Experimental Study of Shear Resistance and Failure Behavior of Reinforced and Un-reinforced Notched Cross-Laminated Timber Plates

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Abstract

This thesis presents a comprehensive experimental investigation aimed at gaining a deeper understanding of the shear resistance and failure modes of un-reinforced and reinforced notched Cross-Laminated Timber (CLT) plates. It addresses the limited availability of experimental data on notched CLT by exploring the structural behavior of notched CLT plates with and without reinforcement. A total of 174 CLT plates with various notches and reinforcement using self-tapping screws (STS) were tested in bending in both major and minor strength directions. Un-notched CLT beams under bending primarily failed in rolling shear in the transverse layers. Notches influenced not only the failure mode but also shear resistance and crack propagation. STS effectively increased the shear resistance of notched plates, with inclined screws showing slightly higher resistance compared to vertical screws. By reinforcing the notches located within the lowest transverse layer in CLTs oriented in minor strength direction, shear resistance of the corresponding un-notched plates could be attained. However, for notch ratios above 35% in those CLTs, only approximately half of the un-notched plates' shear resistance could be achieved by reinforcement. The findings offer insights for engineers involved in designing notched and reinforced CLT plates and can contribute towards developing future design guidelines for notched CLT plates.

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Acknowledgments

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Dedication

To "Iliya" and "Sophia", my heart walking outside my body.

1. Introduction

1.1. Mass-Timber Construction

The increasing focus on sustainability and the optimization of resource efficiency has revitalized the enthusiasm for utilizing timber as a construction material in commercial and multistory buildings [1–3]. This renewed interest is supported by the significant progress made in the development of high-quality and high-performance laminated timber composite products, including Cross Laminated Timber (CLT), Glued-Laminated Timber (Glulam), and Laminated-Veneer Lumber (LVL). These Engineered Wood Products (EWPs) provide architects and engineers with enhanced design possibilities, greater load-carrying capacity, improved dimensional stability, and superior fire protection compared to conventional lumber or solid timber options [7,10–12]. These advancements signify the growing recognition of mass timber as a sustainable and safe alternative for taller structures, thereby expanding the possibilities for timber construction in the built environment.

CLT has become increasingly favored within the realm of mass timber products due to its exceptional versatility. It offers flexible usage options, serving as a viable option for specific components such as floor and wall elements in timber or hybrid structures, as well as being suitable for constructing entire buildings [7–11]. The development of CLT handbooks [12] and their inclusion in building codes have contributed to its popularity.

Composed of kiln-dried lumber elements glued together in alternating directions using structural adhesives, CLT forms a solid panel with multiple wood layers [1,13]. While there are similarities in the manufacturing processes, it is important to note that CLT differs significantly from Glulam or LVL. Unlike LVL and Glulam, where the orientation of grain remains parallel across their layers, CLT possesses a heterogeneous structure characterized by alternating layers with grain orientation of 0^o (longitudinal layer) and 90^o (transverse layer). This heterogeneity gives rise to two notable consequences. Firstly, it introduces new failure modes, dependent on whether the failure takes place within a longitudinal or transverse layer. Secondly, variations of moisture or temperature levels in CLT result in the development of residual stresses due to the mismatch of moisture or thermal expansion characteristics of individual layers [14,15] and adhesive bonding timber layers [16].

1.2. Notches in mass timber products

Notches in timber and laminated timber composite members pose significant challenges and a major risk of failure due to crack initiation and subsequent growth, starting from the notched corner. Timber's low strength in tension perpendicular to the grain and shear exacerbates the problem, making notched members susceptible to brittle failure.

In structural design, it is advisable to avoid notches or approach them cautiously due to the sudden and unpredictable failure of notched beams without noticeable deformations prior to failure. However, notches become necessary in certain situations, such as limitations in construction height, member intersections, and joint details.

The shear resistance of notched members is influenced by various factors, including material properties, geometric parameters, and environmental conditions. Numerous studies have been carried out in the literature to gain a comprehensive understanding of the characteristics exhibited by notched timber and Glulam structural members. These investigations have yielded significant knowledge, providing valuable insights for the development of design guidelines and code provisions. As a result, the existing wood design codes such as Canadian (CSA O86-19) [17], European (EC5, 2004) [18], Australian (AS 1720, 2010) [19], and American (NDS, 2018) [20] standards now include specific design provisions for notched solid timber and Glulam beams.

1.3. Research Need

Previous studies on notched members, as reviewed in detail in Chapter 2, have focused on notches in solid timber and Glulam members. However, there has been comparatively limited investigation in the literature concerning the impact of notches on CLT members. Wood design codes such as Canadian (CSA O86-19) [17], European (EC5, 2004)[18], Australian (AS 1720, 2010) [19], and American (NDS, 2018) [20] standards, do not yet provide any design provisions for notched CLT. While the European Technical Assessment (ETA) [21] and the German CLT handbook [22] do offer some guidance for notched CLTs based on the provisions for notched solid timber and Glulam beams in EC5 [23,24], it is essential to explore the effect of notches on CLT members further to ensure their safe and reliable use in construction applications.

The currently available experimental data on notched CLT in literature are limited, necessitating further testing to advance our knowledge and provide valuable insights for the development of standards and guidelines in this field. This research will address these existing knowledge gaps. In particular, the focus of this thesis will be on the relatively unexplored area of reinforced notched CLT plates. This research needs are crucial in ensuring the safe and optimal use of CLT, as its unique properties and behavior require specialized investigation to promote its sustainable and efficient application in mass timber constructions.

The available experimental data on notched CLT is quite limited, and further testing seems necessary to advance our knowledge on the behaviour of such plates and provide insights for developing standards and guidelines in this area.

1.4. Research Objectives

The primary objective of this study is to gain a deeper understanding of the shear resistance and failure modes of both un-reinforced and reinforced notched CLT plates. For this purpose, a comprehensive experimental investigation is designed and conducted at the University of Northern British Columbia, Wood Innovation Research Laboratory (WIRL) in Prince George, Canada.

The secondary objectives of this study are:

i. to conduct a comprehensive literature review on notched laminated timber products to highlight research gaps in the area of notched CLT plates.

ii. to run an experimental campaign on two notched CLT products; un-reinforced and reinforced CLT plates are considered.

iii. to explore the effect of different notch characteristics and the layer types in which the notch is located on the failure mode and shear resistance of CLT members with notches. A particular emphasis is given to exploring the relatively unexplored area of reinforced notched CLT plates. The shear resistances are evaluated statistically by conducting a statistical analysis.

iv. to investigate reinforcing notched CLT plates using STS and their effect on their shear resistance and failure modes. Special attention is given to examining reinforced notched CLT plates oriented in the minor strength direction, an area that lacks sufficient testing data at the time of writing this thesis.

v. to assess the available design equations provided in ETA [21] and WN-Handbook [22] for notched CLT, using the experimental results obtained from this study.

By addressing these objectives, this research will contribute valuable insights to the field of timber engineering, enabling designers and practitioners to make more informed decisions when working with notched CLT plates.

1.5. Thesis Overview

In Chapter 2, a comprehensive presentation of the state-of-the-art in notched timber and laminated timber composite beams is provided. A review of experimental, analytical, and numerical studies on notched solid timber, Glulam, and CLT beams is also conducted and presented. Furthermore, the research on reinforcing these notched beams is presented, providing valuable insights for enhancing their structural capabilities. Finally, a concise summary of the current design approaches applied to these structural members is presented. To better understand the behaviour of un-reinforced and reinforced notched CLT, an experimental campaign was conducted. The experimental campaign and its results are presented in Chapter 3. The shear resistance and failure modes of a range of notched CLT plates are determined and compared. In Chapter 4, a summary of the work is presented.

1.6. Scope and limitations

The scope of this thesis is focused on the shear resistance and failure modes of both un-reinforced and reinforced notched CLT plates. The study is based on a comprehensive experimental investigation conducted at the University of Northern British Columbia, Wood Innovation Research Laboratory (WIRL) in Prince George, Canada. However, it is important to acknowledge the limitations and constraints of the research:

i. Experimental Scope: The experimental campaign is conducted on specific types of CLT panels. Different CLT manufacturers may use various adhesives, timber species, and production methods that could influence the behavior of notched CLT plates.

ii. Sample Size: Due to practical constraints and resource limitations, the number of specimens used in the experimental investigation is limited. While statistical analyses are performed to evaluate the shear resistance, a larger sample size could further enhance the reliability of the findings.

iii. Reinforcement Types: The study focuses on examining the effect of reinforcing notched CLT plates using STS. Other potential reinforcement methods or materials might not be explored, leaving room for further research in this area.

iv. Notch Characteristics: While the study aims to explore different notch characteristics and their effect on failure modes and shear resistance, it may not cover the entire spectrum of possible notch configurations and locations. Some unique notch geometries or various locations within the CLT layers might be left unexplored.

2. Literature Review

2.1. Notches in Solid Timber and Laminated Timber Composite Members

Notches pose a significant risk of failure due to crack initiation and subsequent crack growth starting from the notched corner. This crack formation leads to the division between the lower and upper sections of a timber or laminated timber composite beam, reducing its effective height and causing unfavorable visual aspects, along with potential failure in the reduced cross-sectional area [25]. The increase of tensile stress acting perpendicular to the grain and shear stress at the notched corner contributes to the stress concentration, similar to stress singularity around sharp cracks [25,26]. When a crack experiences pure tensile stress perpendicular to the grain, its stress state is identified as fracture mode 1. Fracture mode 2 pertains to loading induced by shear stresses. A mixed-mode fracture takes place at the notch due to stress concentrations caused by tensile stress perpendicular to the grain as well as shear stress [27]. Timber's low strength in tensile across the grain and shear, along with the concentration of these stresses, significantly diminishes the notched beams' shear resistance. As a consequence, notched timber or laminated timber composite members are prone to brittle failure.

A typical notched beam with a rectangular cross-section with a width of b and a depth of d, is shown in Figure 1. In this figure, d_n, d_{ef}, and i are the notch depth, effective depth, and notch inclination, respectively. The notch length, e, is defined as the horizontal distance from the support to the notched corner.

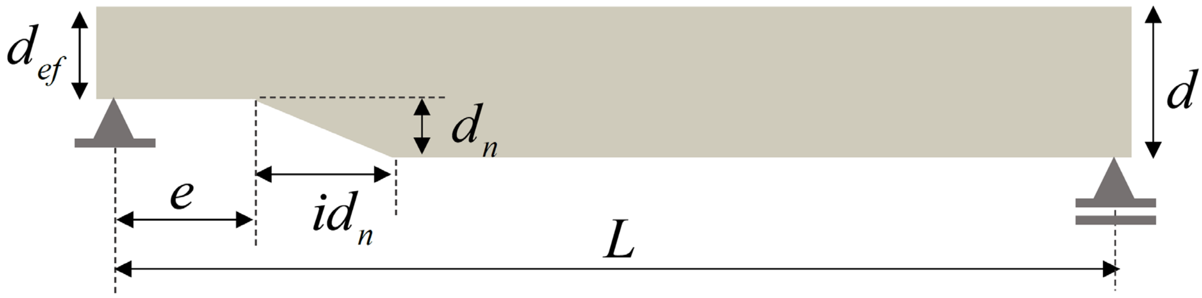


Figure 1: Schematic of a typical notched beam.

In design, it is advisable to avoid notches or approach them cautiously, as the failure of beams with notches can occur suddenly, without noticeable deformations prior to failure. However, notches become necessary in some situations, such as limitations in construction height, structural element stabilization, joint details, or member intersections [25]. The design of notches requires careful attention to the notable reduction in shear resistance, the presence of stress concentrations, and the risk of brittle failure. If it is not feasible to avoid notches, reinforcement often becomes essential.

Various factors, including material, geometric, and environmental parameters, significantly influence the shear resistance of notched beams. To begin with, due to the non-uniform concentration of stresses at a notched corner, common strength properties are rendered inadequate for reliable assessment. Consequently, it becomes crucial to incorporate the fracture energies associated with both modes 1 and 2 to accurately evaluate the material's resistance [26–29]. Furthermore, the notch ratio, determined by the depth of the cutting, plays a crucial role in reducing the shear resistance. The notch's location on the beam affects the ratio between shear force and bending moment, while the notch length ratio considers this effect. The implementation of rounded and tapered notch corners facilitates a smoother transition in the cross-section, effectively mitigating stress concentration [28–31]. Moreover, moisture content variations introduce internal stresses, making notched beams prone to moisture-induced failure [15,25]. Thus, the design of notched timber members should account for these parameters to mitigate stress concentration and minimize the risk of failure.

Notches in solid timber and laminated timber composite structural members have been the subject of design considerations and extensive research due to their significant influence on these members' shear resistance. In the following sub-sections, the research on notched solid timber, Glulam, and CLT in the literature are reviewed, respectively.

2.1.1. Notches in Solid Timber

Gustafsson [29] studied the short-term strength of timber beams that were notched with a rectangular shape on the tension side. A closed-form equation to calculate the strength of the notch was developed by employing fracture mechanics, demonstrating good agreement with test results and offering valuable insights for design equation development. The research highlighted the influence of size, material's modulus of elasticity (MOE), shear modulus, and fracture energy on notch strength. It also showed the significance of the distance between the notch tip and the support in determining notch strength. A comparison of test results regarding the failure of end-notched timber beams and design equation predictions was conducted by Smith et al. in [28]. The study focused on Gustafsson's formula [29] and its applicability in structural design codes. Smith et al. [31] discussed the development of design guidelines for preventing brittle failure of end-notched solid timber beams. By combining linear elastic fracture mechanics (LEFM), concepts of structural reliability, and material property data, precise equations to restrict the reaction force in members with notches on either the tension or compression side were determined. The factored reaction force resistance depends on the factors such as the beam's depth and the size and geometry of the notch when located on the tension face. For notches on the compression face, the resistance was based on the factored shear resistance of the residual cross-section. Based on fracture mechanics principles and the concepts of structural reliability, the proposed design formulations provided calculations of resistances considering the depth of the beam, the geometry of the notch, and the service conditions.

A comprehensive review of the impact of notches on the timber members' capacity has been provided by Jockwer et al. [32]. This study highlighted the limitations of existing design approaches based on small specimen tests and emphasized the need for further research on larger beam specimens to account for size effects. The article also addressed the variability in material strength parameters and design approaches among different codes and standards. It concluded by suggesting the necessity of developing reliable design approaches and material strength parameters validated by experimental data, with the aim of simplifying the existing complex design processes.

Jockwer [25] highlighted that notches cause a significant reduction in the timber beams' capacity because of the concentration of stresses and the brittle failure mechanisms of timber. It emphasized the need to avoid notches or reinforce them if necessary. The research reviewed different design approaches and material properties, indicating a weak experimental basis for practical beam dimensions (size effect). The influence of knots on notch fracture was analyzed, and a sensitivity analysis revealed the significant impact of fracture energy.

Navaratnam et al. [33] studied the strength properties of notched timber girders in colonial bridges in Australia to ensure structural safety. Experimental tests were conducted on notched rectangular timber girder samples, and finite element (FE) models were developed and validated. The models were then used to predict the flexural and shear strengths of rectangular and circular timber girders with different spans, notch angles, and depths. The results showed that increasing the notch depth reduced the capacity of rectangular girders more significantly than circular girders, and changing the notch angle increased the capacity of both types of girders. The study also compared different design standards and found that some had limitations in accurately predicting the behavior of notched timber sections.

2.1.2. Notches in Glulam

Gustafsson et al. [26] examined the strength of notched members constructed from LVL and Glulam in the long-term loading condition. The beams were subjected to different sizes and conditions, including moisture sealing at the notch. Tests conducted in different climates and humidity conditions revealed that transient moisture variations had a significant impact on the short-term and long-term strength of beams without moisture sealing, while the magnitude of humidity had minimal influence if kept constant. Reduction factors for six months of loading were evaluated, showing average reductions in ultimate failure strength ranging from 0.68 to 0.81, depending on beam size and moisture sealing. The study highlighted the importance of considering moisture fluctuations and the choice of modification factors in designing crack initiation and load capacity.

Weckendorf et al. [30] reported tests conducted on softwood structural Glulam beams with end notches on the tension side to calibrate a LEFM design method for bending members. The findings indicated that despite damage from notches, the members did not fail completely due to splitting and still had sufficient residual material to support additional loads.

The damage progression involved stable crack growth near the notches, followed by episodic crack growth. It was observed that loads positioned near the end support significantly influenced the strengths of members with notches, highlighting the need to consider their presence when estimating shear forces. The results successfully supported the application of LEFM in predicting the shear capacities of notched Glulam members, leading to their implementation in the 2014 edition of the Standard CSA-O86 [34].

Malek et al. [35] developed a 3D FE model in ANSYS© software to evaluate the stress distribution in Glulam beams with longitudinal and transverse end notches. They compared the numerically predicted load-carrying capacities of the notched beams with those determined through design equations outlined in the codes and existing test data. They also used the validated model to perform a comprehensive analysis of the impact of rounded notched corners and longitudinal notches on the stress fields of Glulam beams.

2.1.3. Notches in CLT

Notches in CLT members are commonly employed for half-and-half joint connections between CLT plates and supports. Similar to other laminated timber products, cracks in notched CLT may develop due to localized concentration of tensile stress perpendicular to the grain and shear, which, depending on the orientation of the layers, lead to longitudinal or rolling shear stresses.

Flaig et al. [36] presented a two-part approach to developing design guides for CLT with notches and holes. The first phase involved FE calculations to determine shear stress in various CLT walls, which were then utilized to develop stress concentration factors for practical design purposes. The second phase included conducting tests on single crossing areas and performing bending tests on CLT walls with notches and holes to determine internal stresses, failure modes, and their capacity. The findings highlighted the importance of accurately calculating shear stresses and understanding the interaction of various components of stress for a reliable and economical design of CLT members.

Serrano et al. [37] focused on the design of notched CLT plates and compared it with the design approach for solid timber plates outlined in Eurocode 5 (EC5) [2]. The study investigated the load-carrying capacity of notched CLT members through analytical and numerical calculations as well as experimental evidence. Their findings indicated that the design formulations provided in EC5 for solid timber members with notches were generally not applicable to notched CLT. This study also emphasized the importance of excluding outer transverse layers at the notch when defining the effective member depth. Serrano et al. [38] presented new test results and numerical findings that complement previous research [37]. It was shown that the current design provisions of EC5 for notched solid timber members could yield unrealistic outcomes, making it unsuitable for inclusion in design codes.

Malagic et al. [39] proposed a new analytical approach, the Beam on Elastic Foundation (BEF), to analyze CLT notches, and they verified it with test results. The conclusions drawn from the research included the effectiveness of the Structural Element Model [37,38], the overestimation of load-carrying capacity by the Virtual Crack Closing Technique (VCCT) approach, and the inadequacy of the models given in the European Technical Assessment (ETA) [40] and the WN CLT handbook [22].

Nairn [15] derived analytical predictions for delamination in notched CLT plates using fracture mechanics theory. The analysis took into account the heterogeneity of CLT and residual stresses resulting from temperature and humidity changes. By comparing the predictions to FE analysis and experimental results, Nairn [15] found that residual stress effects were considerable and dependent on the size of the notch. The calculations emphasized the importance of accounting for residual stresses in notch failure and suggested strategies to mitigate these effects.

2.2. Reinforcing Notched beams

2.2.1. Overview

In order to prevent timber beam failure resulting from excessive crack growth, low shear and tension resistance perpendicular to the grain, and brittle failure mechanisms, it is essential to reinforce notched members [25]. This reinforcement aims to enhance the capacity while minimizing the risk of brittle failure in members with notches. It is imperative to employ appropriate reinforcement methods and accurate design strategies to attain the desired outcome. In [19], a comprehensive examination of the design aspects of reinforced notches was undertaken, followed by a detailed analysis of the failure mechanisms. The study emphasized the importance of accounting for mixed-mode fracture at the notched corner when reinforcing beams. It was mentioned that this reinforcement should effectively carry loads from perpendicular tensile stresses and shear stresses.

Various available methods to strengthen notched beams in situations involving high tension perpendicular to the grain, shear stresses, and the risk of fracture were summarized in [19]. The reinforcement process can be categorized as either internal or external. According to the German national annex of EC5, DIN EN 1995-1-1/NA (2013) [41], internal reinforcement options include the use of glued-in threaded rods or ribbed concrete reinforcement bars, screwed-in threaded rods, and fully threaded screws [19]. On the other hand, external reinforcement methods encompass adhered plywood or LVL, adhered lamellas of solid timber, and pressed-in punched metal plate fasteners. In some specific applications, carbon fiber reinforcement (CFR) or glass fiber reinforcement (GFR) may be employed [19].

Oudjene et al. [42] introduced an efficient numerical approach for modeling woodscrews as reinforcement for timber structures and joints, drawing inspiration from steel reinforcement in concrete structures. The effectiveness of the approach was validated through experiments conducted on notched reinforced beams, which show a satisfactory level of agreement. The model was coupled with cohesive zone modeling to simulate progressive failure within the notch detail. Furthermore, the approach was applicable to inclined screws and large-scale applications with a substantial number of screws. Through a hybrid approach combining experimental and numerical modeling, the paper demonstrated the good correlation between three-point bending tests on both un-reinforced and reinforced notched beams and the corresponding numerically predicted values, highlighting the effectiveness and efficiency of the presented numerical approach in timber reinforcement using screws.

Fawwas et al. [43] focused on investigating the structural behavior of notched Glulam beams reinforced with adhered plywood panels and FRP. The main objective was to determine the shear resistance of these beams at their ends. Experimental tests using three-point bending were conducted on various configurations of reinforced notched Glulam beams. The results revealed that the reinforcement increased the shear resistance by approximately two and a half times compared to un-reinforced beams. The study recommended plywood reinforcement due to its cost-effectiveness and environmental friendliness, and it found that the diagonal configuration exhibited higher strength than the vertical configuration.

Todorović et al. [44] presented an experimental study on end-notched Glulam beams' bending behavior and subsequent repair using glass fiber-reinforced polymer (GFRP) bars. The initial tests revealed that the beams failed in a brittle manner due to crack propagation resulting from excessive tensile and shear stresses. However, repairing the beams with GFRP bars successfully restored and significantly improved their shear resistance by an average increase of 194%. The failure mechanism changed from brittle tensile failure to a more ductile bending failure after repair. The study highlighted the potential of using advanced materials like GFRP bars to repair existing structures, providing insights for further investigation and the development of design models for reinforced and repaired timber members with notches.

Todorović et al. [45] discussed the effect of notches on the load-carrying capacity of timber beams and proposed reinforcement using GFRP bars. The study employed a numerical analysis using the Abaqus software, incorporating Cohesive Zone Modelling (CZM) to simulate crack growth. The model was verified through comparison with experimental results, demonstrating good agreement. The findings indicated that while initial cracking at the notched corner cannot be prevented, the use of GFRP bars restricted uncontrolled crack growth, leading to increased load-carrying capacity and deformability of the beams. The presented models served as a foundation for further parametric analyses, exploration of different reinforcement types and positions, and the development of analytical design methods for reinforced notched timber elements.

Todorović et al. [46] presented an extensive experimental study on the reinforcement of end-notched Glulam beams using GFRP bars. Bending tests were conducted on both un-reinforced and reinforced beams, and the behavior of the beams was analyzed through load-deflection diagrams, failure modes, and ultimate loads. The results demonstrated the effectiveness of GFRP bars in improving the load-carrying capacity and deformability of end-notched Glulam beams. The study also compared the experimental results with design procedures based on Eurocode 5 [18] and the German national annex [41], highlighting the need for adjustments in the design approaches.

2.2.2. Reinforcement with Self-Tapping Screw

Self-tapping screws (STS) are a cost-efficient and time-saving option for use as reinforcement, as they eliminate the need for pre-drilling. With hardened continuous threads, these screws offer high strength in terms of yield moment, tensile, and torsional resistance. Their cutting thread and surface coating are designed to facilitate easy assembly without the need for pre-drilling. STS are particularly popular in mass timber construction, mainly because of their straightforward installation process and superior withdrawal resistance, offering a robust mechanical connection that reinforces timber and reduces splitting [47]. Furthermore, they enhance the connection capacity in the direction perpendicular to the grain and provide a failure mode with greater ductility. Extensive research has been conducted on factors such as screw parameters, connection parameters, and environmental conditions to formulate design equations pertaining to the pull-out strength of STS, with design approaches available in EN 1995-1-1 [48], supplemented by product-specific approvals [47,49–53].

Tran et al. [54] studied reinforcing timber structures using STS, considering the anisotropic nature of timber. Experimental and numerical studies were conducted on notched timber beams. The results demonstrated that screw reinforcement significantly improved the strength of the notched beams, showing a 34% gain compared to un-reinforced beams.

Todorović et al., in the experimental study [55], investigated the use of screws as reinforcement for end-notched Glulam beams. The results demonstrated that un-reinforced beams experienced brittle failure due to stress concentration at the notched corner, while reinforced beams exhibited delayed failure and increased deformability and capacity. They emphasized the importance of using high-strength and stiffness reinforcement screws and recommended the use of STS for improved anchorage.

Malagic et al. [39] investigated the behavior of CLT specimens oriented in the major strength direction with notches reinforced by STS. The results showed a notable increase in failure load compared to un-reinforced notches, indicating that the reinforcement improved load-carrying capacity and crack growth stability after the initial crack formation. The failure mode of the reinforced notches was identified as screw withdrawal failure, with subsequent unstable crack growth. This study emphasized that while the load-carrying capacity significantly improved with reinforcement, it did not reach the level of the reference specimen without notches, which failed due to rolling shear.

Malagic et al. [56] examined the calculation of design force in STS employed as reinforcement in CLTs with notches, aiming to enhance their capacity and attain a more ductile behavior. The authors developed an analytical model using the theory of Timoshenko Beam as a foundation, validated through a parametric numerical analysis, which demonstrated good agreement with the results of the numerical study. Additionally, the capacity was assessed employing a fracture mechanics model, accounting for the reinforcement's effect and exhibiting promising correlations with experimental findings.

2.3. Design Provisions for Notches in solid Timber and Laminated Timber Beams

Design provisions for notched timber members are derived from empirical or rational theoretical approaches rooted in fracture mechanics [37]. The commonly used fracture mechanics method for end-notched solid timber and laminated composite timber beams is based on energy balance principles [57] and utilizes linear elastic beam theory [29]. This theory assumes homogeneity and orthotropy of the material, considering fracture as a result of crack propagation originating from the notch's tip.

2.3.1. Current Design Approaches for Notched Solid Timber and Glulam Beams

For a typical notched solid timber and Glulam beam with beam depth of d and notch depth of d_n, shown in Figure 1, the effective depth of the notched beam, d_{ef}, is obtained by:

$$d_{ef} = d - d_n \tag{1}$$

According to the design provisions in CSA O86-19 [17], the shear force at the notched support of Glulam beams with less than $2.0\ \mathrm{m}^3$ in volume and solid timber should be verified by:

$$V \leq F_r \tag{2}$$

and

$$V \leq V_r \tag{3}$$

where F_r is the factored fracture shear resistance at a notch on the tension side at support obtained by:

$$F_r = 0.9F_f dbK_N \tag{4}$$

In Equation (4), $F_f = f_f(K_D K_H K_{Sf} K_T)$. It should be noted that f_f is the specified fracture shear strength at a notch and obtained by $2.5(b)^{-0.2}$ or 0.9 MPa (whichever is greater) for Glulam and considered 0.5 MPa for solid timber. Other factors, K_D, K_H, K_{Sf}, and K_T are the load-duration factor, system factor, service-condition factor for fracture shear, and treatment factor, respectively. K_N is the notch factor calculated as follows:

$$K_N = \left[0.006d\left(1.6\left(\frac{1}{\alpha}-1\right)+\left(\frac{e}{d}\right)^2\left(\frac{1}{\alpha^3}-1\right)\right)\right]^{\frac{-1}{2}} \tag{5}$$

Here, α is the notch ratio defined by $\alpha = d_{ef}/d$. In Eq. (3), V_r is the factored shear resistance obtained by:

$$V_r = 0.9F_v\frac{2bd}{3} \tag{6}$$

For Glulam when $e < d$, and

$$V_r = 0.9F_v\frac{2bd_{ef}}{3} \tag{7}$$

for Glulam when $e > d$ and solid timber. In the above equations $F_v = f_v(K_D K_H K_{SV} K_T)$. f_v is the specified strength in shear and K_{SV} is the service-condition factor for shear.

Based on the design provision provided in Eurocode 5 [18], the shear force at the notched support of the beam should be verified using:

$$V \leq \frac{2}{3}\, b d_{ef} k_v f_{v,d} \tag{8}$$

where $f_{v,d}$ is the design shear strength and k_v is a reduction factor calculated by:

$$k_v = \min\left\{ \frac{k_n \left(1 + \frac{1.1\, i^{1.5}}{\sqrt{d}}\right)}{\sqrt{d}\left(\sqrt{\alpha(1-\alpha)} + 0.8\, \frac{e}{d}\, \sqrt{\frac{1}{\alpha} - \alpha^2}\right)}, 1 \right\} \tag{9}$$

where k_n is 5 and 6.5 for solid timber and Glulam beam, respectively.

According to the design approach provided in NDS 2018 [20], the shear force at support for notched solid timber should satisfy:

$$V \leq \frac{2}{3} F_v' b d_{ef} \left(\frac{d_{ef}}{d}\right)^2 \tag{10}$$

in which, F_v' is the adjusted shear design value parallel to the grain. For the notched Glulam beam, the reference shear design value shall be multiplied by a shear-reduced factor, C_{vr} , which is equal to 0.72.

A general comparison of the limitations stated for notched solid timber and Glulam members in Canadian, European, and U.S. codes has been provided in Table 1.

As can be seen in Table 1, CSA O86-19 and Eurocode 5 account for notch length, while taper notches are only considered in Eurocode 5. On the other hand, NDS 2018 and CSA O86-19 impose strict limitations on notch depth, while Eurocode 5 is comparatively more flexible.

Table 1: Comparison of design approaches for notched solid timber and Glulam beams in CSA O86-19, Eurocode 5, and NDS 2018 Standards, considering taper notches, notch length, and allowable notch depth.

Standards	**Taper Notch**	**Notch Length**	**Limitation on Maximum Notch Depth**
CSA O86-19	-	✓	$0.25\ d$
Eurocode 5	✓	✓	-
NDS 2018	-	-	$0.25\ d$ for Solid Timber $0.1\ d$ or 3" for Glulam

2.3.2. Current Design Approaches for Notched CLT Plates

Canadian (CSA O86-19) [17], European (EC5, 2004) [18], Australian (AS 1720, 2010) [19], and American (NDS, 2018) [20] wood design standards do not include provisions for CLT notches. However, the European Technical Assessment (ETA) [40], and the German CLT handbook [22], written by Wallner-Novak et al., labeled herein "WN", provided guidance on notched CLT based on the EC5 provisions for notched solid timber and Glulam beams. Accordingly, the shear force, V, at the reduced cross-section of a notched CLT plate should be verified by:

$$V \leq \frac{2}{3} b d_{ef} k_v f_{v,r,d} \tag{11}$$

in which $f_{v,r,d}$ is the characteristic rolling shear strength, and k_v is a reduction factor obtained by:

$$k_v = min\begin{cases} 1 \\ \dfrac{k_n}{\sqrt{d}\left(\sqrt{\alpha(1-\alpha)} + 0.8\dfrac{e}{d}\sqrt{\dfrac{1}{\alpha} - \alpha^2}\right)} \end{cases} \tag{12}$$

where k_n is a constant value related to the material properties and assumed to be equal to 4.7 and 4.5 in the ETA and WN formulations, respectively; e is the notch length, defined as the horizontal distance from the support to the notched corner; d_n and d_{ef} are the notch depth and the effective depth of the notched CLT beam, and α is the notch ratio defined as the ratio of the effective depth to the plate depth ($\alpha = d_{ef}/d$). In WN, the effective depth is defined by Eq. (1). The effective depth of notched CLT in ETA is obtained by Eq. (1) when the CLT beam/panel is oriented in its major strength direction and the notched corner is located in a longitudinal layer. In other cases, the outer layer's thickness is ignored if it is a transverse layer, as depicted in Figure 2.

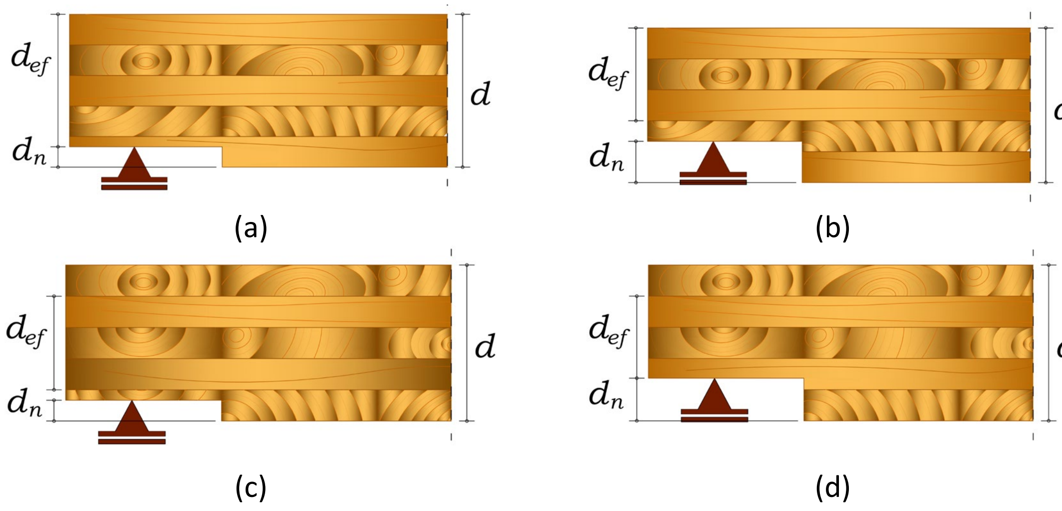


Figure 2: Effective depth, d_{ef}, defined in the ETA for the notched CLT plates oriented in (a), (b): the major strength, and (c), (d): minor strength direction.

3. Experimental Campaign

3.1. Materials and Methods

3.1.1. Materials

Two types of CLT panels with thicknesses of 100 mm and 139 mm were used in a testing campaign that was conducted at the University of Northern British Columbia, Wood Innovation Research Laboratory (WIRL) in Prince George, Canada. The 100 mm panels, labeled herein CLT 100, were BBS 125 (Binderholz), made from Spruce of strength class C18, composed of five layers with uniform 20 mm thickness. The 139 mm panels, labeled herein CLT 139, were 139 V (Structurlam), comprised of three 35 mm longitudinal and two 17 mm thick Spruce-Pine-Fir (SPF) layers of grade V2.1.

Both types of the CLT panels were tested with different notch depths (d_n) in both major and minor strength directions. A total of 174 plates were cut from the CLT panels; 36 of them were tested without any notches to obtain their maximum shear resistance. The other 138 specimens were notched at their ends. Among notched plates, 48 specimens were reinforced with STS to study the effect of reinforcement on their shear resistance. Fully threaded STS [58,59] with a diameter of 10 mm and lengths of 100 mm (Ø10x100 for CLT 100) and 120 mm (Ø10x120 for CLT 139) were used as reinforcement of the notched plates.

The cross-section of plates cut from the CLT 100 panel was 100 mm × 295 mm, the length of the plates was 600 mm, and major and minor strengths directions are labeled, respectively, CLT 100 ∥ and CLT 100 ⊥ in this thesis. The plates cut from CLT 139 were 750 mm long with a 139 mm × 245 mm cross-section and labeled CLT 139 ∥ and CLT 139 ⊥ in major and minor strength directions, respectively.

Moisture content (MC) was measured for each plate before testing. The MC varied between 7.8% and 8.9%, with an average of 8.2% and a Coefficient of Variation (CoV) of 2.5%.

3.1.2. Test Series Overview

The notch depths and the number of specimens for each test series are listed in Table 2. In the series name, the first number represents the total thickness and type of the CLT, and "ǁ" and "⊥" refer to the CLTs tested along the major and minor strength directions, respectively. The second number in the series name shows the depth of the notch in mm. The notations "R" and "IR" refer to reinforced notched CLT plates with vertical (90°) and inclined (45°) screws, respectively.

Table 2: Summary of test series conducted on CLT specimens.

Test series name	Number of specimens	Notch depth, d_n [mm]	Reinforcing by STS
100 ‖-00	12	0	-
100 ‖-10	6	10	-
100 ‖-20		20	-
100 ‖-30		30	-
100 ‖-40		40	-
100 ‖-20-R		20	3 Ø10 x 100 mm @ 90°
100 ‖-40-R		40	3 Ø10 x 100 mm @ 90°
100 ⊥-00	12	0	-
100 ⊥-10	6	10	-
100 ⊥-20		20	-
100 ⊥-30		30	-
100 ⊥-40		40	-
100 ⊥-20-R		20	3 Ø10 x 100 mm @ 90°
100 ⊥-40-R		40	3 Ø10 x 100 mm @ 90°
139 ‖-00	6	0	-
139 ‖-17		17	-
139 ‖-35		35	-
139 ‖-52		52	-
139 ‖-70		70	-
139 ‖-35-R		35	3 Ø10 x 120 mm @ 90°
139 ‖-35-IR		35	3 Ø10 x 120 mm @ 45°
139 ‖-52-R		52	3 Ø10 x 120 mm @ 90°
139 ⊥-00	6	0	-
139 ⊥-17		17	-
139 ⊥-35		35	-
139 ⊥-52		52	-
139 ⊥-52-R		52	3 Ø10 x 120 mm @ 90°

3.1.3. Methods

The CLT plates were tested under three-point bending in a Universal Testing Machine (Figure 3) following the recommendations of ISO 6891 [60]. The tests were carried out under displacement control, and the load was applied to the middle of the simply supported beam with a rate of 2 to 4 mm/min. The plates were supported on two curved bearing supports, and a 25 mm thick and 100 mm wide steel plate was used to apply the load (see Figure 4). The curved supports and the plate reduced the indentation effects.

Figure 3: Test setup: Universal Testing Machine.

Figure 4: Location of bearing supports and steel loading plate.

For CLT 100 and CLT 139 specimens, the support-to-support distance in the bending test was 515 mm and 665 mm, respectively. Schematic of tested specimens and configurations of panels for CLTs 100 and 139 are shown in Figure 5 and Figure 6, respectively. The notch length, *e*, was 37.5 mm for all the specimens.

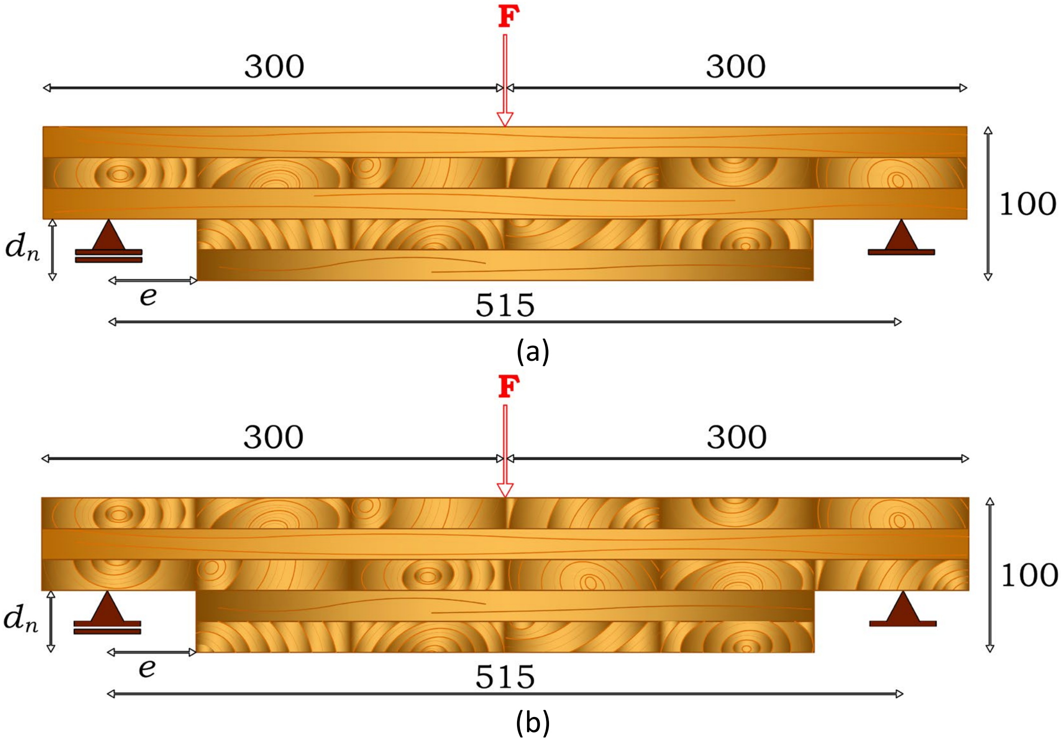


Figure 5: Schematic of tested specimens and configurations of panels for (a) CLT 100 ∥ and (b) CLT 100 ⊥. All dimensions are in mm.

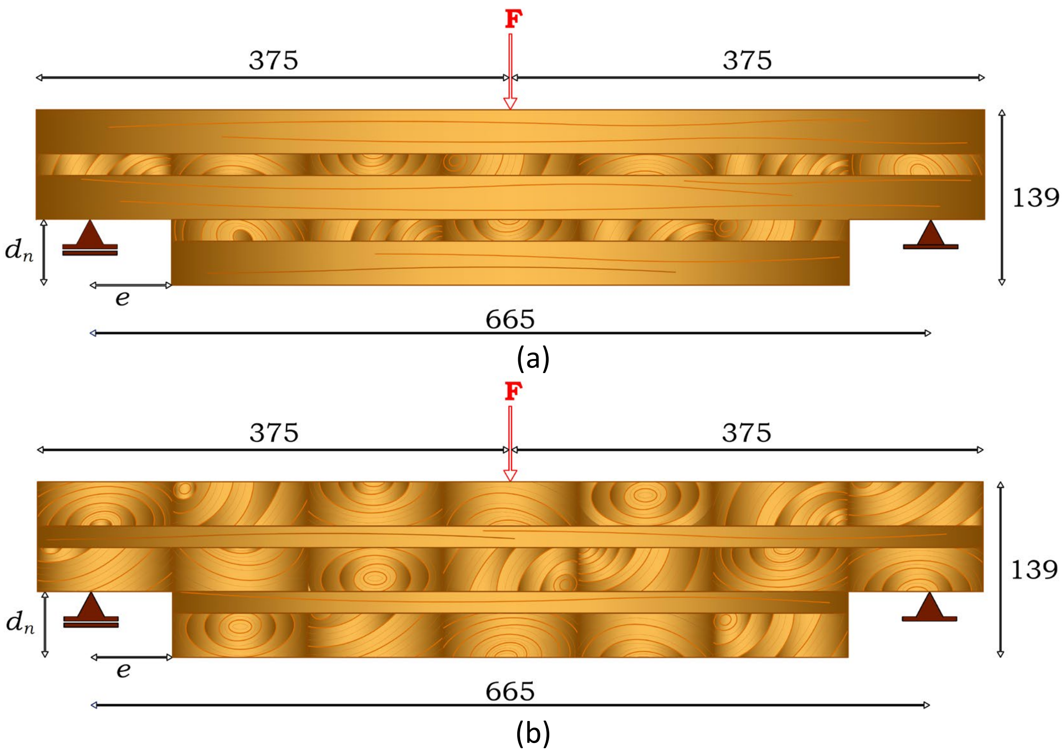


Figure 6: Schematic of tested specimens and configurations of panels for (a) CLT 139 ∥ and (b) CLT 139 ⊥. All dimensions are in mm.

For most reinforced specimens, three STS were applied at both notched ends from the bottom face of the plate in a row at a 30 mm horizontal distance from the notched corners, installed at a 90° angle to the surface. Reinforced CLT 100 (100 ‖-20-R, 100 ‖-40-R, 100 ⊥-20-R, and 100 ⊥-40-R) and reinforced CLT 139 (139 ‖-35-R, 139 ‖-52-R, and 139 ⊥-52-R) with vertically applied screws are depicted in Figure 7 and Figure 8, respectively. For six specimens of CLT 139 ‖ with a 35 mm notch, the STS were installed at a 45° angle (Figure 9). The configuration of the reinforcement is shown in Figure 10. The edge distance, e_d, and spacing between screws, s, are 75 mm and 72.5 mm for the Ø10 x 100 screws and 61 mm and 61.5 mm for Ø10 x 120 screws, respectively.

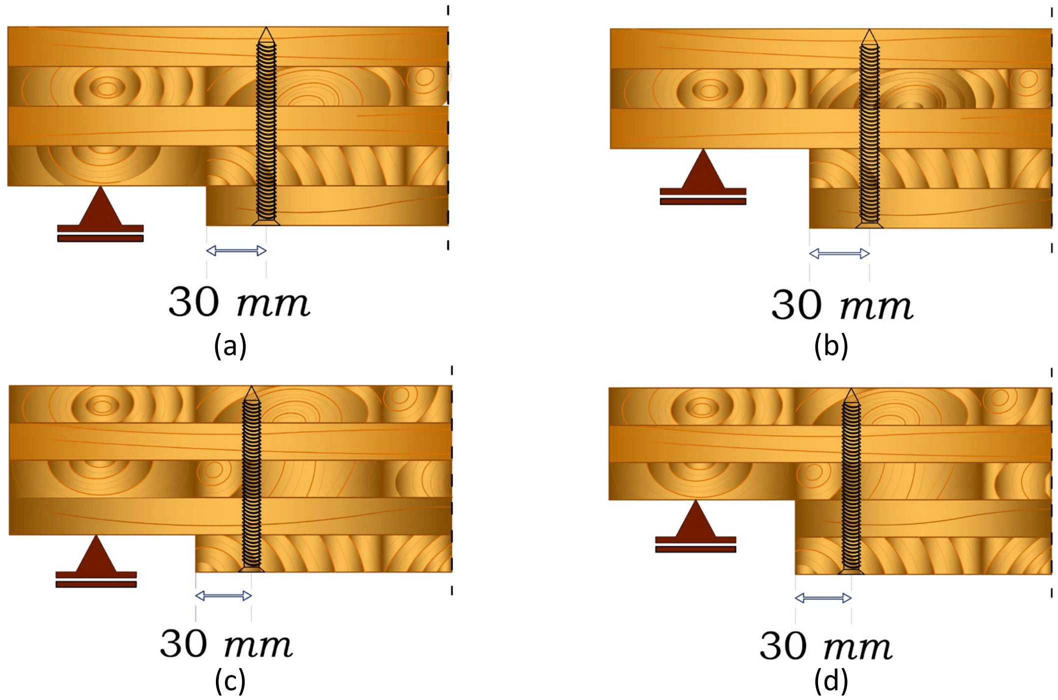


Figure 7: The reinforced series with vertical screws (a) 100 ‖-20-R, (b) 100 ‖-40-R, (c) 100 ⊥-20-R, and (d) 100 ⊥-40-R.

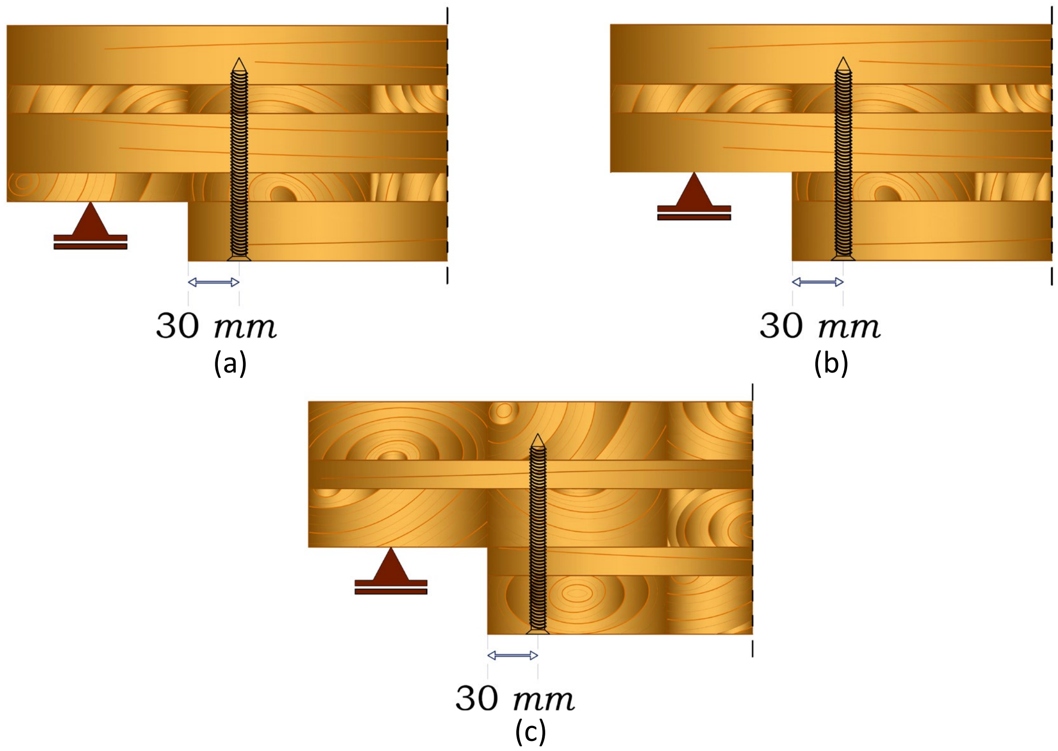


Figure 8: The reinforced series with vertical screws (a) 139 ‖-35-R, (b) 139 ‖-52-R, and (c) 139 ⊥-52-R.

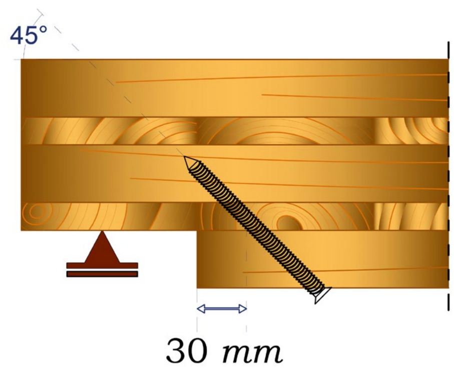


Figure 9: The reinforced CLT plates with inclined screws: 139 ‖-35-IR

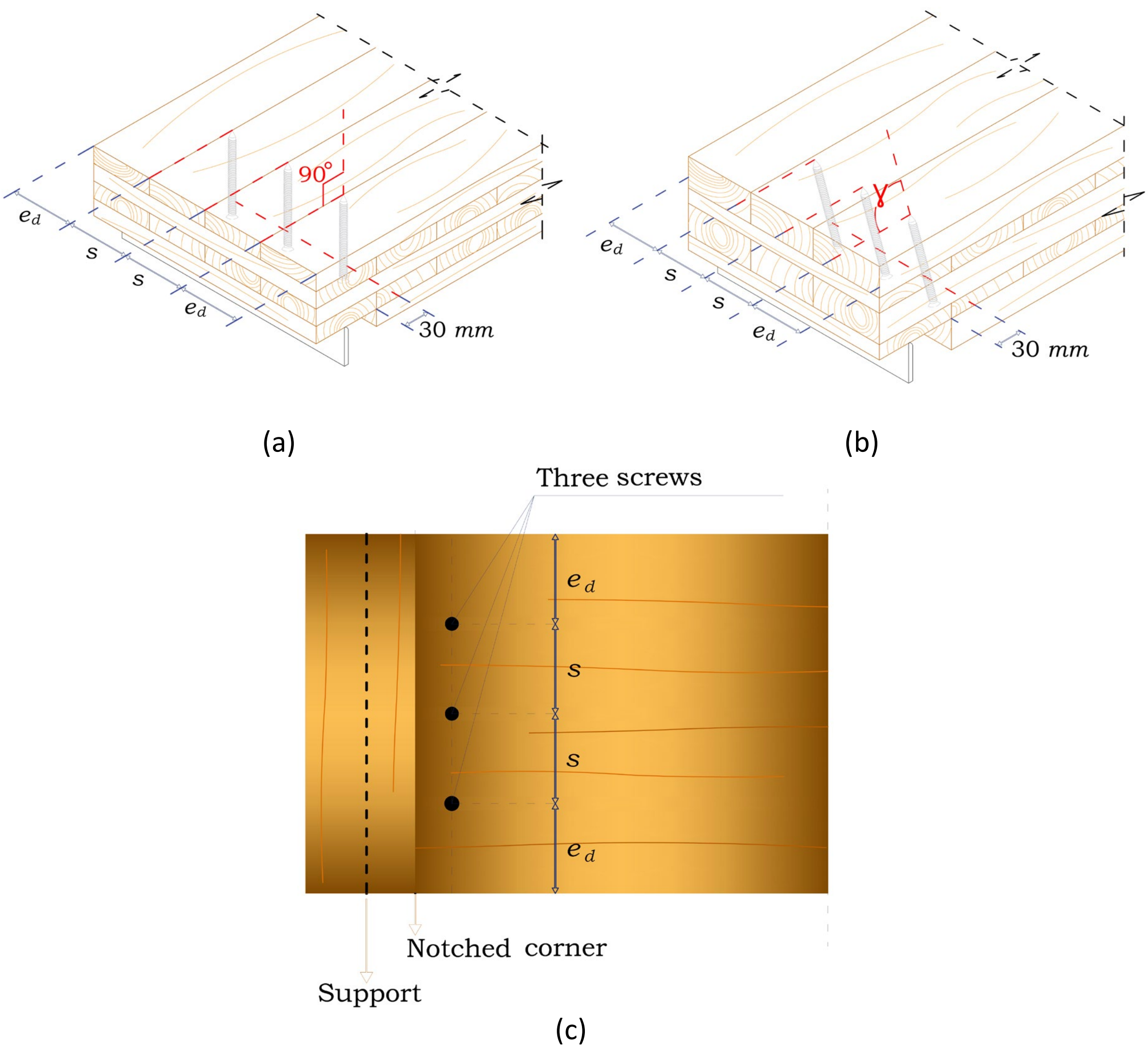


Figure 10: (a) Reinforced CLT 100, (b) Reinforced CLT 139 with γ=90° and 45°, and (c) Bottom view of reinforced plates.

For each specimen, the applied load and the mid-span displacement were recorded. The ultimate load and the corresponding maximum mid-span deflection of all specimens were obtained for each series; then, their mean value and their coefficient of variation (CoV) were determined. For each series, the shear resistance at support was also calculated as 50% of the recorded ultimate loads.

3.2. Analysis

3.2.1. Calculation of Characteristic Values

The characteristic value (5th percentile value) of the shear resistance at support, $V_{f,005}$, was calculated based on the approach provided in EN 14358:2016 [61], assuming a log-normal distribution of the shear resistance of the specimens, V_i. For each series with n specimens, the mean value, $\bar{V}$, and the standard deviation, S_V, of shear resistance were obtained using Eqs. (13) and (14), respectively:

$$\bar{V} = \frac{1}{n}\sum_{i=1}^{n} \ln V_i \tag{13}$$

$$S_V = \max\begin{cases} \sqrt{\dfrac{1}{n-1}\displaystyle\sum_{i=1}^{n}(\ln V_i - \bar{V})^2} \\ 0.05 \end{cases} \tag{14}$$

The characteristic 5th percentile value of the shear resistance at supports, $V_{f,005}$, for each series was obtained by:

$$V_{f,005} = \exp(\bar{V} - k_s(n)S_V). \tag{15}$$

in which, $k_s(n)$ was calculated using:

$$k_s = \frac{6.5n + 6}{3.7n - 3} \tag{16}$$

3.2.2. Statistical Analysis

We conducted a three-way between-subjects analysis of variance (ANOVA) to examine whether there is a significant interaction among three independent factors of orientation, notch ratio, and reinforcement concerning the dependent variable of shear resistance at support, V_f. An interaction effect is observed when the impact of one independent factor on a dependent variable varies across different levels of the other independent factors. The statistical significance is evaluated by computing a *p*-value, which is then compared with a significance level. If the calculated *p*-value for the three factors interaction is higher than the pre-defined significance level, here assumed to be 0.05, there is no statistically significant three-way interaction effect.

A one-way ANOVA can also be employed to compare the means of levels within each factor and determine whether the observed differences in means hold statistical significance. Calculated *p*-values are to determine whether the observed variations in the means are statistically significant. If the calculated *p*-value is less than the pre-defined significance level (0.05), it is highly unlikely that the null hypothesis of no differences between means is accurate, and it is, therefore, rejected [48–51]. In this research, we are specifically interested in finding out where the level differences specifically lie with respect to the notch ratio factor. Therefore, we followed up the statistical analysis by conducting one-way ANOVA with specific pairwise comparisons of levels within the notch ratio factor.

3.3. Results and Discussions

3.3.1. Load-Deflection Curves

The load-deflection curves of one representative specimen from each test series are shown in Figure 11. Most curves have the same slope for the linear part of the loading, indicating that notches or screws have no impact on the bending stiffness of the plates; however, notches have a significant impact on the ultimate load. All the un-reinforced notched plates except series 139 ⊥-17 and 139 ⊥-35 showed sudden failure. The rolling shear failure can be seen in the load-deflection curves of the reinforced plates, such as series 100 ‖-20-R, 100 ‖-40-R, 100 ⊥-20-R, 139 ‖-35-R, and 139 ‖-35-IR. The reinforcing increased the failure load and the maximum deflection of notched plates. For series 100 ‖-20-R and 139 ‖-35-IR, the maximum deflections were even higher than the maximum deflection of the corresponding un-notched plates.

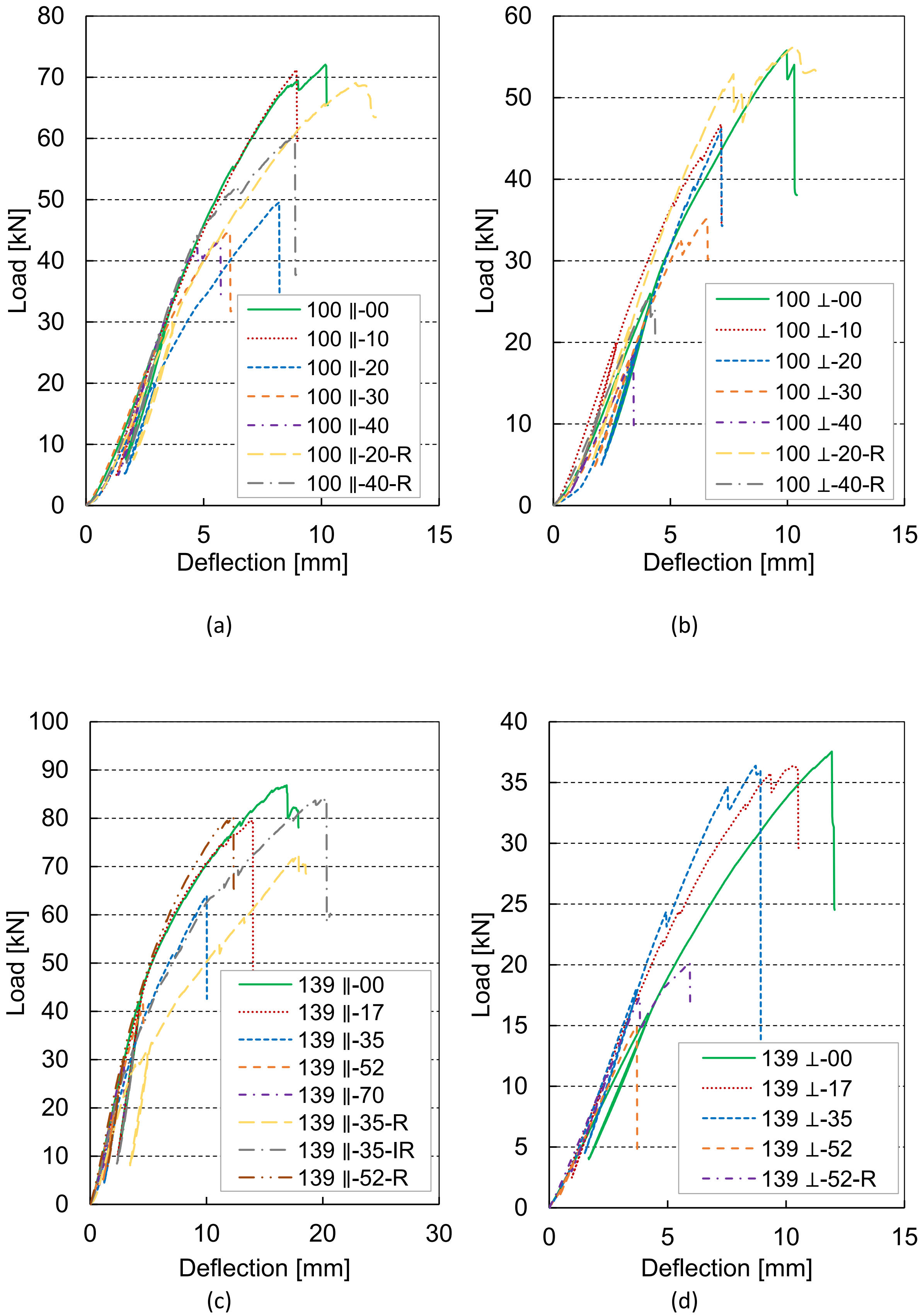
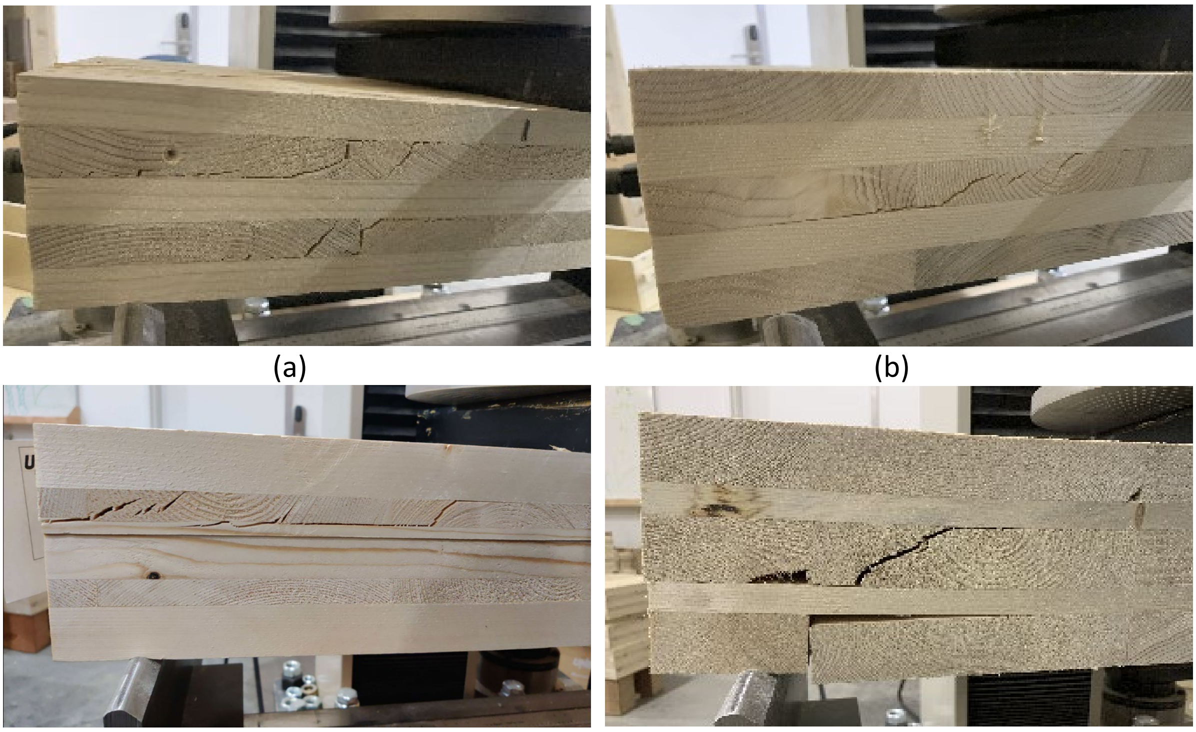


Figure 11: Load-deflection curves for (a) CLT 100 ∥, (b) CLT 100 ⊥, (c) CLT 139 ∥, and (d) CLT 139 ⊥.

3.3.2. Failure Modes

3.3.2.1. Failure Modes Un-reinforced CLT Plates

For the un-notched test series (100 ∥-00, 100 ⊥-00, 139 ∥-00, and 139 ⊥-00), the failure mode was a rolling shear failure in the transverse layers, as shown in Figure 12. Subsequent to rolling shear failure, debonding of laminations at the bottom transverse layer occurred in series 139 ⊥-00 (see Figure 12(d)).



(a) (b)

(c) (d)

Figure 12: Failure modes of the un-notched CLT beams; (a) 100 ∥-00, (b) 100 ⊥-00, (c) 139 ∥-00, and (d) 139 ⊥-00.

For notch depths of 10% of the plate depth, the failure modes of CLT 100 ∥ (series 100 ∥-10) were the rolling shear failure. The observed rolling shear failure showed that this notch ratio did not change the failure mode of the beam. For notch depths of less than 15% of the plate depth, the failure modes of CLT 139 ∥ (series 139 ∥-17) were the combination of the rolling shear and notch failure, as shown in Figure 13(a).

For notch ratios of 20% and higher, the failure modes of the notched CLT 100 ∥ and CLT 139 ∥ were notch failures. It was observed that when the notched corner was located within or under a transverse layer, such as series 100 ∥-20, 100 ∥-30, and 139 ∥-35, the cracks usually started at the notched corner; then, the cracks propagated at an angle between 30°-60° with respect to the horizontal axis until they reached the interface of the layers and then went along the interface (see Figure 13(b)). It should be mentioned that the failure of some specimens started by initiating a crack at a place between the support and the notched corner (Figure 13(c)) or debonding of the layers (Figure 13(d)). It is also observed that the cracks might go through the upper layer (Figure 13(e)). When the notched corner was located within or under a longitudinal layer (series 100 ∥-40, 139 ∥-52, and 139 ∥-70), the cracks started at the notched corner; then, the cracks spread along the grain of the longitudinal layer, as shown in Figure 13(f). Therefore, the type of the layer in which the notch was located affected the crack propagation path. A similar failure pattern has been reported by Malagic et al. in [34].

For the CLT 100 ⊥ and CLT 139 ⊥, when the notch was located within the lowest transverse layer, such as 100 ⊥-10, 100 ⊥-20, 139 ⊥-17, and 139 ⊥-35, the failure mode was the rolling shear failure (shown in Figure 13(g) and Figure 13(h)). For notches located within the lowest longitudinal layer (series 100 ⊥-30), the failure mode was the combination of the rolling shear and notch failure, as shown in Figure 13(i). When the notched corner was located under the middle transverse layer of the CLT 100 ⊥ and CLT 139 ⊥, the failure mode was notch failure. For three specimens in series 139 ⊥-52 a debonding failure was observed, as shown in Figure 13(j).

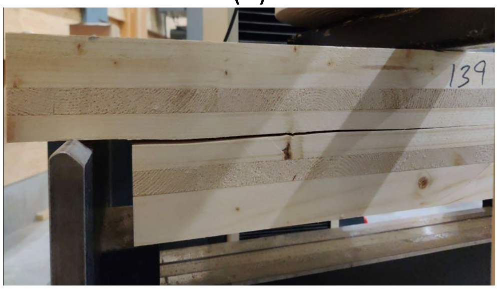
(a)

(b)

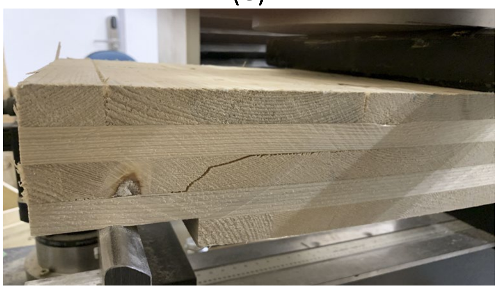
(c)

(d)

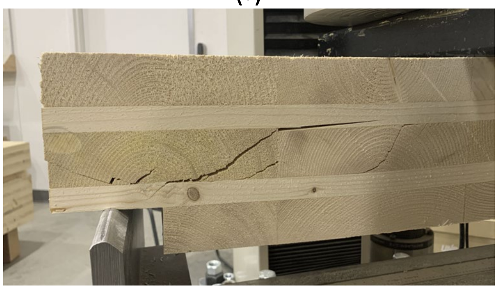
(e)



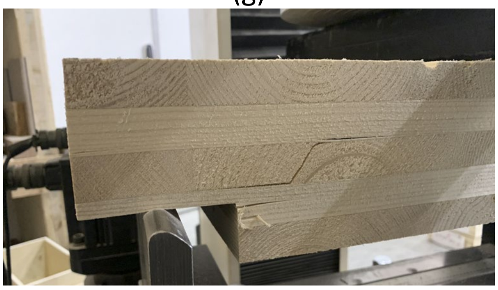
(f)



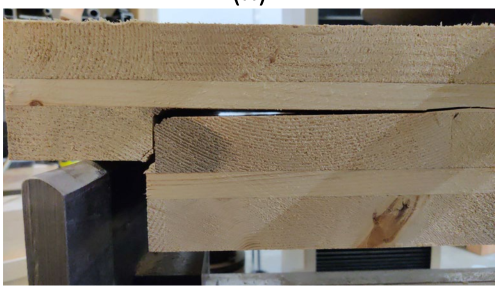
(g)



(h)



(i)



(j)

Figure 13: (a) Rolling shear-notch failure (139 ‖-17), (b) notch failure (100 ‖-20), (c) crack started before the notched corner (100 ‖-20), (d) debonding failure (100 ‖-30), (e) crack propagated to the upper layer (139 ‖-35), (f) notch failure (139 ‖-70), (g) and (h) rolling shear failure (100 ⊥-20 and 139 ⊥-35), (i) Rolling shear-notch failure (100 ⊥-30), and (j) debonding failure (139 ⊥-52).

3.3.2.2. Failure Modes Reinforced CLT Plates

By reinforcing the notched CLT 100 ∥ and CLT 139 ∥ (test series 100 ∥-20-R, 100 ∥-40-R, 139 ∥-35-R, 139 ∥-35-IR, and 139 ∥-52-R), their failure modes changed from notch failure to rolling shear-notch failure, as shown in Figure 14(a)-8(e). The reinforcement limited the notched crack propagations.

By reinforcing the notched CLT 100 ⊥, when the notch ratio was 20% (series 100 ⊥-20-R), the failure mode of the reinforced plates was rolling shear failure (Figure 14(f)), which was the same as the failure mode of the un-reinforced plate 100 ⊥-20. For the CLT 100 ⊥ and CLT 139 ⊥ with notches deeper than 20% of the plate depth (series 100 ⊥-40-R and 139 ⊥-52-R), the failure mode of the reinforced plates was notch failure (shown in Figure 14(g) and 8(h)), which was the same as the failure mode of the un-reinforced plates 100 ⊥-40 and 139 ⊥-52. It was observed that reinforcing the notched CLT 100 ⊥ and CLT 139 ⊥ did not change the failure mode of the notched plates. It should be mentioned that the debonding failures observed in series 139 ⊥-52 did not occur in the reinforced specimens (series 139 ⊥-52-R).

(a) (b) (c) (d) (e) (f) (g) (h)

Figure 14: Rolling shear-notch failure mode of reinforced specimens; (a) 100 ∥-20-R, (b) 100 ∥-40-R, (c) 139 ∥-35-R, (d) 139 ∥-35-IR, and (e) 139 ∥-52-R, and rolling shear failure mode of (f) 100 ⊥-20-R, (g) 100 ⊥-40-R, and (h) 139 ⊥-52-R.

3.3.3. Shear Resistance at Supports

3.3.3.1. Overview

The mean values and CoVs of the shear resistance at support (half of the recorded ultimate load), denoted herein by V_f, as well as the mean values and CoVs of the mid-span deflections corresponding to the ultimate load, w_{max}, of each test series are reported in Table 3. The normalized mean value of the shear resistance at support, denoted by $V_{normalized}$, were also calculated and included in this table. For each series, the normalized mean value of the shear resistance at support is the V_f of that series normalized by the corresponding value of the un-notched series.

Table 3: Summary of test results.

Test series name	V_f **[kN]**	**CoV** V_f **(%)**	w_{max} **[mm]**	**CoV** w_{max} **(%)**	$V_{normalized}$
100 ǁ-00	36.09	4	9.68	19	1.00
100 ǁ-10	35.31	7	8.37	7	0.98
100 ǁ-20	22.52	11	7.10	15	0.62
100 ǁ-30	22.14	6	6.50	9	0.61
100 ǁ-40	21.68	9	5.43	4	0.60
100 ǁ-20-R	33.36	6	12.73	10	0.92
100 ǁ-40-R	31.89	5	8.96	17	0.88
100 ⊥-00	26.66	9	10.20	12	1.00
100 ⊥-10	22.93	6	8.06	18	0.86
100 ⊥-20	22.25	8	7.87	11	0.83
100 ⊥-30	18.69	8	6.38	8	0.70
100 ⊥-40	7.10	19	3.12	17	0.27
100 ⊥-20-R	26.21	8	8.66	15	0.98
100 ⊥-40-R	11.78	13	4.87	20	0.44
139 ǁ-00	48.02	14	15.85	21	1.00
139 ǁ-17	39.26	18	12.38	21	0.82
139 ǁ-35	33.20	25	11.40	27	0.55
139 ǁ-52	26.20	16	4.49	12	0.45
139 ǁ-70	21.50	13	3.26	13	0.32
139 ǁ-35-R	38.36	4	14.62	23	0.80
139 ǁ-35-IR	40.22	5	15.31	17	0.84
139 ǁ-52-R	39.72	6	11.98	18	0.83
139 ⊥-00	17.17	10	9.42	18	1.00
139 ⊥-17	17.56	12	10.27	10	1.02
139 ⊥-35	19.25	4	9.41	12	1.12
139 ⊥-52	6.62	12	3.90	11	0.39
139 ⊥-52-R	10.55	8	8.67	31	0.61

3.3.3.2. Statistical Analysis of Shear Resistance

In this research, we performed a three-way factorial ANOVA to investigate the presence of a significant interaction among the three independent factors of orientation, notch ratio, and reinforcement regarding the dependent variable of shear resistance at support, V_f. The blocks, factors, and levels of the factors are listed in Table 4.

Table 4: Factors and levels of the factorial ANOVA.

Blocks	**Factors**	**Levels**				
CLT 100	Orientation	Major			Minor	
	Notch Ratio	0.0	0.1	0.2	0.3	0.4
	Reinforcement	N[(a)]			R[(b)]	
CLT 139	Orientation	Major			Minor	
	Notch Ratio	0.0	0.12	0.25	0.37	0.5
	Reinforcement	N		R	IR[(c)]	

(a) No Reinforcement

(b) Reinforcement with applied screws at 90°

(c) Reinforcement with applied screws at 45°

We are interested in the simple two-way interaction between notch ratio and reinforcement (Notch Ratio*Reinforcement) at the different levels of orientation (i.e., "major" and "minor"). The three-way tests between-subjected ANOVA are presented in Table 5.

Table 5: Tests of between-subjects effects for CLT 100. Dependent variable: shear resistance.

Source	*p*-value
Orientation	<.001
Notch Ratio	<.001
Reinforcement	<.001
Orientation * Notch Ratio	<.001
Orientation * Reinforcement	<.001
Notch Ratio * Reinforcement	0.966
Orientation * Notch Ratio * Reinforcement	0.524

From Table 5, it can be concluded that there is no statistically significant three-way interaction between orientation, notch ratio, and reinforcement, *p*-value=0.524. Therefore, the effect of the interaction between the notch ratio and the reinforcement on the shear resistance is not affected by whether the CLT is oriented in the major or minor strength direction.

Given that the three-way interaction does not show statistical significance, it is necessary to take into account the two-way interactions. From Table 5, it can be seen that the two interactions of "Orientation*Notch Ratio" and "Orientation*Reinforcement" are statistically significant with a *p*-value<0.001. This means that the effect of orientation on shear resistance depends on the level of notch ratio and vice-versa. Furthermore, the effect of orientation on shear resistance depends on the level of reinforcement and vice-versa. We ran simple main effects in SPSS Statistics following two statistically significant two-way interactions of "Orientation*Notch Ratio" and "Orientation*Reinforcement."

The simple main effects for notch ratio are the effects of notch ratio at each group of orientation. This means we are concerned with the simple main effect of notch ratio for "major" and "minor" strength directions of CLT whilst ignoring reinforcement. From Table 6, it can be observed that the simple main effects of the notch ratio for major and minor orientation are statistically significant. We will follow this up with pairwise comparisons.

Table 6: Univariate Tests: The simple main effects for notch ratio at each group of orientation

Orientation	*p*-value
Major	<0.001
Minor	<0.001

The simple main effects for orientation are the effects of orientation at each group of notch ratio. This means we are concerned with the simple main effect of orientation for different notch ratios whilst ignoring reinforcement. From Table 7, it can be observed that the simple main effects of orientation for different notch ratios are statistically significant. We will follow this up with pairwise comparisons.

Table 7: Univariate Tests: The simple main effects for orientation at each group of notch ratio

Notch Ratio	*p*-value
0.0	<0.001
0.10	<0.001
0.20	<0.001
0.30	0.002
0.40	<0.001

The simple main effects for reinforcement are the effects of reinforcement at each group of orientation. This means we are concerned with the simple main effect of reinforcement for the "major" and "minor" strength directions of CLT whilst ignoring the notch ratio. From Table 8, it can be observed that only the simple main effect of reinforcement for major orientation is statistically significant. We will follow this up with pairwise comparisons.

Table 8: Univariate Tests: The simple main effects for reinforcement at each group of orientation

Orientation	*p*-value
Major	<0.001
Minor	0.397

The simple main effects for orientation are the effects of orientation at each group of reinforcement. This means we are concerned with the simple main effect of orientation for different reinforcements whilst ignoring notch ratios. From Table 9, it can be observed that the simple main effects of orientation for a different group of reinforcement are statistically significant. We will follow this up with pairwise comparisons.

Table 9: Univariate Tests: The simple main effects for orientation at each group of notch ratio

Notch Ratio	*p*-value
N	<0.001
R	<0.001

A detailed ANOVA for CLT 100 and CLT 139 and the output of the SPSS software are presented in Appendix A.

3.3.3.3. Statistical Analysis Based on Pairwise Comparisons

The *p*-values obtained from the ANOVA conducted on various series are listed in Table 10. The *p*-value for the un-reinforced notched series is determined by comparing it to the series with a smaller depth of the notch. For the reinforced series, the *p*-value is derived from comparing the reinforced series with the corresponding un-reinforced notched series.

Table 10: Summary of ANOVA conducted on various testing series.

	CLT 100		CLT 139	
	Selected Series	*p*-value	Series	*p*-value
I	100 ∥-00 100 ∥-10	0.396	139 ∥-00 139 ∥-17	0.054
II	100 ∥-10 100 ∥-20	<0.001	139 ∥-17 139 ∥-35	0.008
III	100 ∥-20 100 ∥-30	0.742	139 ∥-35 139 ∥-52	0.154
	100 ∥-30 100 ∥-40	0.651		
	100 ∥-20 100 ∥-30 100 ∥-40	0.762		
IV	100 ∥-20 100 ∥-20-R	<0.001	139 ∥-35 139 ∥-35-R	<0.001
	100 ⊥-20 100 ⊥-20-R		139 ∥-35 139 ∥-35-IR	
	100 ∥-40 100 ∥-40-R		139 ∥-52 139 ∥-52-R	
	100 ⊥-40 100 ⊥-40-R		139 ⊥-52 139 ⊥-52-R	
V	100 ⊥-00 100 ⊥-10	0.295	139 ⊥-00 139 ⊥-17	0.746
VI	100 ⊥-10 100 ⊥-20	0.490	139 ⊥-17 139 ⊥-35	0.104
VII	100 ⊥-30 100 ⊥-40	<0.001	139 ⊥-35 139 ⊥-52	<0.001
VIII	139 ∥-52 139 ∥-70	0.004		

The *p*-values listed in Table 10 are crucial in assessing the statistical significance of the differences between the various experimental conditions, thereby facilitating the interpretation and understanding of the results. The findings of conducted ANOVAs are listed below:

I. Notching half of the outer longitudinal layer of CLTs in the major strength direction has a negligible impact on the shear resistance of the plates.

II. Removal of the first longitudinal layer of CLTs in the major strength direction significantly reduces the shear resistance of the CLT plates.

III. Increasing the notch depth within the middle transverse layer of CLTs in the major strength direction does not substantially affect the shear resistance of the CLT plates.

IV. Introducing reinforcements to notched CLT plates significantly enhances their shear resistance.

V. A notch in half of the outer transverse layer of the CLTs in the minor strength direction does not notably reduce the shear resistance of the CLT plates.

VI. Increasing the notch depth in the outer transverse layer of the CLTs in the minor strength direction does not have a significant impact on the shear resistance of the CLT beam.

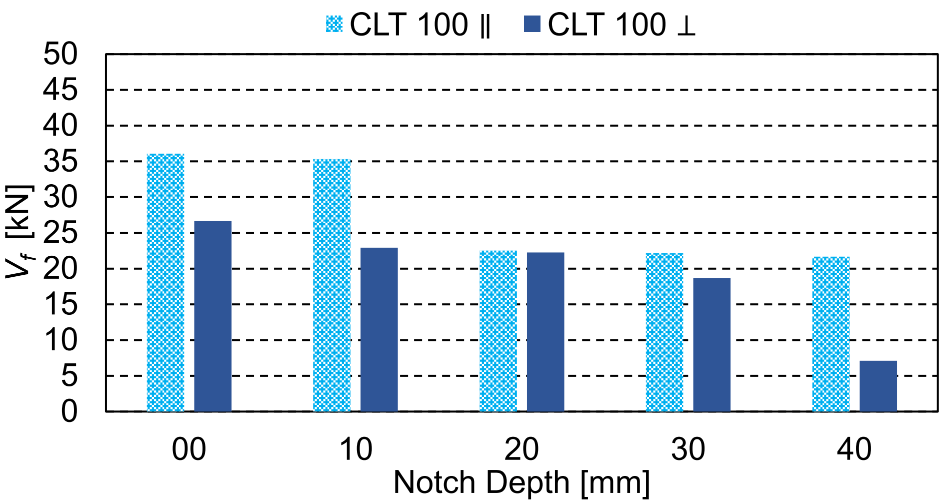
VII. Increasing the notch depth within the middle longitudinal layer of the CLT in the minor strength direction significantly reduces the shear resistance of the CLT beam.

VIII. Removing half of the plate depth in the CLT oriented in the major strength direction significantly decreases the shear resistance of the CLT beam.

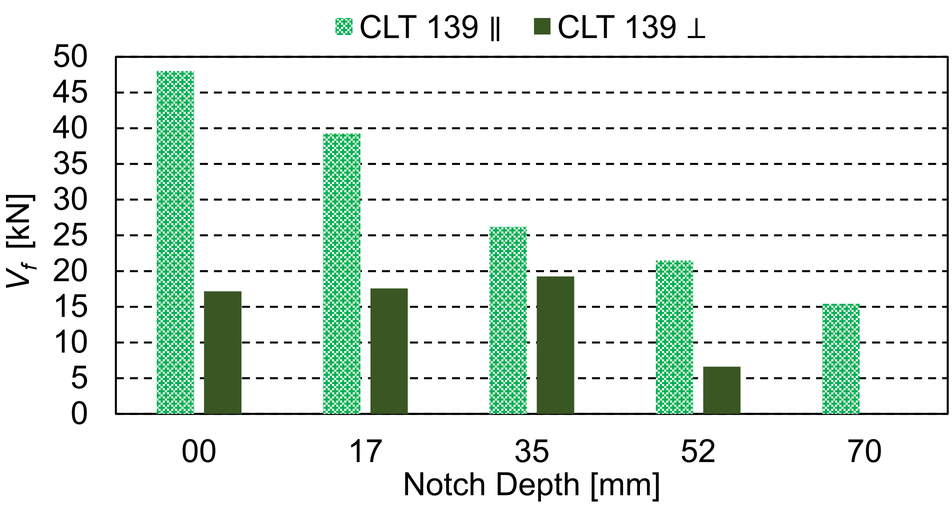
In summary, Table 10 highlights that reinforcement has a statistically significant effect on the increase of the shear resistance at support (p-value < 0.05). It can also be observed that an increase in the notch depth has a statistically significant impact on the shear resistance at supports, except when the notches are located within the same transverse layer, such as notch depths 20 mm, 30 mm, and 40 mm for CLT 100 ∥; notch depths 10 mm and 20 mm for CLT 100 ⊥ ; notch depths 35 mm and 52 mm for CLT 139 ∥ ; notch depths 17nmm and 35 mm for CLT 139 ⊥.

3.3.3.4. Shear Resistance for Un-reinforced CLT Plates

The mean values of the shear resistance at the support of the un-reinforced notched plates are shown in Figure 15. It has been observed that shear resistance at support for 100 ||-00 and 139 ||-00 were about 26% and 64% higher than those for 100 ⊥-00 and 139 ⊥-00, respectively. The notches with a less than 15% ratio in CLT 100 || and CLT 139 || (series 100 ||-10 and 139 ||-17) reduced V_f by 2% and 18%, respectively.



(a)



(b)

Figure 15: Mean values of the shear resistance at the support of the un-reinforced notched plates; (a) CLT 100 || and CLT 100 ⊥ and (b) CLT 139 || and CLT 139 ⊥.

For CLT 100 ǁ and CLT 139 ǁ, the notch depths greater than 15% of the plate depth significantly reduced the shear resistance at support. The various notch depths of 20, 30, and 40 mm in CLT 100 ǁ (series 100 ǁ-20, 100 ǁ-30, and 100 ǁ-40) reduced V_f by 38%, 39%, and 40%, respectively. For these series, the notched corner was located within the lowest transverse layer. It could be concluded that the transverse layer's capacity does not contribute to the beam's shear resistance when the notch is located in transverse layers. The shear resistance at supports of the CLT 139 ǁ with 35 and 52 mm notches (series 139 ǁ-35 and 139 ǁ-52) decreased by 45% and 55%, respectively, from those of the un-notched specimen (series 139 ǁ-00). Hence, removing the lowest longitudinal layer by the end-notch reduced V_f by 45%, while increasing the notch depth to remove the second layer, which was the transverse layer, caused just a 10% more reduction in V_f. From Table 3 and Figure 15(b), it can be seen that extending the notch depth to half of the third CLT's layer (the middle longitudinal layer) led to a severe reduction (~68%) of the shear resistance of the notched CLT 139 ǁ (series 139 ǁ-70).

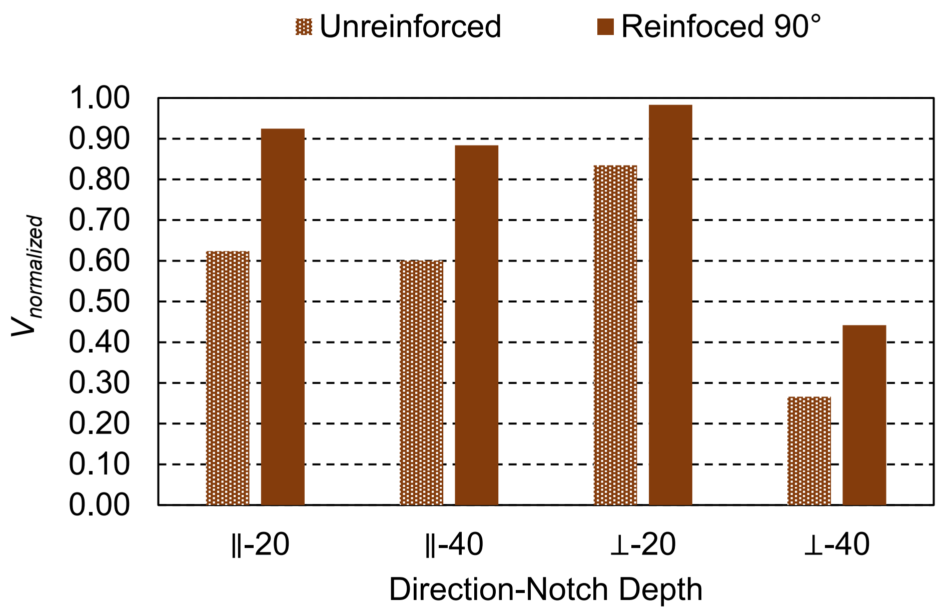
The shear resistance at the support of the CLT 100 ⊥ and CLT 139 ⊥ with the notches located within their lowest transverse layer, such as 100 ⊥-10, 100 ⊥-20, 139 ⊥-17, and 139 ⊥-35, did not significantly change compared to the corresponding un-notched plates. The series 100 ⊥-10 and 100 ⊥-20 showed a 14% and 17% reduction in V_f, respectively, while the series 139 ⊥-17 and 139 ⊥-35 had about 2% and 12% increase V_f. The rise in V_f of the series 139 ⊥-17 and 139 ⊥-35 might be coincidental and attributed to experimental error. This might happen because of an initial crack or defect in the specimens.

For CLT 100 ⊥ and CLT 139 ⊥, when the notch was located within the second layer (the lowest longitudinal layer), e.g., in series 100 ⊥-30, V_f decreased by 30%. In the series 100 ⊥-

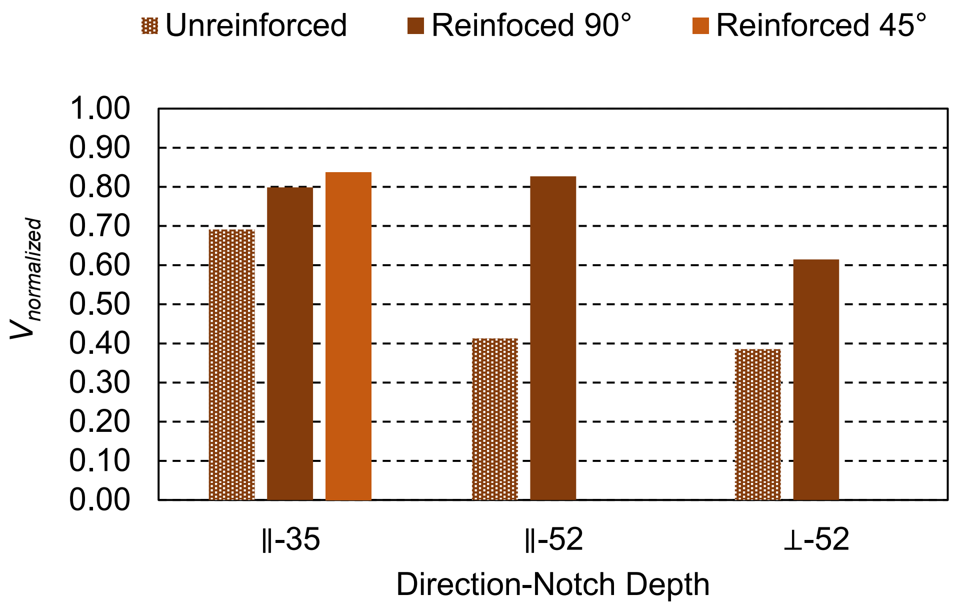
40 and 139 ⊥-52, a drastic reduction of about 73% and 62%, respectively, was noted due to removing the second layer by the notch.

3.3.3.5. Shear Resistance for Reinforced CLT Plates

The normalized mean value of the shear resistance at supports, $V_{normalized}$, for the un-reinforced and reinforced notched CLT 100 and CLT 139 are compared in Figure 16(a) and 16(b), respectively. The normalized mean value of the maximum mid-span deflection, $w_{normalized}$, is also compared for the un-reinforced and reinforced notched CLT 100 and CLT 139 in Figure 17(a) and 17(b), respectively. For each test series, the $w_{normalized}$ is the w_{max} of that series normalized with respect to the w_{max} of the corresponding un-notched series.

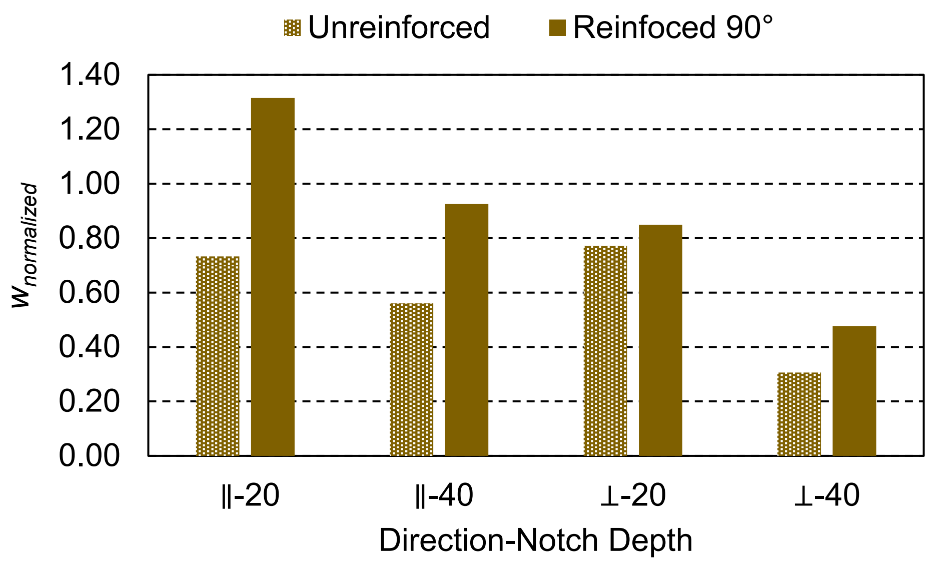


(a)

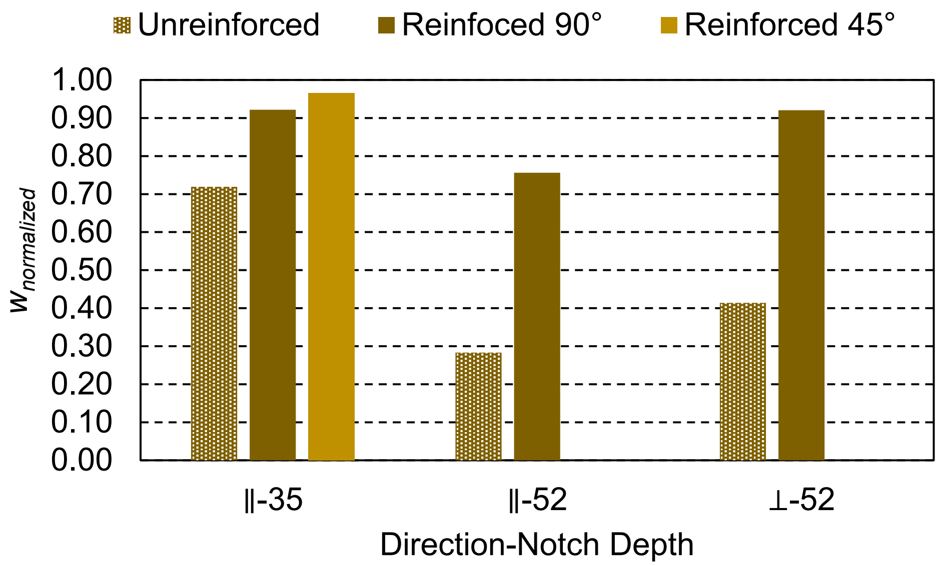


(b)

Figure 16: Comparison of the normalized mean value of the shear resistance at supports of the un-reinforced and reinforced notched CLT beams; (a) CLT 100 and (b) CLT 139.



(a)



(b)

Figure 17: Comparison of the normalized mean value of the maximum mid-span deflections for the un-reinforced and reinforced notched CLT plates; (a) CLT 100 and (b) CLT 139.

The reinforcing of the notched CLT 100 ∥ and CLT 139 ∥, such as series 100 ∥-20-R, 100 ∥-40-R, 139 ∥-35-R, 139 ∥-35-IR, and 139 ∥-52-R, increased $V_{normalized}$ of about 30%, 28%, 11%, 15%, and 42%, respectively. The shear resistance of the series 100 ∥-20-R, 100 ∥-40-R, 139 ∥-35-R, 139 ∥-35-IR, and 139 ∥-52-R was found to be 92%, 88%, 80%, 84%, and 83% of its corresponding un-notched plates' shear resistance, respectively. It was also observed that the inclined screws (series 139 ∥-35-IR) had a 4% better performance in increasing the shear resistance of the notched plates in comparison with vertical screws (series 139 ∥-35-R).

For notched CLT 100 ⊥, when the notch was located within the lowest transverse layer (series 100 ⊥-20-R), the reinforcing of the plate increased its shear resistance by 15%, reaching 98% of the shear resistance of the corresponding un-notched CLT. When the notched corner located under the middle transverse layer, such as series 100 ⊥-40-R and 139 ⊥-52-R, the screws still increased the plates' shear resistance by 17% and 22%, respectively. However only two-thirds of the un-notched plates' shear resistance was achieved by introducing reinforcing screws. Therefore, for notched CLT in the minor direction with notch ratios higher than 35%, the corresponding un-notched beam's shear resistance could not be achieved by reinforcement.

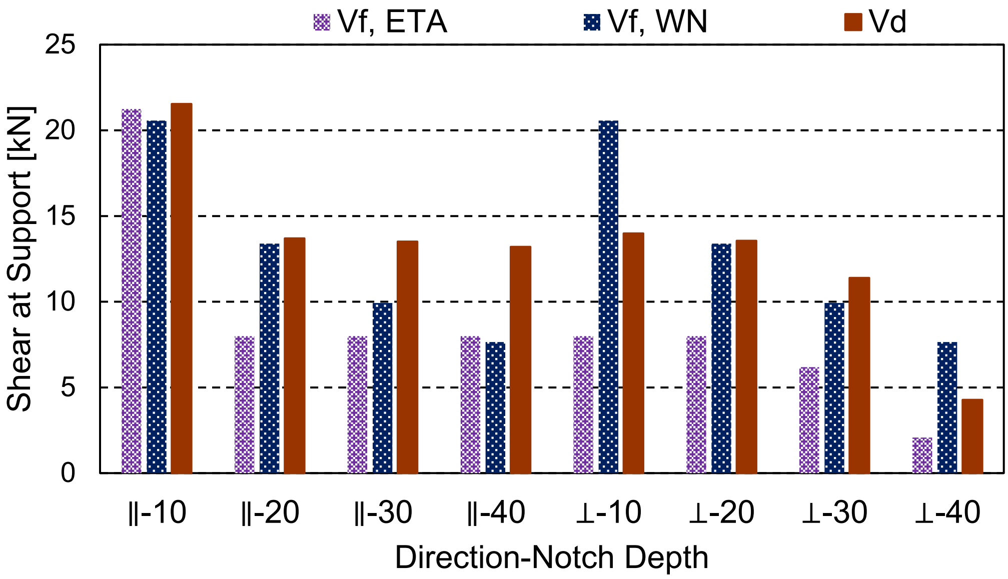
According to Figure 17, the reinforcing increased the normalized mean value of the maximum mid-span deflections, $w_{normalized}$. For the series 100 ∥-20-R, the mean value of maximum mid-span deflections, w_{max}, was about 80% and 32% higher than the w_{max} of the corresponding un-reinforced notched (series 100 ∥-20) and un-notched plates (series 100 ∥-00), respectively. The inclined (45°) and vertical (90°) screws increased the mean value of maximum mid-span deflections by 34% and 28% in alignment with the corresponding un-reinforced plates, respectively. Therefore, in addition to the 4% higher shear resistance, plates reinforced with inclined screws had a 6% greater maximum deflection than those with vertical screws.

3.3.4. Comparison with Design Approaches

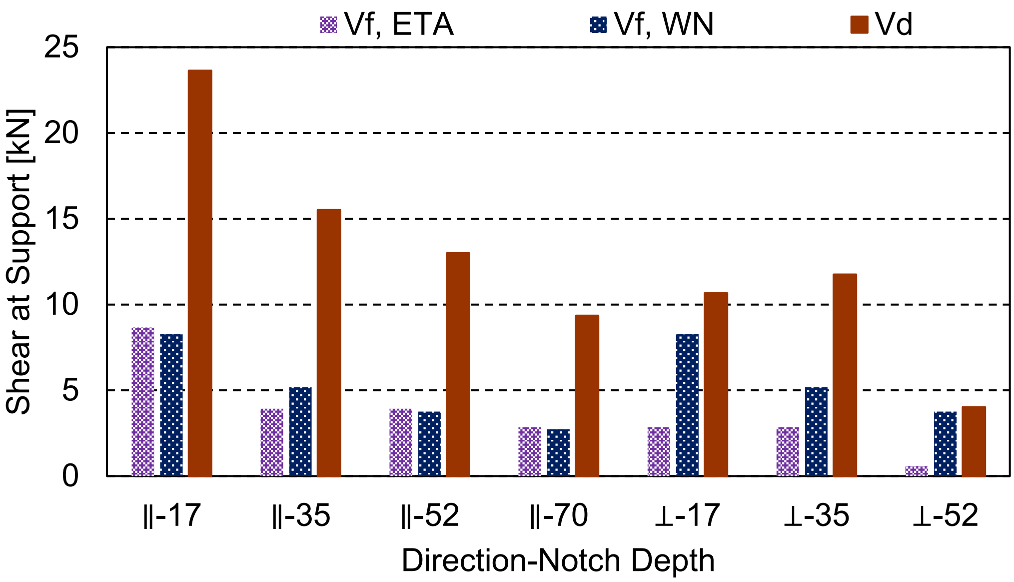
For each un-reinforced notched test series, the shear resistance at supports was calculated based on the design formulations in the ETA and WN and included in Table 11. In Eq. (11), the characteristic rolling shear strengths of CLT 100 and CLT 139 were assumed to be equal to 1.2 and 0.5 MPa, respectively, based on the European Assessment Document 130005-00-0304 [62] and CSA O86-19 [17]. The characteristic values (5th-percentile values) of the shear resistance at supports were also obtained from the experiments using Eq. (15) and then adjusted based on the load-duration factor in CSA O86-19 [17] to obtain design shear resistance. The design shear resistance values, V_d, were also included in Table 11. The predicted design shear resistance based on the design approaches and experiments are compared in Figure 18.

Table 11: The design values of the shear resistance at supports based on the experiments and the prediction of design approaches in the ETA and WN for un-reinforced notched CLT plates.

Test series	$\boldsymbol{d_n}$ [mm]	$\boldsymbol{V}_d$ [kN]	$\boldsymbol{V}_{f,\ \mathrm{ETA}}$ [kN]	$\boldsymbol{V}_{f,\ \mathrm{WN}}$ [kN]
100 ǁ-10	10	21.54	21.24	20.57
100 ǁ-20	20	13.70	7.99	13.39
100 ǁ-30	30	13.51	7.99	9.93
100 ǁ-40	40	13.21	7.99	7.65
100 ⊥-10	10	13.99	7.99	20.57
100 ⊥-20	20	13.56	7.99	13.39
100 ⊥-30	30	11.39	6.18	9.93
100 ⊥-40	40	4.28	2.08	7.65
139 ǁ-17	17	23.64	8.66	8.29
139 ǁ-35	35	15.52	3.93	5.19
139 ǁ-52	52	12.99	3.93	3.76
139 ǁ-70	70	9.36	2.85	2.73
139 ⊥-17	17	10.66	2.85	8.29
139 ⊥-35	35	11.76	2.85	5.19
139 ⊥-52	53	4.02	0.59	3.76



(a)



(b)

Figure 18: Comparison between the design values of the shear resistance at supports obtained from the experiment, V_d, and the predicted shear resistance based on the ETA and WN for un-reinforced notched CLT plates, (a) CLT 100 and (b) CLT 139.

As can be seen in Figure 18, WN [22] is not conservative if the notched corner is located within the lowest transverse layer or under the middle transverse layer for CLT100 ⊥. From Figure 18 and Table 11, it can be seen that the suggested design methods in WN overestimated the shear resistance by 47% and 78% for series 100 ⊥-10 and 100 ⊥-40, respectively. It can also be observed that the suggested design method in ETA is on the very safe side for CLT100 ⊥ and CLT 139 ⊥ with deep notches (Series 100 ⊥-40 and 139 ⊥-52). The design approach in ETA underestimated the shear resistance of series 100 ⊥-40 and 139 ⊥-52 by 51% and 85%, respectively.

4. Conclusions

4.1. Summary

In this study, the performance of CLT plates with notches and their reinforcement with STS was investigated. The following conclusions can be drawn:

i. For un-notched CLT plates, the failure mode was primarily a rolling shear failure in the transverse layers, with subsequent debonding of laminations in certain tests for CLTs oriented in the minor strength direction.

ii. The presence of notches had a significant impact on the shear resistance, failure mode, and crack propagation path of the plates, depending on the location of the notch within the layers of CLT. Notably, the transverse layer's capacity did not contribute to the beam's overall shear resistance when the notch was located within those layers.

iii. Despite not affecting the bending stiffness, notches and reinforcements significantly influenced the load-deflection curves of the CLT plates. Reinforcements, in particular, increased the failure load and maximum deflection of notched plates, with some reinforced specimens even surpassing the maximum deflection of their corresponding un-notched counterparts.

iv. The plates with inclined screws exhibited negligible improvement in shear resistance (4%) and an increase in maximum deflection (6%) compared to those reinforced with vertical screws. Although the CLT plates' ductility with reinforcements was higher than un-reinforced plates, the effect of reinforcement screw angle on ductility was limited.

v. For notches in the "minor" strength direction, the shear resistance of their corresponding un-notched plates could be achieved by reinforcement if the notch was located within their lowest transverse layer. However, for notch ratios greater than 35%, the attained shear resistance was only half of the full shear resistance of the un-notched plates.

vi. A factorial ANOVA was performed to investigate interactions among orientation, notch ratio, and reinforcement affecting shear resistance at the support. Although no significant three-way interaction was found, two-way interactions were examined. Notably, the interactions between orientation and notch ratio, as well as orientation and reinforcement, were both statistically significant. Simple main effects were further analyzed, revealing significant effects of notch ratio and orientation, depending on each other. The results of ANOVA indicated that introducing reinforcements enhanced shear resistance, while varying notch depths affected shear resistance, with exceptions noted for certain cases.

vii. Finally, the study highlighted that the WN design [22] approach might not be conservative when the notched corner was located within the lowest or middle transverse layers for CLTs oriented in the minor strength direction.

4.2. Further work

There are areas that could be addressed in future experimental investigations:

i. Conduct additional experiments to explore a broader range of notch configurations, including different geometries for notches with varying lengths, depths, and tapered notches. This will help to understand the influence of different notch shapes on the shear resistance and failure modes of CLT plates.

ii. Extend the experimental investigation to include notches located on the compression side of the CLT plates. Understanding the behavior of notches on the compression side is essential for comprehensive design guidelines and a deeper understanding of the overall structural performance.

iii. Study the effect of inclined screws with different angles of inclination as reinforcement for notched CLT plates. Comparing the performance of different screw angles will help identify the most efficient and practical reinforcement approach.

iv. Investigate the effectiveness of different types of reinforcement beyond self-tapping screws. This may include GFRP bars, steel plates, or other innovative methods for enhancing the shear resistance and ductility of notched CLT plates.

v. Investigate the impact of edge gluing on the behavior of notched CLT plates. Edge gluing may affect the failure modes and shear resistance, and understanding this aspect will be valuable for practical applications and design guidelines.

In addition to experimental studies, numerical modeling using the finite element method (FEM) and computer simulation of the presented experimental results would be insightful. Numerical studies can provide a deeper understanding of the underlying mechanics and structural response of notched and reinforced CLT plates under various static and dynamic loads. Numerical modeling can be conducted to predict the behavior of CLT plates beyond the tested conditions, leading to more comprehensive design guidelines.

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Appendix A: ANOVA Detailed Analysis Results

A.1: Univariate Analysis of Variance for CLT 100

Table 12: Between-Subjects Factors for CLT 100

		N
Oriatation	Major	48
	Minor	48
Notch Ratio	.00	24
	.10	12
	.20	24
	.30	12
	.40	24
Reinforcement	N	72
	R	24

Table 13: Descriptive Statistics for CLT 100; Dependent Variable: Shear Resistance (kN)

Orientation	Notch Ratio	Reinforcement	Mean	Std. Deviation	N
Major	.00	N	36.0898	1.45461	12
		Total	36.0898	1.45461	12
	.10	N	35.3128	2.34498	6
		Total	35.3128	2.34498	6
	.20	N	22.5208	2.38852	6
		R	33.3643	1.92118	6
		Total	27.9426	6.02815	12
	.30	N	22.1390	1.39714	6
		Total	22.1390	1.39714	6
	.40	N	21.6838	1.94497	6
		R	31.8888	1.57498	6
		Total	26.7863	5.59012	12
	Total	N	28.9727	7.18275	36
		R	32.6266	1.84363	12
		Total	29.8862	6.46309	48

Minor	.00	N	26.6554	2.36559	12
		Total	26.6554	2.36559	12
	.10	N	22.9285	1.47867	6
		Total	22.9285	1.47867	6
	.20	N	22.2517	1.78027	6
		R	26.2057	2.05361	6
		Total	24.2287	2.76069	12
	.30	N	18.6897	1.49785	6
		Total	18.6897	1.49785	6
	.40	N	7.1008	1.34255	6
		R	11.7838	1.53957	6
		Total	9.4423	2.80673	12
	Total	N	20.7136	6.99444	36
		R	18.9948	7.72779	12
		Total	20.2839	7.13960	48
Total	.00	N	31.3726	5.18728	24
		Total	31.3726	5.18728	24
	.10	N	29.1207	6.73216	12
		Total	29.1207	6.73216	12
	.20	N	22.3862	2.01335	12
		R	29.7850	4.19177	12
		Total	26.0856	4.96211	24
	.30	N	20.4143	2.26979	12
		Total	20.4143	2.26979	12
	.40	N	14.3923	7.78062	12
		R	21.8363	10.60398	12
		Total	18.1143	9.85831	24
	Total	N	24.8431	8.17574	72
		R	25.8107	8.86923	24
		Total	25.0850	8.31735	96

Table 14: Levene's Test of Equality of Error Variances for CLT 100

		Levene Statistic	df1	df2	Sig.
Shear Resistance (kN)	Based on Mean	.429	13	82	.955
	Based on Median	.405	13	82	.964
	Based on Median and with adjusted df	.405	13	51.733	.962
	Based on trimmed mean	.428	13	82	.955

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.[a,b]

a. Dependent variable: Shear Resistance (kN)

b. Design: Intercept + Orientation + NotchRatio + Reinforcement + Orientation * NotchRatio + Orientation * Reinforcement + NotchRatio * Reinforcement + Orientation * NotchRatio * Reinforcement

Table 15: Tests of Between-Subjects Effects for CLT 100; Dependent Variable: Shear Resistance (kN)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	6291.605[a]	13	483.970	141.567	<.001	.957
Intercept	50162.795	1	50162.795	14673.256	<.001	.994
Orientation	2117.762	1	2117.762	619.472	<.001	.883
NotchRatio	3240.309	4	810.077	236.958	<.001	.920
Reinforcement	660.922	1	660.922	193.328	<.001	.702
Orientation * NotchRatio	690.243	4	172.561	50.476	<.001	.711
Orientation * Reinforcement	115.534	1	115.534	33.795	<.001	.292
NotchRatio * Reinforcement	.006	1	.006	.002	.966	.000
Orientation * NotchRatio * Reinforcement	1.403	1	1.403	.410	.524	.005
Error	280.330	82	3.419			
Total	66980.728	96				
Corrected Total	6571.934	95				

Table 16: Estimated Marginal Means for CLT 100

Orientation * Notch Ratio * Reinforcement
Dependent Variable: Shear Resistance (kN)

Orientation	Notch Ratio	Reinforcement	Mean	Std. Error	95% Confidence Interval	
					Lower Bound	Upper Bound
Major	.00	N	36.090	.534	35.028	37.152
		R	.[a]	.	.	.
	.10	N	35.313	.755	33.811	36.814
		R	.[a]	.	.	.
	.20	N	22.521	.755	21.019	24.022
		R	33.364	.755	31.863	34.866
	.30	N	22.139	.755	20.637	23.641
		R	.[a]	.	.	.
	.40	N	21.684	.755	20.182	23.185
		R	31.889	.755	30.387	33.390
Minor	.00	N	26.655	.534	25.594	27.717
		R	.[a]	.	.	.
	.10	N	22.929	.755	21.427	24.430
		R	.[a]	.	.	.
	.20	N	22.252	.755	20.750	23.753
		R	26.206	.755	24.704	27.707
	.30	N	18.690	.755	17.188	20.191
		R	.[a]	.	.	.
	.40	N	7.101	.755	5.599	8.602
		R	11.784	.755	10.282	13.285

a. This level combination of factors is not observed, thus the corresponding population marginal mean is not estimable.

A.2: Profile Plots for CLT 100

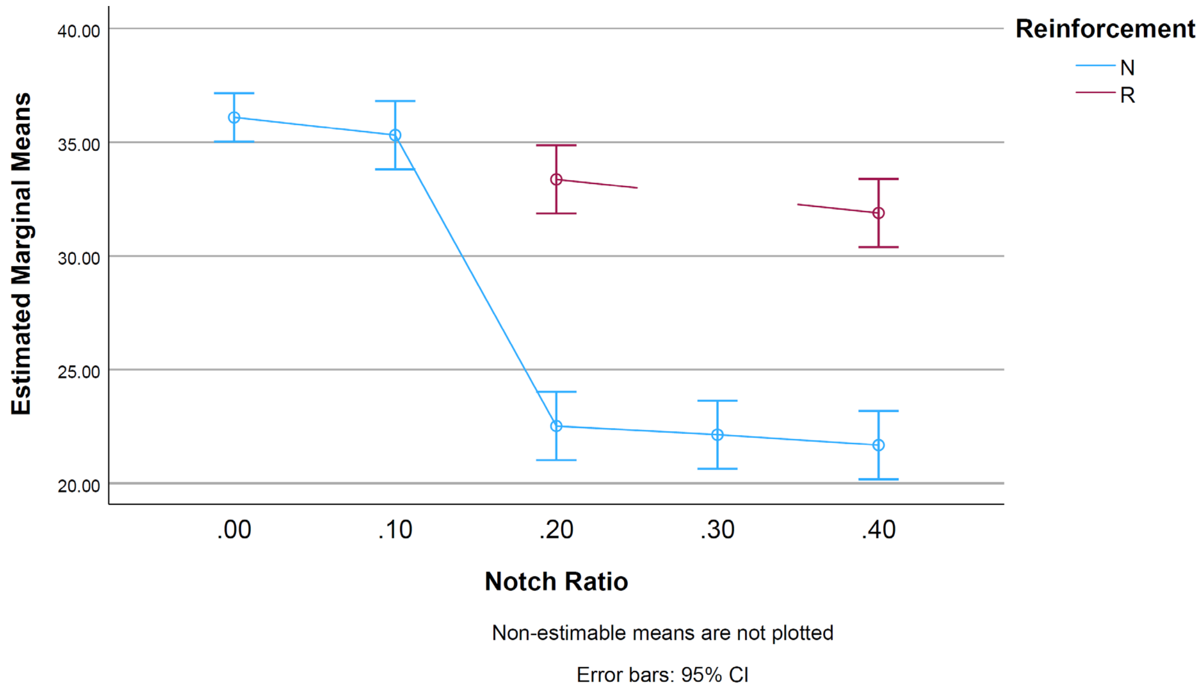

Figure 19: Estimated Marginal Means of Shear Resistance (kN) for CLT 100 at Orientation: Major

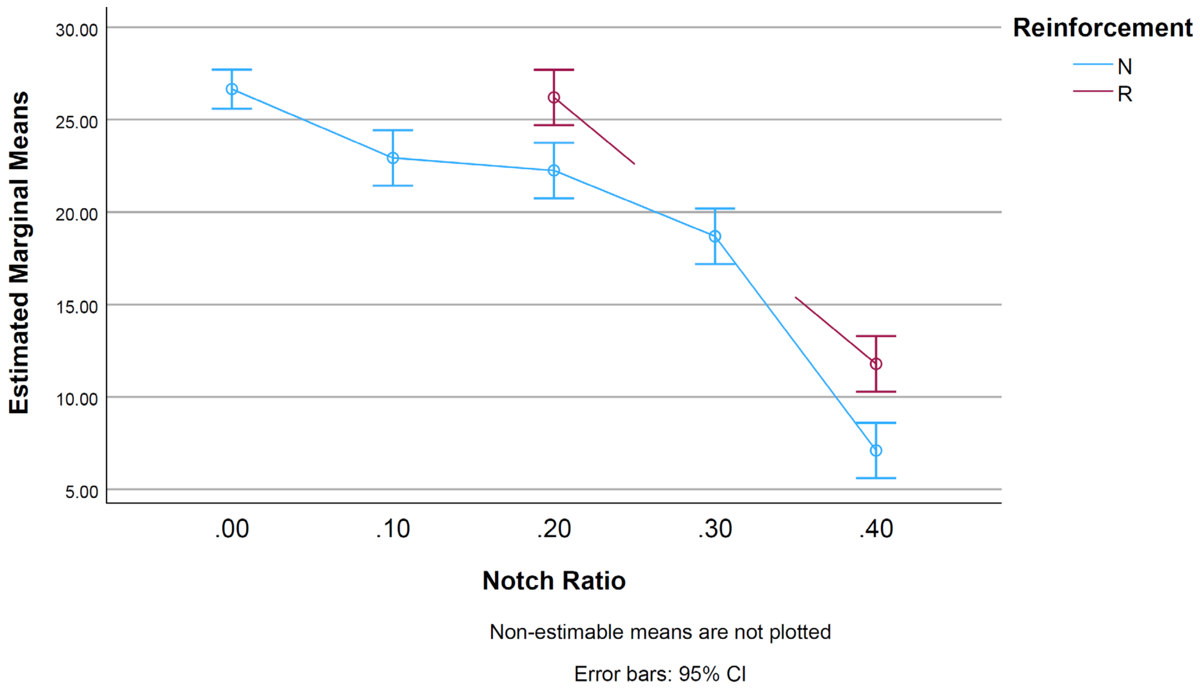

Figure 20: Estimated Marginal Means of Shear Resistance (kN) for CLT 100 at Orientation: Minor

A.3: Univariate Analysis of Variance for CLT 139

Table 17: Between-Subjects Factors for CLT 139

		N
Oriatation	Major	48
	Minor	30
Notch Ratio	.00	12
	.12	12
	.25	24
	.37	24
	.50	6
Reinforcement	IR	6
	N	54
	R	18

Table 18: Descriptive Statistics for CLT 139; Dependent Variable: Shear Resistance (kN)

Orientation	Notch Ratio	Reinforcement	Mean	Std. Deviation	N
Major	.00	N	48.0213	6.76747	6
		Total	48.0213	6.76747	6
	.12	N	39.2623	7.15868	6
		Total	39.2623	7.15868	6
	.25	IR	40.2207	1.89415	6
		N	26.1957	6.58864	6
		R	38.3583	1.63202	6
		Total	34.9249	7.45380	18
	.37	N	21.4953	3.52836	6
		R	39.7233	2.34375	6
		Total	30.6093	9.93841	12
	.50	N	15.4195	2.01710	6
		Total	15.4195	2.01710	6
	Total	IR	40.2207	1.89415	6
		N	30.0788	13.18881	30
		R	39.0408	2.05322	12
		Total	33.5871	11.39138	48

Minor	.00	N	17.1750	1.79442	6
		Total	17.1750	1.79442	6
	.12	N	17.5590	2.18049	6
		Total	17.5590	2.18049	6
	.25	N	19.2507	.79150	6
		Total	19.2507	.79150	6
	.37	N	6.6197	.81357	6
		R	10.5537	.86503	6
		Total	8.5867	2.20495	12
	Total	N	15.1511	5.28834	24
		R	10.5537	.86503	6
		Total	14.2316	5.08014	30
Total	.00	N	32.5982	16.78631	12
		Total	32.5982	16.78631	12
	.12	N	28.4107	12.40641	12
		Total	28.4107	12.40641	12
	.25	IR	40.2207	1.89415	6
		N	22.7232	5.75944	12
		R	38.3583	1.63202	6
		Total	31.0063	9.44827	24
	.37	N	14.0575	8.14311	12
		R	25.1385	15.32620	12
		Total	19.5980	13.26971	24
	.50	N	15.4195	2.01710	6
		Total	15.4195	2.01710	6
	Total	IR	40.2207	1.89415	6
		N	23.4443	12.78176	54
		R	29.5451	13.92456	18
		Total	26.1427	13.36969	78

Table 19: Levene's Test of Equality of Error Variances for CLT 139

		Levene Statistic	df1	df2	Sig.
Shear Resistance (kN)	Based on Mean	5.795	12	65	<.001
	Based on Median	3.130	12	65	.001
	Based on Median and with adjusted df	3.130	12	20.771	.011
	Based on trimmed mean	5.440	12	65	<.001

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.[a,b]

a. Dependent variable: Shear Resistance (kN)

b. Design: Intercept + Orientation + NotchRatio + Reinforcement + Orientation * NotchRatio + Orientation * Reinforcement + NotchRatio * Reinforcement + Orientation * NotchRatio * Reinforcement

Table 20: Tests of Between-Subjects Effects for CLT 139; Dependent Variable: Shear Resistance (kN)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	12869.989a	12	1072.499	78.009	<.001	.935
Intercept	36134.373	1	36134.373	2628.261	<.001	.976
Oriatation	6319.891	1	6319.891	459.682	<.001	.876
NotchRatio	3725.144	4	931.286	67.738	<.001	.807
Reinforcement	1099.844	2	549.922	39.999	<.001	.552
Orientation * NotchRatio	927.938	3	309.313	22.498	<.001	.509
Oriatation * Reinforcement	306.478	1	306.478	22.292	<.001	.255
NotchRatio * Reinforcement	55.182	1	55.182	4.014	.049	.058
Orientation * NotchRatio * Reinforcement	.000	0	.	.	.	.000
Error	893.646	65	13.748			
Total	67071.826	78				
Corrected Total	13763.634	77				

Table 21: Estimated Marginal Means for CLT 139

1. Orientation
Dependent Variable: Shear Resistance (kN)

Orientation	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Major	33.587a	.535	32.518	34.656
Minor	14.232a	.677	12.880	15.584

a. Based on modified population marginal mean.

2. Notch Ratio
Dependent Variable: Shear Resistance (kN)

Notch Ratio	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
.00	32.598a	1.070	30.460	34.736
.12	28.411a	1.070	26.273	30.548
.25	31.006a	.757	29.495	32.518
.37	19.598a	.757	18.086	21.110
.50	15.420a	1.514	12.396	18.443

a. Based on modified population marginal mean.

3. Reinforcement
Dependent Variable: Shear Resistance (kN)

Reinforcement	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
IR	40.221[a]	1.514	37.198	43.244
N	23.444[a]	.505	22.437	24.452
R	29.545[a]	.874	27.800	31.291

a. Based on modified population marginal mean.

4. Orientation * Notch Ratio
Dependent Variable: Shear Resistance (kN)

Orientation	Notch Ratio	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Major	.00	48.021[a]	1.514	44.998	51.044
	.12	39.262[a]	1.514	36.239	42.285
	.25	34.925	.874	33.179	36.670
	.37	30.609[a]	1.070	28.472	32.747
	.50	15.420[a]	1.514	12.396	18.443
Minor	.00	17.175[a]	1.514	14.152	20.198
	.12	17.559[a]	1.514	14.536	20.582
	.25	19.251[a]	1.514	16.228	22.274
	.37	8.587[a]	1.070	6.449	10.724
	.50	.[b]	.	.	.

a. Based on modified population marginal mean.
b. This level combination of factors is not observed, thus the corresponding population marginal mean is not estimable.

5. Oriatation * Reinforcement
Dependent Variable: Shear Resistance (kN)

Orientation	Reinforcement	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Major	IR	40.221[a]	1.514	37.198	43.244
	N	30.079	.677	28.727	31.431
	R	39.041[a]	1.070	36.903	41.179
Minor	IR	.[b]	.	.	.
	N	15.151[a]	.757	13.640	16.663
	R	10.554[a]	1.514	7.531	13.577

a. Based on modified population marginal mean.
b. This level combination of factors is not observed, thus the corresponding population marginal mean is not estimable.

6. Notch Ratio * Reinforcement

Dependent Variable: Shear Resistance (kN)

Notch Ratio	Reinforcement	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
.00	IR	.[a]	.	.	.
	N	32.598	1.070	30.460	34.736
	R	.[a]	.	.	.
.12	IR	.[a]	.	.	.
	N	28.411	1.070	26.273	30.548
	R	.[a]	.	.	.
.25	IR	40.221[b]	1.514	37.198	43.244
	N	22.723	1.070	20.585	24.861
	R	38.358[b]	1.514	35.335	41.381
.37	IR	.[a]	.	.	.
	N	14.058	1.070	11.920	16.195
	R	25.138	1.070	23.001	27.276
.50	IR	.[a]	.	.	.
	N	15.420[b]	1.514	12.396	18.443
	R	.[a]	.	.	.

a. This level combination of factors is not observed, thus the corresponding population marginal mean is not estimable.

b. Based on modified population marginal mean.

7. Orientation * Notch Ratio * Reinforcement

Dependent Variable: Shear Resistance (kN)

Orientation	Notch Ratio	Reinforcement	Mean	Std. Error	95% Confidence Interval	
					Lower Bound	Upper Bound
Major	.00	IR	.[a]	.	.	.
		N	48.021	1.514	44.998	51.044
		R	.[a]	.	.	.
	.12	IR	.[a]	.	.	.
		N	39.262	1.514	36.239	42.285
		R	.[a]	.	.	.
	.25	IR	40.221	1.514	37.198	43.244
		N	26.196	1.514	23.173	29.219
		R	38.358	1.514	35.335	41.381
	.37	IR	.[a]	.	.	.
		N	21.495	1.514	18.472	24.518
		R	39.723	1.514	36.700	42.746
	.50	IR	.[a]	.	.	.

		N	15.420	1.514	12.396	18.443
		R	.[a]	.	.	.
Minor	.00	IR	.[a]	.	.	.
		N	17.175	1.514	14.152	20.198
		R	.[a]	.	.	.
	.12	IR	.[a]	.	.	.
		N	17.559	1.514	14.536	20.582
		R	.[a]	.	.	.
	.25	IR	.[a]	.	.	.
		N	19.251	1.514	16.228	22.274
		R	.[a]	.	.	.
	.37	IR	.[a]	.	.	.
		N	6.620	1.514	3.597	9.643
		R	10.554	1.514	7.531	13.577
	.50	IR	.[a]	.	.	.
		N	.[a]	.	.	.
		R	.[a]	.	.	.

a. This level combination of factors is not observed, thus the corresponding population marginal mean is not estimable.

A.4: Profile Plots for CLT 139

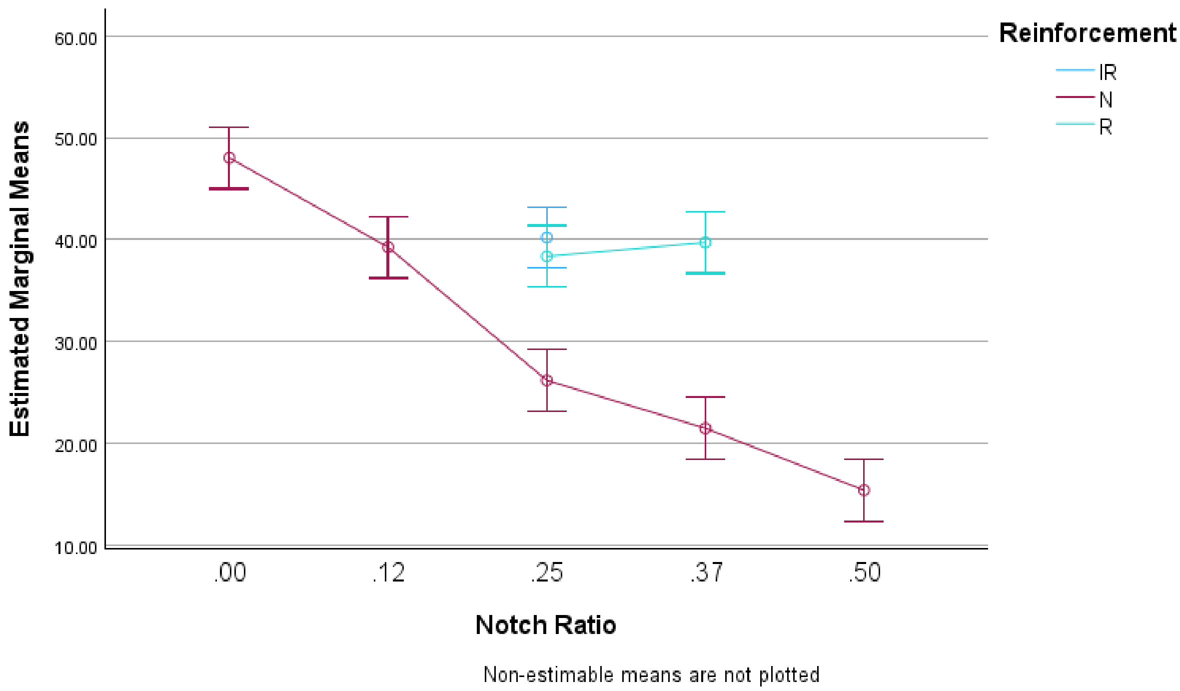

Figure 21: Estimated Marginal Means of Shear Resistance (kN) for CLT 139 at Orientation: Major

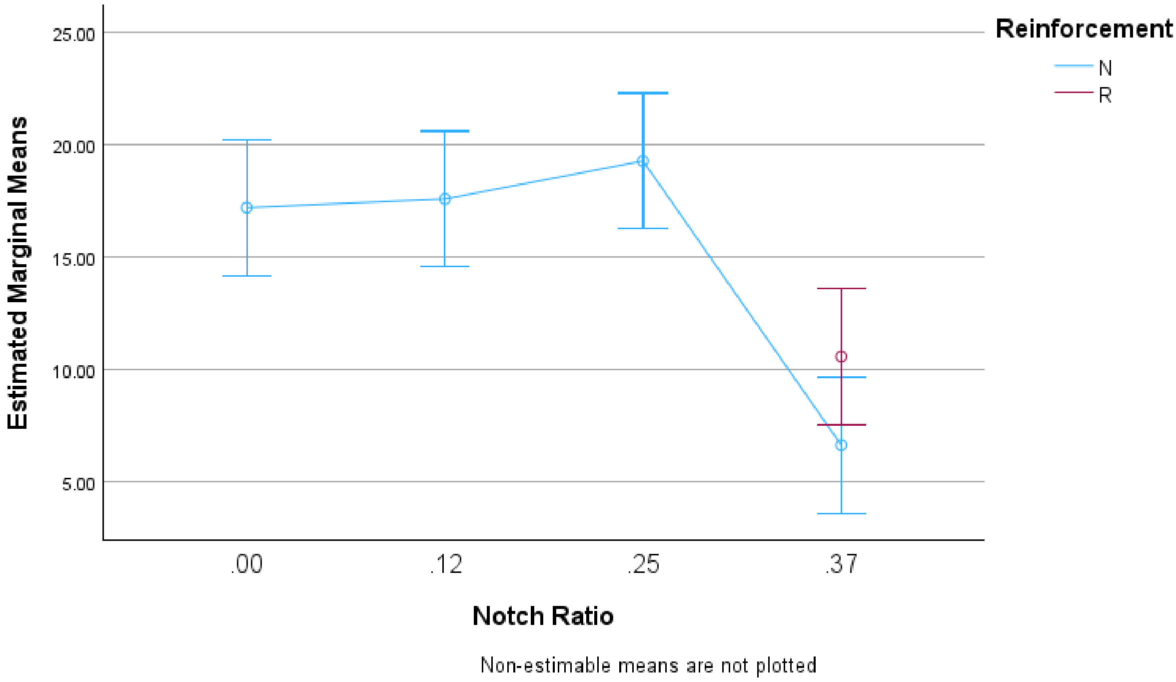

Figure 22: Estimated Marginal Means of Shear Resistance (kN) for CLT 139 at Orientation: Minor