WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA
Advancing Timber for the Future Built Environment

DYNAMIC RESPONSE OF DIAGONAL LAMINATED TIMBER – PARAMETER STUDIES AND MODELLING APPROACHES

Erik Serrano[1], Henrik Danielsson[2], Peter Persson[3]

ABSTRACT: The paper provides an overview and preliminary results from ongoing research with the aim to evolve cross-laminated timber (CLT) into the next generation of Tailored Laminated Timber (TLT). This is done by exploring innovative concepts that optimize the mechanical performance, while simultaneously ensuring adherence to circular economy principles. The current study aims at investigating the potential in terms of Diagonal Laminated Timber (DLT), where adjacent layers are oriented at a non-orthogonal direction relative to each other. Finite element parameter studies were performed, showing differences in dynamic behaviour for DLT compared to CLT. The study highlights the potential of using DLT as a means of tailoring the vibration performance. In addition, the paper discusses strength and weaknesses of different modelling approaches, with special emphasis on choice of element types and the detailed modelling of non-edge glued laminations.

KEYWORDS: cross-laminated timber, diagonal-laminated timber, structural design, floor vibrations, serviceability limit state

1 – INTRODUCTION

1.1 BACKGROUND

To maintain competitiveness in the future, CLT must undergo innovations to enhance material efficiency and address its reliance on a limited range of softwood species. The Innovative Tailored Laminated Timber (InnoTLT) research initiative, part of the Bioeconomy in the North program, seeks to advance CLT by devising innovative strategies to strengthen the future competitiveness of timber construction and by developing optimized, tailored solutions referred to as *Tailored Laminated Timber* (TLT).

One such tailored solution is diagonal laminated timber (DLT), in which the orthogonally oriented layers of CLT have been rotated, so that adjacent layers may be oriented at any angle relative each other.

1.2 PREVIOUS WORK AND MOTIVATION

DLT has been researched in several previous studies, *e.g.* [1–5], where static strength and stiffness properties have been investigated, and where the DLT has been used for in-plane loads as a beam or as a wall element, and for out-of-plane loading as a floor element. According to [4, 5], the technical benefits of using DLT in such out-of-plane loading situations, is very much dependent on the specific design situation, meaning floor span, support conditions and loading. Benefits of introducing DLT for 5-layer slabs seem limited, and thus larger spans and applications demanding seven layers or more seem to be of main interest [4, 5].

The low frequency range is of prime concern for timber floors in terms of their vibrational response. As an example, for timber floors, at eigenfrequencies <200 Hz, various mitigation strategies can be applied to arrive at competitive enough solutions, see Gibson [6]. However, such mitigation strategies become increasingly inefficient at lower frequencies, with floating floors being less efficient below about 120 Hz and resilient ceiling mounts below approximately 60 Hz [6, 7, 8]. To simplify and reduce the need for such mitigation strategies, it is crucial to find floors with better performance in those low-frequency ranges.

It seems that inadequate attention has been drawn to the dynamic properties of DLT and, consequently, there is a lack of knowledge. The current study includes numerical investigations on the dynamic properties of DLT for frequencies below 500 Hz.

1.3 AIM

The main aim of the research of which this study forms a part, is to gain increased knowledge about the mechanical performance of various innovative (non-standard) CLT-like products. Our research deals with both load-bearing characteristics, for ultimate limit state situations, and stiffness and vibrational response relevant for serviceability limit state design. This paper aims at presenting a first pilot study relating to the latter area of research and discusses the results in relation to the use of diagonal laminated timber (DLT) in floor elements.

[1] Erik Serrano, Division of Structural Mechanics, Lund University, Lund, Sweden, erik.serrano@construction.lth.se,
ORCID iD: 0000-0002-5333-0682

[2] Henrik Danielsson, Division of Structural Mechanics, Lund University, Lund, Sweden, henrik.danielsson@construction.lth.se,
ORCID iD: 0000-0002-8805-6687

[3] Peter Persson, Division of Structural Mechanics, Lund University, Lund, Sweden, peter.persson@construction.lth.se,
ORCID iD: 0000-0003-1591-9258

https://doi.org/10.52202/080513-0242

A secondary aim has been to investigate different modelling techniques to find efficient yet accurate modelling approaches for research and (possibly other) modelling approaches for use in everyday design practise. With such knowledge structural design can be more time efficient, results be more accurate, and software developers can find efficient approaches for implementation (recommendations for programme users can also be formulated). The secondary aim should also be seen in the light of the standardisation work in Europe. Late 2024, a new working group (WG11+subgroups) of CEN/TC250/SC5 started its work with formulating a standard relating to finite element-supported structural design of timber structures.

1.4 OVERVIEW

The paper presents various results from finite element analyses, where parameter studies of the dynamic response of DLT represent the main content. The parameters investigated are primarily those related to geometry and lay-up, *i.e.* the size of the panels, the number of layers and the layer thicknesses, and the orientation (angle) of the individual layers.

In addition to the structural behaviour of DLT, the paper also discusses modelling approaches, and especially the influence of detailed modelling of non-edge-bonded laminations, comparing FE-models based on 3D solid elements and models based on composite shell elements.

2 – METHODS

2.1 MODELLING APPROACHES

Abstraction levels

Level 1: This level of abstraction involves the most number of simplifications in terms of geometry and kinematics by introducing plate/shell theory (*e.g.* Reissner-Mindlin theory (Timoshenko)) and modelling only the geometry of the mid-surface of the plate. Depending on the software used, it is possible to build up the shell section by defining the properties (material, orientation and thickness) of each layer. In addition, by partitioning the model it is possible to represent different parts of the plate where alternative materials are placed. The main benefit of this approach is the greatly reduced number of degrees of freedom (DOFs). The approach is also the one most used in engineering practice.

Unless higher order plate/shell theory is used, it can be difficult to capture shear deformations accurately (influence of shear compliant layers). It should also be mentioned that it is not always possible to implement DLT in a standard shell element in a consistent manner, depending on the software available: some off-diagonal (coupling terms) of the stiffness matrix of the plate/shell element need to be set to non-zero values due to the shell elements directions not coinciding with the principal material directions, see Arnold [9].

Level 2a: For this level of abstraction (and levels 3 & 4), the thickness of the DLT is geometrically modelled. Homogeneous material properties and constant material directions are assumed within each layer. This gives a simple geometry, which is easy to mesh. The main drawback compared to Level 1 is the increased number of DOFs (3D solid elements need to be used). The main benefit would be the possibility to more accurately model the deformation field, not having to resort to assumptions of *e.g.* plane sections remaining plane.

Level 2b: Further developing the approach of Level 2a, each layer is now partitioned into volumes, each such volume representing a lamination. With this approach it is possible to introduce different lamination materials at different locations. However, the effect of gaps between non-edge-glued laminations is not captured.

Level 3: Here a model including the geometry of the individual laminations is used but including also the modelling of non-edge glued laminations. Thus, a complete 3D-representation of the geometry is used, giving the benefit of being able to model gaps of arbitrary width between the laminations (with or without contact interactions).

Element types

The current study involves models based on the use of different element types, depending on abstraction level of the models, and depending also on the meshing functionality of the software used (ABAQUS [10]). Standard, brick-shaped hexahedral 3D solid continuum elements were used in the convergence studies for comparison to other element types and both linear 8-node bricks ("C3D8") and quadratic 20-node bricks with reduced integration ("C3D20R") were investigated. To simplify the meshing process, 3D solid continuum elements with a tetrahedral shape were used for some of the models including non-orthogonal orientation of the laminations. In such cases quadratic, 10-node, tetrahedral elements were employed ("C3D10").

Linear, brick-shaped continuum solid shell elements ("CSS8") were used for the main part this work – the vibrational studies. This element was chosen based on the conclusions drawn from the convergence studies. The elements are geometrically fully compatible with standard 3D solid brick elements but are efficient in situations involving bending thanks to being formulated using additional shape functions (incompatible modes) and assumed strain fields.

Standard quadrilateral, linear shell elements, involving five degrees of freedom per node ("S4R"), were also used in the convergence studies, for comparison with other element types.

Analysis types

Different types of analysis have been performed: a) static stress analysis, b) eigenvalue extraction and c) steady-state response analyses (modal analysis based on reduced number of eigenmodes).

As regards analysis of type a), these were performed to benchmark the performance of various element types, and to perform convergence studies as regards the static stiffness of DLT plates.

Analysis of type b) were performed during convergence studies but are also necessary to perform prior to conducting modal steady-state analyses.

https://doi.org/10.52202/080513-0242

Analysis of type c), finally, constitutes the main approach used. All analyses results, as regards vibrational response, are based on calculations under free-free conditions, for a unit point load applied in one corner of the DLT plate. Loading is applied in a frequency sweep 1–562 Hz to cover the entire one-third octave band with centre frequency 500 Hz. The steady-state response is based on eigenmodes corresponding to eigenfrequencies below 1124 Hz (*i.e.* twice the loading frequency range).

The evaluation metric used for the vibrational analyses is based on the response (acceleration) of all nodes on the top surface of the plate. Since unit loading is applied, the resulting acceleration represents an accelerance frequency response function (FRF).

The different types of models used are summarised in Tab. 1. Results presented here do not cover all studies performed.

Table 1. Overview of modelling approaches.

Abstraction level	Element types	Analysis type
1, 2b, 3	S4R, C3D8, CSS8, C3D10, C3D20R	Convergence studies, and influence of modelling approaches
2a	CSS8	Parameter studies

2.2 PARAMETER STUDIES

Material parameters

All material parameters used in the FE-analyses were chosen based on the material parameters used in previous studies, for comparability reasons. Consequently, the material data used, and given in Tab. 2, were found by calibrating FE-models to experimental results (in terms of eigenvalues, modes and damping) as described in [11, 12]. The material parameter values are close to the ones given in EN338 for timber strength class C24.

Table 2. Overview of material parameters used in FE-analyses.

Parameter	Value	Comment
E_L	12 000 MPa	Longitudinal MOE
E_R=E_T	370 MPa	Transverse MOE
G_{LR}=G_{LT}	600 MPa	Longitudinal shear modulus
G_{RT}	62 MPa	Rolling shear modulus
ν_{LR}= ν_{LT} = ν_{RT}	0.40 (-)	Poisson's ratio
ρ	428 kg/m^3	Density
ξ	0.7 %	Damping

Geometries

Three different plate sizes have been investigated in this study, one for the convergence studies, and two plate sizes for the main parameter studies on vibrational performance.

The convergence studies were performed on a *small* 5-ply CLT plate, measuring 1.2×2.5 m^2. It had a total thickness of 150 mm with a lay-up of 5×30 mm thick layers, oriented 0-90-0-90-0.

The vibrational response analyses were conducted using two exemplary plates sizes, one *medium* five-ply plate measuring 2.4×5.0 m^2 with 5×30 mm thick layers, oriented 0-α_1-90-(-α_1)-0 and a *large,* seven-ply plate measuring 2.4×9.0 m^2 with 7×45 mm thick layers, oriented 0-α_1-α_2-90-(-α_2)-(-α_1)-0. Here α_i is the angle of orientation of a layer, relative the outermost layer. Thus, the total thicknesses were 150 and 315 mm for the *medium* and *large* plates, respectively.

For reasons of making comparisons easier and clarifying the influence of changing only the orientation of laminations, the total plate thicknesses have not been varied. This might result in some of the combinations investigated not being relevant for a design situation in practice, since they might not fulfil design requirements.

The parameter studies are based on the reference layups of the *medium* and the *large* plates. These, and the various combinations investigated are presented in Tab. 3.

Table 3. Plate sizes and lay-ups investigated. The reference configurations are underlined.

Plate	Layer thickness	Layer orientations
Small 1.2×2.5 m^2	30-30-30-30-30	<u>0-90-0-90-0</u>
Medium 2.4×5.0 m^2	30-30-30-30-30	<u>0-90-0-90-0</u> 0-75-0-75-0 0-60-0-60-0 0-45-0-45-0 0-30-0-30-0 0-15-0-15-0
Large 2.4×9.0 m^2	45-45-45-45-45-45-45	<u>0-0-90-0-90-0-0</u> 0-0-60-0-60-0-0 0-0-45-0-45-0-0 0-15-90-0-90-15-0 0-30-90-0-90-30-0 0-45-90-0-90-45-0 0-60-90-0-90-60-0 0-15-45-0-45-15-0 0-15-60-0-60-15-0

Evaluation metrics

The main results of the FE-analyses of the parameter studies are given in terms of the response of the plate subjected to the dynamic loading. A number of choices are then to be made in terms of evaluation metrics.

Firstly, it could be argued whether acceleration, velocity or displacement should be used. It is, however most commonly assumed that in terms of perception of vibrations, humans are sensitive to acceleration. The current Eurocode 5, and draft versions of the upcoming Eurocode 5, use similar metrics, including the unit impulse velocity response, [m/(s^2·N)] and acceleration. For the investigation of sound radiation, the (spatially averaged) normal velocity response of the structure would be of prime concern.

Secondly, it is necessary to limit the frequency range being investigated. Referring to the introductory discussion on the aim of the study being related to vibrations of floor, we here focus on evaluating the accelerance, *i.e.* the acceleration response per unit loading, highlighting the response for frequencies below 200 Hz.

https://doi.org/10.52202/080513-0242

3 – RESULTS

3.1 PRELIMINARIES – CONVERGENCE

The convergence studies presented here were conducted using the small panel, cf. Tab. 3.

Calculation of eigenfrequencies

The calculated eigenfrequencies and eigenmodes are dependent on the element type used. The main results from convergence studies are given in Fig. 1, depicting the predicted 60 first eigenfrequencies for various choices of element types and mesh densities.

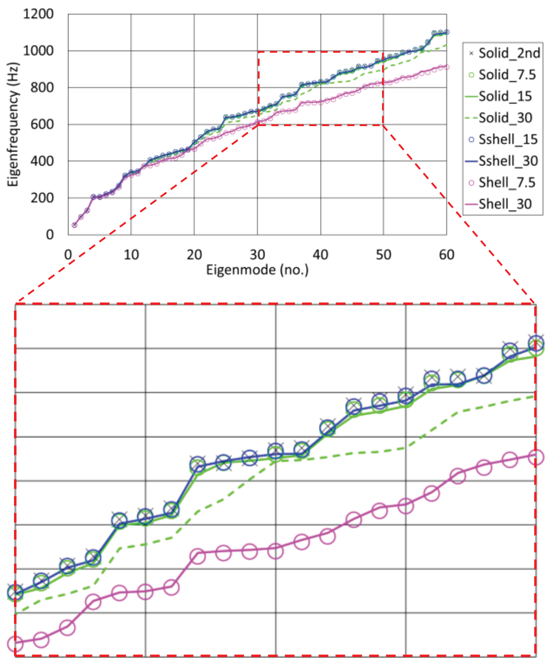

Figure 1. Eigenfrequencies for modes 1-60 for CLT with 5×30 mm layers. Legend: Second order brick (30 mm) "Solid_2nd", linear brick elements (7.5, 15 and 30 mm) "Solid", continuum solid shell elements (15 and 30 mm) "Sshell" and shell element (30 mm) "Shell".

Three main conclusions can be drawn. Firstly, using shell elements, deviating results are obtained after approximately the 10th eigenmode. This is mainly due to the shell element not representing accurately enough the out-of-plane shear stiffness of the CLT. To fully capture the shear deformation pattern, higher order shell elements need to be adapted, such that it would be possible to relax the restraint of "plane cross sections remaining plane" during deformation. A simpler work-around could be to calculate a reduced shear correction factor, possibly based on the so-called shear layer theory, see for example Kreuzinger and Scholz [13].

Secondly, it seems that with only one 2nd order solid element per layer, reasonable accuracy is obtained – compare the curves denoted "Solid_2nd" and "Sshell_15".

Thirdly, it was concluded that the continuum solid shell elements give an accurate enough solution using two elements in the thickness direction of each layer. This was adopted for the parameter studies. Even a single element per layer gives very similar results, cf. Fig. 1.

Accelerance – Influence of element types and size

A convergence study on the acceleration response of the small plate was performed and the results using standard (brick shaped) continuum elements are shown in Fig. 2. For linear brick elements, converged results are obtained at element sizes of 7.5 mm or smaller, meaning that a model of 1.0 m^2 of CLT of 150 mm thickness would consist of approximately 350 000 elements and 1.1 million degrees of freedom (DOFs). For 2nd order elements, roughly 30 mm size seems to give reasonable results, reducing the number of elements to about 5 500 and the number of DOFs to about 80 000, for that 1.0 m^2 CLT.

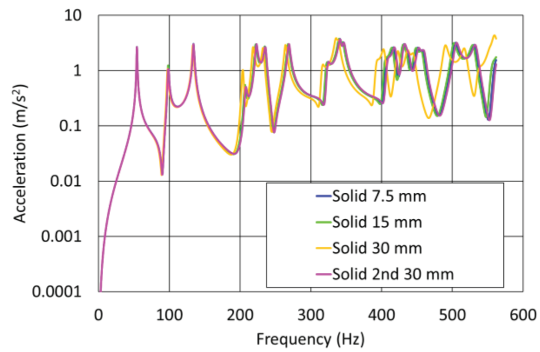

Figure 2. First order solid brick elements 7.5, 15 and 30 mm + 2nd order brick elements, 30 mm.

The efficiency of the continuum solid shell elements is evidenced in Fig. 3, showing a comparison between that element type and again the standard 2nd order brick element. Negligible differences in accelerance are obtained for a solid shell element of the same size as the 2nd order brick element. At equal element size, the cost for the solid shell element is lower, since it only has eight nodes, while the 2nd order brick element has 20 nodes.

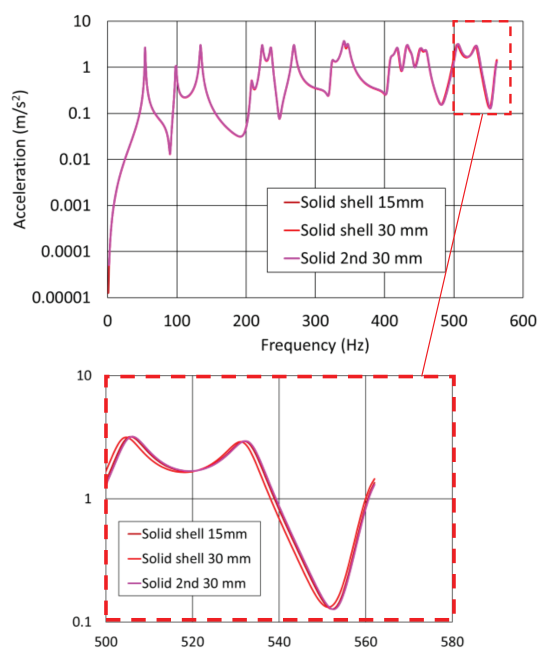

Figure 3. Continuum solid shell elements 15- and 30-mm size vs. 2nd order brick element, 30 mm size. Top: 0–562 Hz. Bottom:500–562 Hz.

https://doi.org/10.52202/080513-0242

Accelerance – Influence of non-glued edges

As mentioned in the introduction, this study also aimed at investigating efficient yet as simple as possible modelling approaches. Thus, a small investigation was performed to verify the influence of the level of detailing in modelling individual laminations in a layer. As an example of the results, the accelerance FRFs of two models are presented in Fig. 4. One model had all layers modelled as continuous, and one where each lamination was individually modelled with the "seam" functionality of the software used, [10], leaving all adjacent lamination edges within the same layer completely free.

As can be seen, cf. Fig. 4, the introduction of seams leads to the accelerance peaks being shifted towards lower frequencies. This is consistent with the expected lower stiffness of the plates containing seams. Consequently, if non-edge glued laminations are modelled in a simplified way, with solid layers, the material properties of that layer should be calibrated (adjusted) to account for that simplification, see *e.g.* [14].

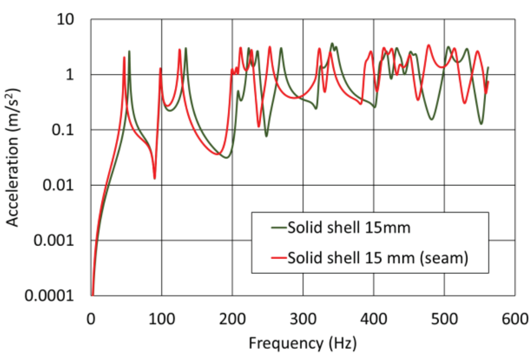

Figure 4. Continuum solid shell elements 15 mm size. Influence of non-edged glued laminations.

3.2 EIGENMODES

Eigenmodes up to 1124 Hz were extracted for all models. As an example of typical behaviour, the first six modes for the reference layups and two TLT-layups are shown in Fig. 5 and Fig. 6, for the medium and the large plates, respectively. The DLT-layups introduce shifts of the natural frequencies, and in some cases the mode orders are switched. For the chosen examples, cf. Fig. 5 and Fig. 6, the frequency shifts are more pronounced for the medium panels (up to 35%) than for the large panels (up to 15%).

3.3 ACCELERANCE

The main results are presented as accelerance FRFs. Below, the different lay-ups are compared to the reference cases, which have the orthogonal orientations 0-90-0-90-0 and 0-0-90-0-90-0-0 for the 5-layer and 7-layer panels, respectively. The loading was a unit point load at one of the plate's corners to excite all modes of interest, and the loading was swept over the frequency range 1–562 Hz, at 0.1 Hz intervals. The spatial root mean square (RMS) of the (complex) acceleration, summed over the top surface of the panel was calculated for each frequency. In addition, for comparison of overall performance, the RMS summed over all frequencies was calculated.

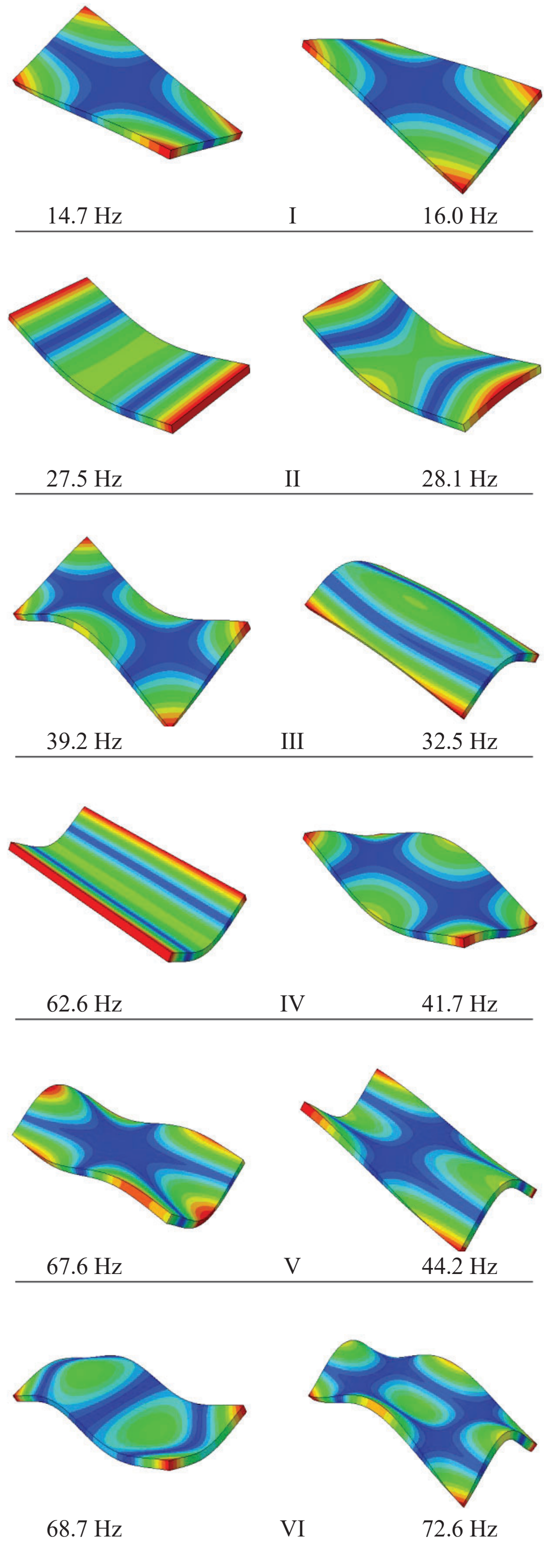

Figure 5. Eigenmodes I-VI, medium panel. Left: reference CLT-layup. Right: Layup 0-45-0-45-0. Continuum solid shell elements (15 mm size, two elements in the thickness direction, per layer).

https://doi.org/10.52202/080513-0242

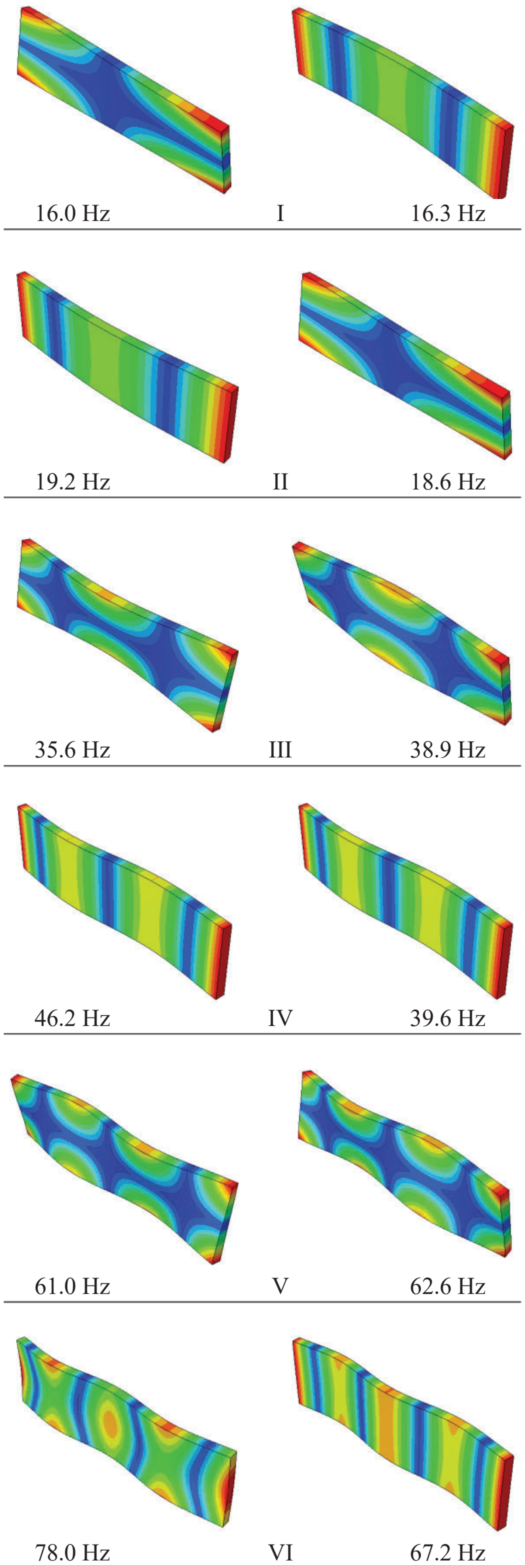

Figure 6. Eigenmodes I-VI, large panel. Left: reference CLT-layup. Right: Layup 0-60-90-0-90-60-0. Continuum solid shell elements (30 mm size, two elements in the thickness direction, per layer).

Overall performance

Tab. 4 summarises the overall performance of the medium panels presenting the results in terms of the RMS value over various frequency intervals. As can be seen, in most cases, the DLT layups investigated here perform poorer than the standard CLT, in terms of overall RMS.

Table 4. RMS of acceleration of different frequency ranges, medium panel. Values given are changes relative the reference case (0%). Red indicates poorer performance and green indicates improved performance.

	Frequency range (Hz)				
Lay-up	**<100**	**<200**	**<300**	**<400**	**<500**
0-90-0-90-0	0%	0%	0%	0%	0%
0-75-0-75-0	-2%	-1%	-1%	-2%	-1%
0-60-0-60-0	-5%	4%	-1%	3%	-0%
0-45-0-45-0	11%	4%	2%	-0%	-2%
0-30-0-30-0	9%	1%	1%	3%	-3%
0-15-0-15-0	9%	8%	4%	1%	-4%

Likewise, Tab. 5 summarises the results in terms of the RMS value over the same frequency intervals for the large panels. The response in the range 1–100 Hz is improved for most lay-ups. For two lay-ups an improvement is found for all frequency ranges investigated, see Tab. 5. The improvement is a 10–20% smaller response. For the lay-ups with worse performance a 30–40% increased response is found.

Table 5. RMS of acceleration of different frequency ranges, large panel. Values given are changes relative the reference case (0%). Red indicates poorer performance and green indicates improved performance.

	Frequency range (Hz)				
Lay-up	**<100**	**<200**	**<300**	**<400**	**<500**
0-0-90-0-90-0-0	0%	0%	0%	0%	0%
0-0-60-0-60-0-0	-10%	15%	11%	26%	31%
0-0-45-0-45-0-0	-30%	16%	14%	40%	32%
0-15-90-0-90-15-0	2%	2%	0%	-3%	-3%
0-30-90-0-90-30-0	-2%	0%	-2%	-10%	-11%
0-45-90-0-90-45-0	-6%	-5%	-14%	-15%	-9%
0-60-90-0-90-60-0	-12%	-15%	-14%	-14%	-22%
0-15-45-0-45-15-0	-23%	15%	11%	41%	33%
0-15-60-0-60-15-0	-2%	13%	13%	30%	36%

Frequency response functionss

The FRFs of both the medium and the large panels are depicted in Fig. 7, showing the overall behaviour (1–562 Hz) and, for clarity, the behaviour for frequencies below 200 Hz. Again, for clarity, only the reference lay-ups and the best and worst performing panels are shown, cf. Tab. 4 and Tab. 5.

In all cases investigated, the first eigenmode is shifted towards a higher frequency, and the accelerance response *below* that frequency was always smaller for the DLT layups relative the reference lay-ups.

https://doi.org/10.52202/080513-0242

When evaluating accelerance FRFs, it is important to note the number of eigenmodes included in the range being evaluated, since a small shift in eigenfrequencies might have a large influence on the resulting RMS-value. This is clarified in the 1/3 octave band representation given in Fig. 7. There it is shown that a markedly different response for the DLT relative to the standard CLT can be seen in a specific band. Consequently, even if the performance is much worse in a certain frequency band, it might be very much better in a neighbouring band. In addition, this characteristic is very much dependent on the (arbitrary) choice of band limits, and the usefulness of such a representation for comparison between lay-ups is limited.

4 – DISCUSSION

The computed accelerance FRFs indicate that for certain frequency intervals, it is beneficial to introduce DLT-layups. However, the results also clearly show that such an effect is sensitive to the range of interest.

It should be emphasised that the present study has used free-free conditions in the dynamic analyses and, consequently, relate to the inherent properties of the plate (at cross section level). The behaviour of DLT plates in specific design situations, including service-like displacement boundary conditions, remains to be investigated

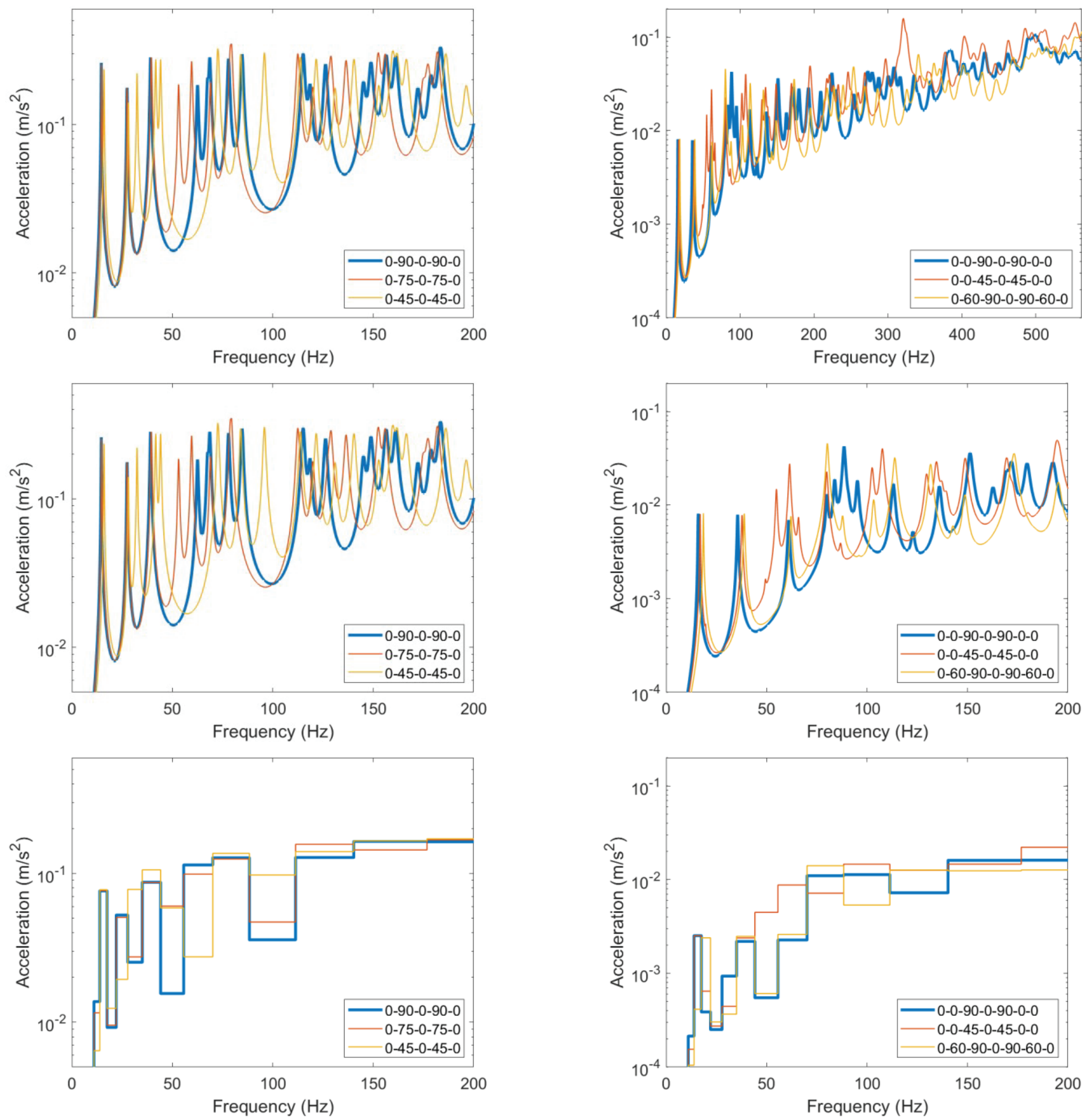

Figure 7. Left: Root mean square of the acceleration for the medium (5-layer) panels. Right: Root mean square of the acceleration for the large (7-layer) panels. Frequency ranges are 1-562 (top), 1–200 Hz (mid) and 1–200 Hz in 1/3 octave bands (bottom).

https://doi.org/10.52202/080513-0242

The rating of the dynamic performance is sensitive to, and thus dependent on, which frequency bands that are being investigated. As a consequence, it is on the one hand likely that finding a DLT-layup that in general has a lower vibration response than standard CLT, would constitute a considerable challenge. This means, on the other hand, that it might be possible to find *tailored* solutions for specific situations.

In terms of static performance, the studies of Arnold [4, 9] showed examples of such specific situations: situations involving twisting and/or bi-axial bending, and where, DLT can perform considerably better that standard CLT. Situations involving such loading include 3- and 4-sided supported plates, plates on point supports and plates with (large) holes.

5 – CONCLUSIONS

The main conclusions drawn from the work presented are:

- DLT can be part of a vibration mitigation strategy when well-defined loading scenarios need to be addressed.
- In modelling DLT, it was shown that so-called continuum solid shell elements provided an efficient approach.
- Models where the laminations are assumed to be perfectly edge-bonded (level 1, 2a and 2b) give different results in terms of dynamic response, compared to when non-edge-glued laminations are included (level 3), especially for higher frequencies.

Of special interest for future work would be to study:

- Equivalent shell element properties and equivalent properties for continuous layer-models, to account for the contribution of shear deformations due to non-edge-glued laminations.
- Additional lay-ups and panel sizes.
- Situations involving realistic loading and support conditions, to be able to characterise the performance of building structures (e.g. a floor supported by walls, free edges, floor panels with holes etc.).

6 – ACKNOWLEDGEMENTS

The research presented here was performed within the project *InnoTLT*, a part of the Bioeconomy in the North programme, and within the project *Opportunities for High-Performance CLT*. The financial support received from Sweden's Innovation Agency (Vinnova), Federal Ministry of Education and Research (BMBF), Germany, The Research Council of Norway, the ÅForsk foundation and the Södra research foundation is gratefully acknowledged.

7 – REFERENCES

[1] I. Bejtka. "Cross (CLT) and diagonal (DLT) laminated timber as innovative material for beam elements", Karlsruher Berichte zum Ingenieurholzbau, Band 17, KIT Scientific Publishing, Karlsruhe, 2011.

[2] D. Buck, X. Wang, O. Hagman, and A. Gustafsson. "Bending properties of cross laminated timber (CLT) with a 45° alternating layer configuration", BioRes. 11(2), 2016, 4633–4644.

[3] J. Turesson, Z. Sharifi, S. Berg, and M. Ekevad. Influence of laminate direction and glue area on in-plane shear modulus of cross-laminated timber. SN Appl. Sci. 2, 2126 (2020). https://doi.org/10.1007/s42452-020-03918-1.

[4] M. Arnold, P. Dietsch, and S. Winter. "Mechanical Properties of Innovative Multifunctional Cross–Laminated Timber", WCTE 2020/21 (2020), Technical University of Munich.

[5] A. Svensson. "Innovativ utformning av KL–trä – Diagonalt orienterade brädor" [Innovative design of CLT – Diagonal laminated timber], MSc dissertation, Report TVSM–5269, Division of Structural Mechanics, Lund University, Sweden, 2024.

[6] B. Gibson, T. Nguyen, S. Sinaie, D. Heath, T. Ngo. "The low frequency structure-borne sound problem in multi-storey timber buildings and potential of acoustic metamaterials: A review". Building and Environment, Vol. 224 (109531), 2022, https://doi.org/10.1016/j.buildenv.2022.109531.

[7] P. Sipari. "Sound insulation of multi-storey houses – a summary of Finnish impact sound insulation results", Building Acoustics 7 (1) (2000) 15–30.

[8] M. Caniato et al. "Impact sound of timber floors in sustainable buildings", Building and Environment 120 (2017) 110–122.

[9] M. Arnold. "Mechanical Properties of Diagonal Laminated Timber (DLT) with Respect to Point-Supported Mass Timber Slabs". PhD-thesis, Technical University of Munich, Germany, 2024. http://dx.doi.org/10.13140/RG.2.2.34208.29440

[10] Dassault Systemes Simulia Corp. ABAQUS/CAE, Version 2023, 2022.

[11] S. Johansson, K. A. Ung. "Impact of different lamellae materials on vibrations in CLT panels–A numerical study of concrete, air or elastomer materials". MSc dissertation, Report TVSM–5270, Division of Structural Mechanics, Lund University, Sweden, 2024.

[12] T. Abdallah, E. Jepson. "Utilization of different wood Materials in cross-laminated Timber elements – A study of different configurations". MSc dissertation, Report TVSM–5271, Division of Structural Mechanics, Lund University, Sweden, 2024.

[13] H. Kreuzinger and A. Scholz. Wirtschaftliche Ausführungs- und Bemessungsmethode von ebenen Holzelementen (Brücken, Decken, Wände). Research report, München: Technical University of Munich, 1999.

[14] J. Turesson, S. Berg, and M. Ekevad, M. "Impact of board width on in-plane shear stiffness of cross-laminated timber." Engineering Structures, 196, 109249. https://doi.org/10.1016/j.engstruct.2019.05.090.

https://doi.org/10.52202/080513-0242