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Measurement and analysis mechanical properties of cross-laminated timber (CLT) product: Case study on typical lampung lamina arrangement

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A B S T R A C T

Recently, the development of cross-laminated timber (CLT) products that can substitute large-dimensional wood for structures and reduce waste of wood products with small dimensions and pieces continues to be developed, and demand from industries continues to increase. Therefore, this study aims to measure and analyze the mechanical properties of cross-laminated timber (CLT) products designed with a typical arrangement of the Lampung region, Indonesia, called a screen arrangement. Measurement and analysis of mechanical properties include measuring load tests and analyzing moments and stiffness of CLT products intended for floor and beam structures. The screen-type wood arrangement used in the product consists of an inner screen arrangement, an outer screen arrangement, and a standing screen arrangement with polyvinyl acetate adhesive. Load test measurements were carried out using a universal testing machine (UTM) and moment and bending stress analysis using engineering mechanics. Generally, the results show that CLT products with standing screens have smaller mechanical properties than those intended for floors and beams. This research shows that the typical CLT arrangement of the Lampung region (Indonesia), in the form of a screen, has strong mechanical properties and characteristics that can be compared with other arrangements.

1. Introduction

In recent years, the global construction industry has witnessed a growing interest in sustainable and innovative building materials that possess enhanced mechanical properties while minimizing the environmental impact. Cross-Laminated Timber (CLT) has emerged as a remarkable solution due to its structural efficiency, renewability, and aesthetic appeal (Anthony & Ali, 2023; Bhandari et al., 2023; Ronquillo, Hopkin, & Spearpoint, 2021). This engineered wood product consists of multiple layers of timber planks bonded together at right angles, thereby forming a sturdy and versatile construction material. One of the critical aspects influencing the mechanical performance of CLT is the arrangement of its constituent layers, known as the lamina arrangement. The mechanical behavior of CLT is strongly influenced by factors such as the arrangement of individual laminae, adhesive bonding quality, and wood species employed. The significance of the lamina arrangement lies in its potential to dictate the distribution of loads, control deformation patterns, and determine overall structural integrity (Cheng, Thomas, Glancey, & Karlsson, 2011; Llorca et al., 2011; Naya, González, Lopes, Van der Veen, & Pons, 2017). However, despite its growing popularity, limited scientific literature has been dedicated to understanding and evaluating the mechanical properties of CLT, particularly concerning unique regional arrangements. The Lampung region, nestled in Indonesia, presents an intriguing case study due to its diverse wood resources and traditional construction practices that have given rise to distinctive lamina arrangements, such as the screen arrangement.This study addresses the research gap by investigating the mechanical properties of CLT products designed using the Lampung region's prevalent screen arrangement. The main aim is to comprehensively measure and analyze the critical mechanical parameters that define the performance of the CLT material under various loading conditions. By conducting a rigorous analysis, including bending strength, shear strength, and modulus of elasticity, this research aims to provide valuable insights into how the screen arrangement impacts the structural behavior

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of CLT (Kurent, Brank, & Ao, 2023; Lineham, Thomson, Bartlett, Bisby, & Hadden, 2016; Mayencourt & Mueller, 2019). Such insights are crucial for both the local construction industry in Lampung and the broader scientific and engineering communities interested in the development and utilization of CLT for sustainable construction.

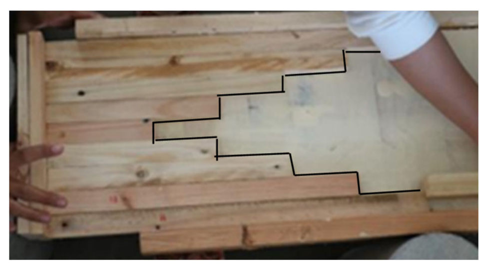
Furthermore, this study seeks to shed light on the feasibility of adopting traditional regional lamina arrangements into contemporary construction practices. The intertwining of traditional knowledge and modern engineering principles can enhance CLT's versatility and applicability, thus promoting the broader acceptance of this eco-friendly building material (Fan & Fu, 2017; Sandberg, Gorbacheva, Lichtenegger, Niemz, & Teischinger, 2023; Familiana, Maulana, Karyadi, Cebro, & Sitorus, 2017). The findings of this research could also contribute to refining existing design codes and guidelines for CLT applications, ensuring safer and more reliable structural systems that harness the inherent benefits of this innovative timber product.

Based on the explanation above, the present study delves into the mechanical properties of CLT, focusing on a specific lamina arrangement found in the Lampung region of Indonesia, referred to as the "screen arrangement." By addressing this research gap, the study aims to provide valuable insights into the performance of CLT under various loading scenarios and shed light on the applicability of traditional regional arrangements in modern construction practices. Ultimately, the research findings could contribute to advancing sustainable building practices, enhancing structural design methodologies, and fostering the evolution of cross-laminated timber as a leading material in the construction industry.

2. Materials and methods

This research used recycled wood with a water content of about 6-12% (w.b.) (ASTM, 2013). The recycled wood material is cleaned and shaved so it is ready to use first. Next, polyvinyl acetate was melted down as a wood adhesive with a predetermined arrangement. The filter arrangement used in this study consists of an inner, outer, and standing screen arrangement (Fig. 1). After the two wood arrangements stick and dry, the test specimen is ready for load testing using the UTM machine. The test specimens consist of 2 designations, including specimens for floor structures and beam structures. The dimensions of the test specimens for the floor structure and beam structure for the inner and outer screen arrangement types are the same, with length, width, and thickness of 1791 mm, 120 mm, and 75 mm, respectively. However, the standing screen arrangement has dimensions of length, width, and thickness of 1791 mm, 120 mm, and 103 mm, respectively. Then the samples were tested using the Universal Testing Machine (UTM) RTF 1350 (capacity of 250 kN) (Sugito, Alisjahbana, & Riyanto, 2022) following the ASTM D905-03 test procedure (Ba et al., 2022).

(a)



(b)

Fig. 1. Screen arrangement specimen (a) Lampung screen (b) specimen with standing screen arrangement

3. Results and Discussions

The results of this study indicate that CLT products designed with standing screens exhibit slightly reduced mechanical properties when compared to those intended for floor and beam applications. This observation highlights the importance of selecting the appropriate arrangement for specific structural requirements (Fig. 2).

Fig. 2. Damage to the connection on the CLT test object

Nevertheless, the overarching finding underscores the robust mechanical characteristics of the typical Lampung region's CLT arrangement, rendering it comparable to other arrangements commonly employed in the construction industry (Guo et al., 2017; Li et al., 2021; Navaratnam et al., 2021). The findings of this research hold significant implications for both the Lampung region's local construction practices and the broader CLT industry. The screen arrangement, rooted in the region's traditional practices, emerges as a viable and competitive option in the contemporary construction landscape. This study not only contributes to the understanding of CLT mechanical behavior but also validates the potential of indigenous arrangements to stand alongside established alternatives (Alshikh, Trepci, & Rodriguez-Ubinas, 2023; Ibañez et al., 2023).

3.1 CLT test results for sieve arrays for floor structures

The provided Table 1 presents the measured mechanical properties of Cross-Laminated Timber (CLT) test specimens with a screen arrangement intended for floor structures. The data includes the inertia, load, moment, and bending stress of three different CLT samples: inner, outer, and standing arrangements. These properties provide valuable insights into the structural behavior and performance of CLT products in this specific arrangement.

Table 1. The results of measurements of the mechanical properties of the CLT test object in the sieve arrangement for the floor structure

Sample	Inertia (mm^4)	Load (kN)	Moment (kN·mm)	Bending stress ($kN{\cdot}mm^{-2}$)
Inner	4,218,750	4,680.7	1,144.57	12.40
Outer	4,218,750	5,237.1	1,560.18	13.87
Standing	10,927,270	7,496.4	2,,235.59	10.54

The calculated inertial values for the inner and outer arrangements are identical, both measuring 4,218,750 mm^4. This indicates that these two arrangements have the same capacity to resist bending deformations. The standing arrangement, with an inertia of 10,927,270 mm^4, has a significantly larger resistance to bending compared to the other two arrangements. This is expected since the Standing arrangement features a higher number of layers, resulting in enhanced stiffness and load-bearing capacity (Bischoff, 2006; Bos, Wolfs, Ahmed, & Salet, 2016; Khaleghi, Salimi, Farhangi, Moradi, & Karakouzian, 2021).

In terms of load distribution, the inner arrangement endured a load of 4,680.7 kN, while the outer arrangement sustained a slightly higher load of 5,237.1 kN. The standing arrangement, despite its increased inertia, supported a load of 7,496.4 kN. These load values highlight the importance of the arrangement in influencing the structural response under applied forces. The higher load-bearing capacity of the standing arrangement is attributed to its greater inertia, indicative of its potential for applications where heavy loads are anticipated (Bechert, Aldinger, Wood, Knippers, & Menges, 2021; Drosos et al., 2012).

The moment values calculated for each arrangement indicate their capacity to resist bending. The inner arrangement demonstrated a moment of 1,144.57 kN·mm, the outer arrangement exhibited a larger moment of 1,560.18 kN.mm, and the standing arrangement had a moment of 2,235.59 kN·mm. These results correspond to the arrangement's ability to resist flexural deformations, where the greater the moment, the more resistant the structure is to bending forces (Martini, Balit, & Barthelat, 2017; Rivera et al., 2021; Yu & Tan, 2013).

The bending stress, or flexural stress, is the stress experienced by the material at the extreme fibers during bending. The inner arrangement had a bending stress of 12.40 $kN{\cdot}mm^{-2}$, the outer arrangement showed a slightly higher value of 13.87 $kN{\cdot}mm^{-2}$, and the standing arrangement exhibited a bending stress of 10.54 $kN{\cdot}mm^{-2}$. These values reveal the stress distribution within the material under bending loads. It's worth noting that the outer arrangement, despite its higher moment and bending stress, showed slightly less inertia and load capacity compared to the Standing arrangement, suggesting a more efficient use of material in the outer configuration.

The data highlights that the Standing arrangement, with its larger inertia and load capacity, is better suited for heavy load-bearing applications such as beams and structural elements subjected to significant bending forces. On the other hand, the inner and outer arrangements offer slightly higher bending stress values, indicating their suitability for scenarios where weight optimization and efficient material utilization are important. The result underscores the importance of considering the arrangement of CLT layers when designing structures. The unique mechanical properties exhibited by each arrangement emphasize the versatility and adaptability of CLT products to different construction contexts. Ultimately, these insights contribute to enhancing the engineering and design practices involving CLT, aiding in the selection of appropriate arrangements for specific project requirements (Gauch, Hawkins, Ibell, Allwood, & Dunant, 2022).

3.2 CLT test results for sieve arrays for beam structures

Table 2 provides a comprehensive overview of the measured mechanical properties of Cross-Laminated Timber (CLT) test specimens with a screen arrangement, specifically designed for beam structures. The data includes key parameters such as inertia, load, moment, and bending stress, for three distinct CLT arrangements: inner, outer, and standing. This data is essential in comprehending the structural performance of CLT elements in beam applications. In line with the data from Table

1, the calculated inertial values for the inner and outer arrangements remain consistent at 4,218,750 mm^4. This signifies the equal resistance to bending deformations exhibited by these two configurations. Conversely, the Standing arrangement possesses an inertia of 10,927,270 mm^4, indicating its significantly improved resistance to bending due to the greater number of layers (Sood, Ohdar, & Mahapatra, 2010).

Table 2. The results of measurements of the mechanical properties of the CLT test object in the sieve arrangement for the beam structure

Sample	Inertia (mm^4)	Load (kN)	Moment (kN·mm)	Bending stress (kN·mm^{-2})
Inner	4,218,750	6,273.5	1,870.49	16.63
Outer	4,218,750	5,873.6	1,750.18	15.56
Standing	10,927,270	8,107.1	2,417.89	11.40

The load capacity of each arrangement is closely aligned with their respective inertial values. The inner arrangement supported a load of 6,273.5 kN, while the outer arrangement carried a load of 5,873.6 kN. The standing arrangement, with its higher inertia, demonstrated a notably increased load capacity of 8,107.1 kN. The enhanced load-bearing ability of the standing arrangement underscores its suitability for scenarios demanding higher structural strength and heavier loads. The moment values offer insights into the arrangements' capacity to resist bending forces. The inner arrangement displayed a moment of 1,870.49 kN·mm, while the outer arrangement exhibited a larger moment of 1,750.18 kN·mm. The standing arrangement, with its greater inertia, presented the highest moment value at 2,417.89 kN.mm. These values indicate the arrangement's ability to withstand bending deformations and the resulting structural stresses (Browning, Ortiz, & Boyce, 2013).

The bending stress, a critical factor in assessing material performance under bending loads, is reflected in the data. The inner arrangement experienced a bending stress of 16.63 kN·mm^{-2}, the outer arrangement displayed a slightly lower value of 15.56 kN·mm^{-2}, and the standing arrangement exhibited a bending stress of 11.40 kN·mm^{-2}. The higher bending stress values for the inner and outer arrangements are consistent with their higher moments, while the slightly lower bending stress of the Standing arrangement is attributed to its larger inertia and load capacity. The data from Table 2 reinforces the conclusion drawn from the previous data analysis (Table 1). The standing arrangement emerges as the optimal choice for applications requiring substantial load-bearing capacity, such as beam structures that experience significant bending forces. The inner and outer arrangements, while maintaining strong mechanical properties, are better suited for contexts where material efficiency and weight optimization are paramount.

The importance of selecting the appropriate CLT arrangement based on specific structural requirements cannot be overstated. The insights derived from this data contribute to informed decision-making in designing and engineering CLT-based structures (Jones, Stegemann, Sykes, & Winslow, 2016). The distinct mechanical properties observed in each arrangement provide a foundation for tailoring CLT products to various construction scenarios while leveraging the inherent benefits of this eco-friendly building material. The findings from Table 2 further validate the versatility and adaptability of CLT products with screen arrangements in different structural applications. By understanding how each arrangement responds to mechanical forces, engineers and designers can confidently integrate CLT into their projects, optimizing both performance and sustainability in the built environment.

3.3 Discussions

The data presented in Table 1 and Table 2 provides a comprehensive insight into the mechanical properties of Cross-Laminated Timber (CLT) test specimens with screen arrangements, intended for different structural applications. A comparative analysis of these tables enables a deeper understanding of how the arrangement of CLT layers influences the mechanical behavior of the material in distinct scenarios: floor structures (Table 1) and beam structures (Table 2). Comparing load capacities across the two tables reveals noteworthy differences. In Table 1, the standing arrangement demonstrated the highest load-bearing capacity for floor structures, carrying a load of 7,496.4 kN. This was followed by the outer arrangement with a load capacity of 5,237.1 kN, and the inner arrangement with a load capacity of 4,680.7 kN. In Table 2, for beam structures, the standing arrangement exhibited the greatest load capacity of 8,107.1 kN, followed by the Inner arrangement with 6,273.5 kN, and the outer arrangement with 5,s873.6 kN.

This comparison highlights the fact that the standing arrangement consistently displays the highest load-bearing capacity in both floor and beam applications. It is evident that the arrangement with the largest inertia benefits from increased load-carrying ability, making the standing arrangement a favorable choice for structures subjected to significant loads. The bending stiffness and stress data also provide insights into the arrangements' performance. In Table 1, the Inner arrangement displayed higher bending stress (12.40 kN·mm^{-2}) compared to the outer arrangement (13.87 kN·mm^{-2}) despite carrying a slightly smaller load. The standing arrangement, which exhibited the lowest bending stress (10.54 kN·mm^{-2}), carried the highest load. In Table 2, the pattern continued, but with interesting nuances. The inner arrangement, despite having the highest bending stress (16.63 kN·mm^{-2}), also demonstrated the highest load-bearing capacity. This could be attributed to the arrangement's efficient use of material. The outer arrangement, despite a lower bending stress (15.56 kN·mm^{-2}), carried a slightly smaller load, possibly due to its material distribution. The comparison between Table 1 and Table 2 underscores the arrangement's pivotal role in influencing mechanical properties based on the structural application. The findings consistently emphasize that the standing arrangement outperforms the inner and outer arrangements in terms of load capacity, while the latter arrangements exhibit higher bending stress.

Designers and engineers must consider these nuances when selecting an arrangement for specific projects. For floor structures demanding higher load-bearing capacities, the Standing arrangement is an ideal choice. On the other hand, for beam structures, where optimizing material usage and bending stress are crucial, the inner and outer arrangements provide efficient alternatives. The comparative analysis reveals a clear relationship between arrangement, load capacity, and bending behavior. The consistent performance of the Standing arrangement in both floor and beam applications underlines its versatility, while the inner and outer arrangements offer tailored solutions depending on project-specific priorities. The data underscores the significance of arrangement selection in achieving structural efficiency and performance while harnessing the capabilities of CLT as a sustainable construction material.

4. Conclusion

The escalating demand for sustainable and innovative construction materials has fueled the advancement of Cross-Laminated Timber (CLT) products as viable alternatives to traditional large-dimensional wood structures. By conducting extensive measurement and analysis, including load tests, moment assessment, and stiffness analysis, this research has shed light on the mechanical behavior of CLT products intended for floor and beam structures. The investigation of the mechanical properties of CLT products unveiled valuable insights into their structural performance under different loading conditions. The utilization of an inner, outer, and standing screen arrangement, combined with polyvinyl acetate adhesive, demonstrated the inherent strength and durability of this configuration.

Finally, this study contributes to the growing body of knowledge surrounding CLT products and their mechanical properties. By examining the Lampung region's screen arrangement, it underscores the feasibility of this arrangement for constructing sturdy and reliable structural elements. As the demand for sustainable construction solutions continues to rise, the insights gleaned from this research can guide both regional and global stakeholders toward the effective implementation of cross-laminated timber in various construction projects. Furthermore, the study emphasizes the importance of preserving and incorporating traditional knowledge into modern engineering practices, fostering a synergy between heritage and innovation for a more sustainable built environment.

References

Alshikh, Z., Trepci, E., & Rodriguez-Ubinas, E. (2023). Sustainable Off-Site Construction in Desert Environments: Zero-Energy Houses as Case Studies. *Sustainability, 15*(15), 11909. doi:doi.org/10.3390/su151511909

Anthony, C. J., & Ali, M. M. (2023). Structural Design of a Single-Family Residential Dwelling Using Cross-Laminated Timber (CLT). Sustainable Built Environment, Ch. 14. doi:doi.org/10.5772/intechopen.110790

ASTM. (2013). American society for testing materials: Standard test method for strength properties of adhesive bonds in shear by compression loading: ASTM D 905. *Annual Book of ASTM Standards, 15*. doi:doi.org/10.1520/D0905-08R13

Ba, J., Ji, X., Wang, B., Li, P., Lin, J., Cao, J., & Qi, J. (2022). Microstructure design of C/C composites through electrochemical corrosion for brazing to Nb. *Journal of Materials Science & Technology, 104*, 33-40. doi:doi.org/10.1016/j.jmst.2021.06.074

Bechert, S., Aldinger, L., Wood, D., Knippers, J., & Menges, A. (2021). Urbach Tower: Integrative structural design of a lightweight structure made of self-shaped curved cross-laminated timber. *Structures, 33,* 3667-3681. doi:doi.org/10.1016/j.istruc.2021.06.073

Bhandari, S., Riggio, M., Jahedi, S., Fischer, E. C., Muszynski, L., & Luo, Z. (2023). A review of modular cross laminated timber construction: Implications for temporary housing in seismic areas. *Journal of Building Engineering, 63*, 105485. doi:doi.org/10.1016/j.jobe.2022.105485

Bischoff, E. E. (2006). Three-dimensional packing of items with limited load bearing strength. *European Journal of Operational Research, 168*(3), 952-966. doi:doi.org/10.1016/j.ejor.2004.04.037

Bos, F., Wolfs, R., Ahmed, Z., & Salet, T. (2016). Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing. *Virtual and Physical Prototyping, 11*(3), 209-225. doi:doi.org/10.1080/17452759.2016.1209867

Browning, A., Ortiz, C., & Boyce, M. C. (2013). Mechanics of composite elasmoid fish scale assemblies and their bioinspired analogues. *Journal of the Mechanical Behavior of Biomedical Materials, 19*, 75-86. doi:doi.org/10.1016/j.jmbbm.2012.11.003

Cheng, L., Thomas, A., Glancey, J. L., & Karlsson, A. M. (2011). Mechanical behavior of bio-inspired laminated composites. *Composites Part A: Applied Science and Manufacturing, 42*(2), 211-220. doi:doi.org/10.1016/j.compositesa.2010.11.009

Drosos, V., Georgarakos, T., Loli, M., Anastasopoulos, I., Zarzouras, O., & Gazetas, G. (2012). Soil-Foundation-Structure Interaction with Mobilization of Bearing Capacity: Experimental Study on Sand. *Journal of Geotechnical and Geoenvironmental Engineering, 138*(11), 1369-1386. doi:doi.org/10.1061/(ASCE)GT.1943-5606.0000705

Familiana, H., Maulana, I., Karyadi, A., Cebro, I. S., & Sitorus, A. (2017). Characterization of aluminum surface using image processing methods and artificial neural network methods. In 2017 *International Conference on Computing, Engineering, and Design (ICCED) (pp. 1-6).* IEEE. doi:10.1109/CED.2017.8308113.

Fan, M., & Fu, F. (2017). 1 - Introduction: A perspective – natural fibre composites in construction. Advanced High Strength Natural Fibre Composites in Construction, 1-20. doi:doi.org/10.1016/B978-0-08-100411-1.00001-7

Gauch, H. L., Hawkins, W., Ibell, T., Allwood, J. M., & Dunant, C. F. (2022). Carbon vs. cost option mapping: A tool for improving early-stage design decisions. *Automation in Construction, 136*, 104178. doi:doi.org/10.1016/j.autcon.2022.104178

Guo, H., Liu, Y., Meng, Y., Huang, H., Sun, C., & Shao, Y. (2017). A Comparison of the Energy Saving and Carbon Reduction Performance between Reinforced Concrete and Cross-Laminated Timber Structures in Residential Buildings in the Severe Cold Region of China. Sustainability, 9(8). doi:doi.org/10.3390/su9081426

Ibañez, D., Salka, M., Guallart, V., Boeri, S., Shamir, L., De Marco, M. L., . . . Boulet, S. (2023). Innovative Design, Materials, and Construction Models for BioCities. *Transforming Biocities: Designing Urban Spaces Inspired by Nature,* 183-215. doi:doi.org/10.1007/978-3-031-29466-2_8

Jones, K., Stegemann, J., Sykes, J., & Winslow, P. (2016). Adoption of unconventional approaches in construction: The case of cross-laminated timber. *Construction and Building Materials, 125*, 690-702. doi:doi.org/10.1016/j.conbuildmat.2016.08.088

Khaleghi, M., Salimi, J., Farhangi, V., Moradi, M. J., & Karakouzian, M. (2021). Application of Artificial Neural Network to Predict Load Bearing Capacity and Stiffness of Perforated Masonry Walls. *CivilEng, 2*(1), 48-67. doi:doi.org/10.3390/civileng2010004

Kurent, B., Brank, B., & Ao, W. K. (2023). Model updating of seven-storey cross-laminated timber building designed on frequency-response-functions-based modal testing. *Structure and Infrastructure Engineering, 19*(2), 178-196. doi:doi.org/10.1080/15732479.2021.1931893

Li, X., Ashraf, M., Subhani, M., Kremer, P., Li, H., & Anwar-Us-Saadat, M. (2021). Rolling shear properties of cross-laminated timber (CLT) made from Australian Radiata Pine – An experimental study. *Structures, 33*, 423-432. doi:doi.org/10.1016/j.istruc.2021.04.067

Lineham, S. A., Thomson, D., Bartlett, A. I., Bisby, L. A., & Hadden, R. M. (2016). Structural response of fire-exposed cross-laminated timber beams under sustained loads. *Fire Safety Journal, 85*, 23-34. doi:doi.org/10.1016/j.firesaf.2016.08.002

Llorca, J., González, C., Molina-Aldareguía, J. M., Segurado, J., Seltzer, R., Sket, F., . . . Canal, L. P. (2011). Multiscale Modeling of Composite Materials: a Roadmap Towards Virtual Testing. *Advanced Materials, 23*(44), 5130-5147. doi:doi.org/10.1002/adma.201101683

Martini, R., Balit, Y., & Barthelat, F. (2017). A comparative study of bio-inspired protective scales using 3D printing and mechanical testing. *Acta Biomaterialia, 55*, 360-372. doi:doi.org/10.1016/j.actbio.2017.03.025

Mayencourt, P., & Mueller, C. (2019). Structural Optimization of Cross-laminated Timber Panels in One-way Bending. *Structures, 18,* 48-59. doi:doi.org/10.1016/j.istruc.2018.12.009

Navaratnam, S., Widdowfield Small, D., Gatheeshgar, P., Poologanathan, K., Thamboo, J., Higgins, C., & Mendis, P. (2021). Development of cross laminated timber-cold-formed steel composite beam for floor system to sustainable modular building construction. *Structures, 32*, 681-690. doi:doi.org/10.1016/j.istruc.2021.03.051

Naya, F., González, C., Lopes, C. S., Van der Veen, S., & Pons, F. (2017). Computational micromechanics of the transverse and shear behavior of unidirectional fiber reinforced polymers including environmental effects. Composites Part A: *Applied Science and Manufacturing, 92*, 146-157. doi:doi.org/10.1016/j.compositesa.2016.06.018

Rivera, J., Murata, S., Hosseini, M. S., Trikanad, A. A., James, R., Pickle, A., . . . Kisailus, D. (2021). Structural Design Variations in Beetle Elytra. Advanced Functional Materials, 31(50), 2106468. doi:doi.org/10.1002/adfm.202106468

Ronquillo, G., Hopkin, D., & Spearpoint, M. (2021). Review of large-scale fire tests on cross-laminated timber. *Journal of Fire Sciences, 39*(5), 327-369. doi:doi.org/10.1177/07349041211034460

Sandberg, D., Gorbacheva, G., Lichtenegger, H., Niemz, P., & Teischinger, A. (2023). Advanced Engineered Wood-Material Concepts. Springer Handbook of Wood Science and Technology, 1835-1888. doi:doi.org/10.1007/978-3-030-81315-4_35

Sood, A. K., Ohdar, R. K., & Mahapatra, S. S. (2010). Parametric appraisal of mechanical property of fused deposition modelling processed parts. *Materials & Design, 31*(1), 287-295. doi:doi.org/10.1016/j.matdes.2009.06.016

Sugito, S., Alisjahbana, S. W., & Riyanto, H. (2022). Modeling of Mechanical Performance from Concrete Made by Combining Iron Sand and Glass Powder Filler under Hot Water Curing Condition. *Mathematical Modelling of Engineering Problems, 9*(2). doi:doi.org/10.18280/mmep.090216

Yu, J., & Tan, K.-H. (2013). Experimental and numerical investigation on progressive collapse resistance of reinforced concrete beam column sub-assemblages. *Engineering Structures, 55*, 90-106. doi:doi.org/10.1016/j.engstruct.2011.08.040