot and the edges of Lamella 4 and 6 are 34 mm and 11 mm, respectively.
- Knot in the tension zone (Lamella 1) located under an FJ shown in Figure 5 Section C. The major diameter is 20 mm, and the distance between the center of the knot to the outer edge and the edge of Lamella 2 are 43 and 2 mm, respectively.

In Section A, the strain concentration mostly happens in Lamella 1. It is slightly distributed to Lamella 2 due to the knot's relatively small diameter compared to the lamella's thickness and the distance to the edge of the two lamellae. In Section B, a knot with a larger diameter is located in the compression zone near the edge of the two lamellae. The strain concentration is distributed to the neighbor lamella. In Section C, the knot in Lamella 1 is under the

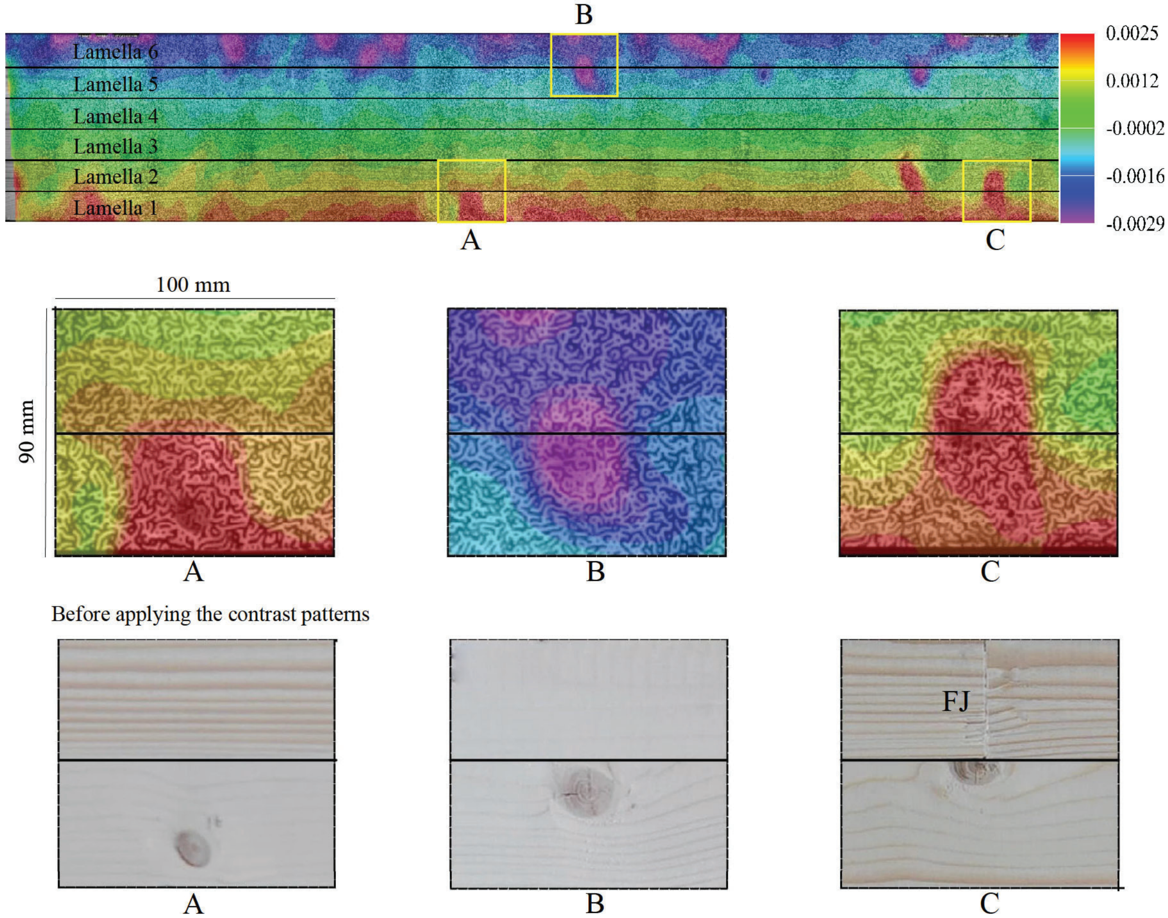

Figure 5: Longitudinal strain distribution in the region of interest in beam no. 10. FJ stands on the finger joint, and the horizontal black lines show the edge of each lamella.

FJ in Lamella 2. This causes a significant strain concentration in the neighbor lamella. Overall, knots in high-stressed zones, such as those in tension or compression zones or near structural irregularities, exhibit pronounced strain concentrations and may contribute to strain concentration across adjacent lamellae. This understanding is critical for assessing the mechanical performance and durability of GLT beams in engineering applications.

4 – CONCLUSION AND OUTLOOK

This paper investigates the influence of the knots on strain distributions within the GLT beams. For the investigation, 22 GLT beams in structural scale were tested under a four-point bending setup. The strain distributions were measured in the region with constant bending moment using the DIC method.

Knots induced strain concentrations in longitudinal and transversal directions. The strain concentration fluctuates the strain distribution over the beam height and along the lamellae. As a result, the maximum strains may happen in the location of the knots. Depending on the size of the knot relative to the lamellae thickness, proximity to the adjacent lamellae, and local defect in the adjacent lamellae, the strain concentrations due to the knots can be extended to the adjacent lamellae.

The DIC method is suitable for measuring strain and investigating the influence of the knots within the GLT beams. The method can be used to investigate the influence of knots and local defects on the mechanical behavior of large-scale GLT beams.

The findings of this study provide a basis for optimizing the arrangement of lamellae in the GLT beams by considering strain concentration effects and the impact of local defects on overall mechanical properties. Combined with previous research (e.g., [4, 15, 16]), these results can be used to develop more reliable GLT beams regarding mechanical properties.

ACKNOWLEDGEMENT

This research has been conducted with funding from the Research Council of Finland (previously known as the Academy of Finland) with decision no. 13334004. The authors thank Versowood Group Oy and MiCROTEC Innovating Wood Oy in Espoo companies for their support and cooperation during specimen fabrication and transportation.

https://doi.org/10.52202/080513-0041

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