Chair of Timber Structures and Building Construction
TUM School of Engineering and Design
Technical University of Munich

Timber Colloquium Munich 2025

Colloquium Proceedings

Chair of Timber Structures and Building Construction
TUM School of Engineering and Design
Technical University of Munich

Logo TimCoM 2025, Foto. Janna Vollrath

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The *Chair of Timber Structures and Building Construction*
is organizing the first ever *Timber Colloquium Munich (TimCoM)*!

During the colloquium, the research of the chair – as well as extraordinarily good master‘s theses – will be presented. It is an event for students and interested parties from research and practice.

The participation fee will be donated to the *Verein zur Förderung des Lehrstuhls für Holzbau und Baukonstruktion an der Technischen Universität München*. The funds will be used to promote research and teaching in the field of timber structures and building construction in accordance with the purpose of the association.

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LaNaSys – Bringing CLT to the Next Level

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Abstract: This article deals with the further development of cross laminated timber (CLT) in the research project LaNaSys. CLT is a widely used mass timber product. The aim of the project was to raise the material efficiency as well as to unlock new areas of application for timber structures. This is accomplished by disintegrating the inner layers of CLT and using hardwood instead of softwood. The disintegration allows adding prestressing cables inside the elements to activate the secondary load bearing direction. Additionally, a new approach for timber concrete composite (TCC) elements, again making use of the disintegration, is developed. The feasibility of the approaches is proven through different mechanical tests.

Keywords: CLT, hardwood, hybrid, disintegration, prestressing, timber concrete composite, mechanical tests

1 – Why must we enhance CLT?

Cross laminated timber (CLT) is a very successful timber product that is widely used in all kinds of timber structures. Its advantages compared to other timber products include

- a good fire safety,
- a good noise protection,
- a good dimensional stability,
- the possibility to manufacture huge elements,
- its design flexibility and
- its versatile architectural usability.

CLT was first established in the 1990's and its production has since grown exponentially to almost 2 Mio. m³ per year [1], [2], cf. Figure 1.

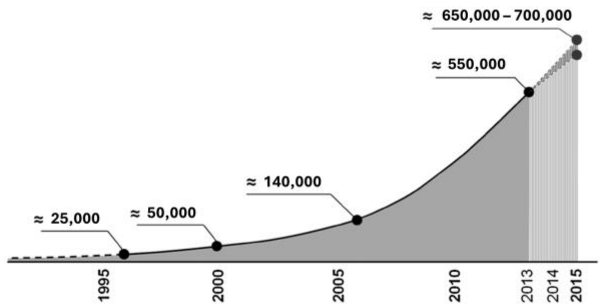

Figure 1: Development of the worldwide production volume of CLT until 2013 and forecast until 2015 in m³ [2]

However, as a mass timber product, CLT uses lots of raw materials, mainly softwood timber. The lumber demand has grown equivalently [1]. But the climate change is putting pressure on the central European softwood forests. High temperatures, dry seasons and storms have become more frequent. The felling of storm-damaged timber has thus increased from 7.8 Mio. m³ in 2016 to 60.1 Mio. m³ in 2020, in 2021 the value amounted to 50.5 Mio. m³ [3].

Hardwood forests and mixed forests, on the other hand, are much more resilient than pure softwood forests. The hardwood also has superior mechanical properties, but it is today often only used for energy extraction, i.e. burned.

So, one might ask – Is CLT really the answer to the future of timber construction? Or do we need to develop new products that raise the material efficiency of CLT, regarding the overall material use as well as regarding the use of softwood in particular. The aim of the research project LaNaSys was exactly this – to enhance CLT to ensure a strong further growth of timber construction in Europe in the future.

2 – Raising the Material Efficiency

Raising the material efficiency was done by

- substituting the inner softwood lamellae (spruce) with hardwood lamellae (beech) and
- arranging the inner lamellae at a distance to each other creating cavities, which is called disintegration.

Additionally, a fire-stop layer was added in the bottom layer to prevent fire from entering the cavities and to achieve a superior fire safety similar to that of concrete elements. The research project focused on floor slab elements.

An example of a typical LaNaSys layup is shown in Figure 2.

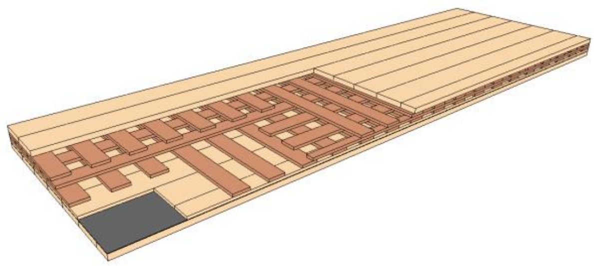

Figure 2: LaNaSys layup with softwood (light brown), hardwood (dark brown) and a fire-stop layer made of modified Cottonid (gray)

In numerous mechanical experiments, the layup was optimized, and the mechanical behavior was investigated. This started with smaller shear tests. Subsequently, bending tests with different spans were executed.

Figure 3 shows the maximum forces from the bending tests with a span of 3.9 m. In addition to the LaNaSys specimens, one specimen made only out of spruce, i.e. standard CLT, was tested as a reference and one specimen where only the cross layers were substituted by beech lamellae was tested as a benchmark, both without disintegration.

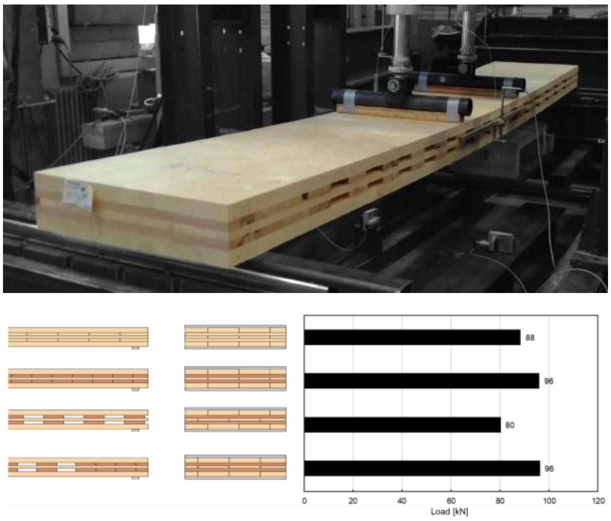

Figure 3: Bending specimen in the test facility (above) and maximum loads from the bending tests (below)

Generally, the disintegrated LaNaSys variant shows a lower load bearing capacity compared to the variants without disintegration. One LaNaSys variant, however, reaches the same load bearing capacity as the benchmark and thus outperforms even the standard CLT. This is accomplished by arranging the cross layers without distances near the supports and only disintegrating the slab near the middle of the span where the shear loads are low. With this variant, about 16 % of the raw material could be saved, or even 32 % when not taking into account the beach lamellae which would normally have been burned.

Besides the load bearing capacity, the bending stiffnesses of the elements are of great interest as they determine the deflection and vibration of the slab which are often decisive for the design. The results concerning the bending stiffnesses of the different variants are shown in Figure 4.

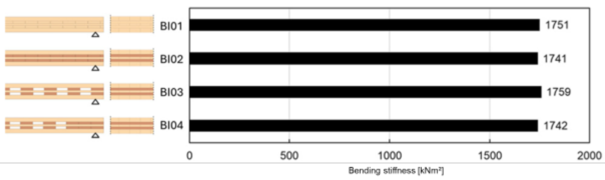

Figure 4: Bending stiffnesses from the bending tests

It can clearly be seen that the differences between the variants are negligible.

Summing up, the LaNaSys layup can achieve a higher load bearing capacity than standard CLT while saving a significant amount of material at the same time. The bending stiffness is practically not influenced by the variation. If the load bearing capacity is not decisive for the design, even more material can be saved, optimizing the layup towards maximum material efficiency.

3 – New Areas of Application

But to be really successful, it is not enough to merely replace CLT. What is needed in the future is a timber product that is competitive against solutions made of concrete, especially for the use in multi-story buildings. To unlock new areas of application, several approaches were investigated in the LaNaSys project.

One approach was to use the cavities inside the elements to integrate prestressing cables that can be used to connect multiple slab elements next to each other. Thus, the secondary load bearing direction can be activated. The principle of this approach is depicted in Figure 5.

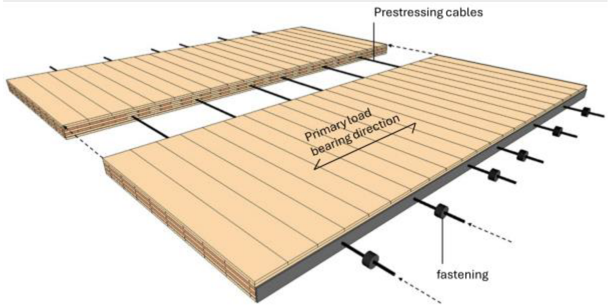

Figure 5: Principle of prestressed LaNaSys elements with biaxial load transfer

Preliminary tests proved that the prestressing can be achieved with relatively low effort using a manual hydraulic pump. Two individual elements were connected using prestressing cables and then tested under uniaxial bending. The prestressing first led to a camber, than the specimens deformed with the same bending stiffness as reference specimens without joint, cf. Figure 6.

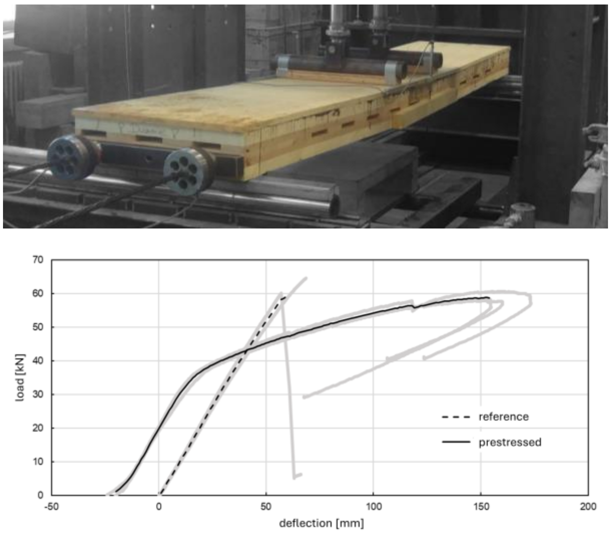

Figure 6: Prestressed specimen under uniaxial bending in the test facility (above) and load-deflection diagram of the prestressed specimens vs. reference specimens without joint (below)

In big biaxial bending tests, the prestressing principle could be validated, cf. Figure 7.

Figure 7: Prestressed specimen under biaxial bending in the test facility

Another approach was to develop a timber concrete composite (TCC) variant without any additional fasteners. This can be achieved by again making use of the LaNaSys layup, disintegrating the top layer and letting the concrete pour into the element forming a form fitted connection. In a production plant that is designed for disintegrated structures, this can be done without any additional effort.

Again, preliminary bending tests proved the feasibility of the TCC approach, cf. Figure 8.

Figure 8: TCC specimen under bending in the test facility

The TCC approach can even be combined with the prestressing to achieve two-way spanning slab elements with higher spans. Respective biaxial bending tests could also be executed within the research project, cf. Figure 9.

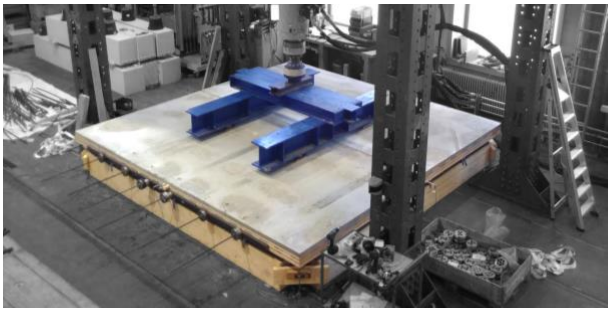

Figure 9: Prestressed TCC specimen under biaxial bending in the test facility

The two-way spanning could be a game changer for the timber building industry allowing for new areas of application like point supported slabs that could until now only be realized with reinforced concrete. This could possibly accelerate the growth of timber constructions even further.

4 – Launching LaNaSys

In order to launch LaNaSys production and the use of such disintegrated elements in real projects, a technical approval is needed. The assessment plan with the tests required for a German technical approval was prepared within the research project and can be used by any interested manufacturer to obtain an approval. A new production facility for LaNaSys elements has also been planned, but with smaller modifications, it is also possible to produce LaNaSys prototypes in a conventional CLT facility.

The advantages of LaNaSys are partly bought by more complex load bearing mechanisms due to the disintegration. For the practical application of LaNaSys, simplified design rules will be developed.

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Numerical Investigation on the Material Behavior of Hardwood Glulam Beam-Columns Subjected to Combined Bending and Axial Compression

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Abstract: This paper presents a numerical investigation of hardwood Glulam beam-columns subjected to combined bending and axial compression. The paper compares the load-bearing capacities resulting from a bilinear elastic-plastic material behavior and a non-linear elastic-plastic material behavior with softening using beech GL 48h. The numerical investigations were performed using SOFiSTiK FEA 2024, based on a 4-point bending test setup. The results show that both material behaviors have similar load-bearing capacities for low axial forces. However, the non-linear material behavior at higher axial loads predicts lower bending capacities up to 35 % due to softening effects. While the bilinear material behavior is suitable for determining the load-bearing capacity under N_x-M_y-interaction more easily, the non-linear material behavior allows the full consideration of plasticization effects. For a more accurate beam-column modeling, stress-strain relationships should be derived from combined bending-compression tests rather than pure bending or compression tests.

Keywords: *timber material model, plasticising, hardwood, finite element method*

1 – Introduction

A common load case in timber engineering is the combined acting of axial force and bending (N_x-M_y interaction). This interaction occurs mostly for beam-columns like slender beams, resulting in lateral torsional buckling, or for columns, resulting in in-plane buckling. For both buckling phenomena, a non-linear material behavior influences the load-bearing capacity caused by the reduction of the bending stiffness EI due to plasticizing. Under compression parallel to the grain, timber shows an elastic-plastic material behavior with plastification before reaching the maximum compression strength $f_{c,0}$. Afterwards, a softening occurs. Hardwood, in comparison to softwood, shows a more pronounced elastic-plastic material behavior. As the interest in using hardwoods in timber engineering continues to grow, existing standards need to be re-evaluated, since they were developed based on material models for softwood.

This paper presents the numerical results of a single-span beam under combined acting of axial force and bending for a bilinear material model and a non-linear material model with softening for beech Glulam (GL 48h). The maximum load-bearing capacities were determined based on the materially non-linear analysis of the numerical model. This paper intends to recommend whether to choose a simple bilinear material model or a non-linear material model for timber elements under N_x-M_y-interaction.

2 – Numerical Investigation

2.1 – General

The numerical simulations were conducted to analyze the influence of two different material behaviors on the N_x-M_y interaction. A materially non-linear analysis was chosen, neglecting geometrical non-linearities and imperfections. The numerical simulations were conducted with shell elements in SOFiSTiK FEA 2024.

2.2 – Modeling

A single-span beam with a cross-section of $b \times h$ = 100 x 600 mm² was investigated (see Figure 1). The span and load application results from a 4-point-bending test setup according to EN 408:2010 [1]. Therefore, the span is 10,800 mm with a load F_z acting at two points at the upper edge of the beam. The distance between the load F_z and the supports A and B is 3.6 m. Additionally, the beam is loaded by an axial compression force F_x. The axial compression force is applied first and kept at a constant level. Secondly, the load F_z is applied. Supports A and B are modelled as an idealized support. The displacement boundary conditions of support A and B are set at a reference point with a horizontal distance to the beam of 10 cm. Using couplings to connect the reference points to the beam elements, support conditions could be transferred.

The numerical simulations are based on a bilinear elastic-plastic material behavior and a non-linear elastic-plastic material behavior with softening (see Figure 2). The simulations were conducted with the characteristic values of Beech GL 48h in Table 1 according to EHRHART [2]. The regular anisotropic material behavior was simplified by assuming an isotropic material behavior. In tension, the stress-strain relationship is described by a linear increasing curve without softening until the bending strength f_m is reached.

Table 1: Material values of GL 48h according to EHRHART [2]

Material	Value
$f_{m,0,k}$	48 N/mm²
$f_{c,0,k}$	50 N/mm²
$E_{c,0,05}$	14,400 N/mm²
G_{05}	900 N/mm²

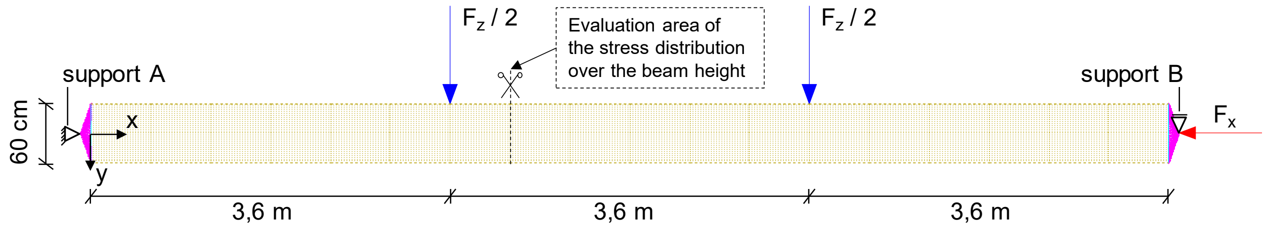

Figure 1: FE model of a 4-point-bending test with bending load F_z, axial loading (F_x) and span 10,800 mm including supports with couplings to the beam and the evaluation area of the stress distribution over the beam height.

In compression, the bilinear elastic-plastic material behavior according to Neely [3] can be described by a linear increasing stress-strain relation until the maximum compression strength $f_{c,0,2}$ is reached. After reaching $f_{c,0,2}$ the cross-section begins to plasticize. In comparison, the non-linear elastic-plastic material behavior under compression was derived from the *Guidelines for a Finite Element Based Design of Timber Structures* [4]. After reaching the proportionality limit $f_{c,1,0}$ plasticizing occurs until the maximum compression strength $f_{c,0,2}$ is reached. Subsequently, a softening starts until the compressive strength after softening $f_{c,0,3}$ is reached and the cross-section fully plasticizes like the bilinear material behavior. No limit for the strain is set for neither the bilinear nor non-linear material behavior under compression.

The stresses $f_{c,0,1}$, $f_{c,0,2}$ and $f_{c,0,3}$ and their related strains $\varepsilon_{el,1,0}$, $\varepsilon_{el+pl,2,0}$ and $\varepsilon_{el+pl,3,0}$ are calculated according to [4]. For the calculation, the factors $k_{lin,c,0} = 0{,}85$ and $k_{pl,2,0} = 0{,}42$ were derived from experimental compression tests according to EHRHART [2]. The factors $k_{end,c,0} = 0{,}85$ and $k_{pl,3,0} = 2 \text{ x } k_{pl,2,0}$ were assumed.

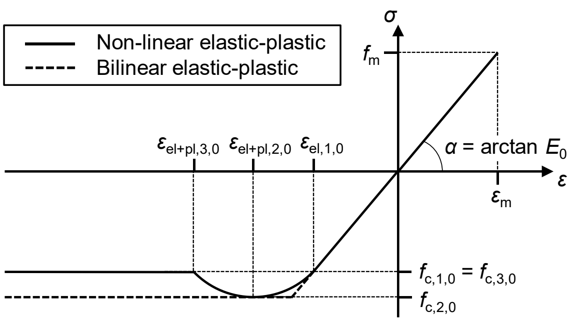

Figure 2: Stress-strain relationships for bilinear elastic-plastic material behavior and non-linear elastic-plastic material behavior with softening used for the numerical investigations.

2.3 – Verification

The numerical model was verified according to the *Guidelines for a Finite Element Based Design of Timber Structures* [4]. The verification steps of the solver convergence study, sensitivity check and imperfection sensitivity were neglected. The following verification steps are given for an axial load $F_x = -850$ kN and the non-linear elastic-plastic material behavior.

2.3.1 – Engineering judgment

The longitudinal stresses σ_x over the beam height at the evaluation area, according to Figure 1, are displayed in Figure 3. The stress distributions correspond well to the defined stress-strain relationships and are plausible.

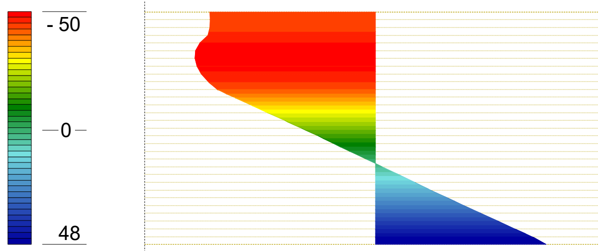

Figure 3: Longitudinal stresses σ_x over the beam height.

2.3.2 – Discretization check

Figure 4 shows the influence of the number of elements over the beam height on the axial load-bearing capacity $N_{x,R}$ according to Eq. (1). The required mesh size was determined by the 5% test [4]. A regression line was used to estimate the correct value of $N_{x,R}$. The mesh size over the length was not investigated. Overall, 30 number of elements over the height and 18 elements of elements over the length satisfied the 5 % test and were chosen for the numerical investigation.

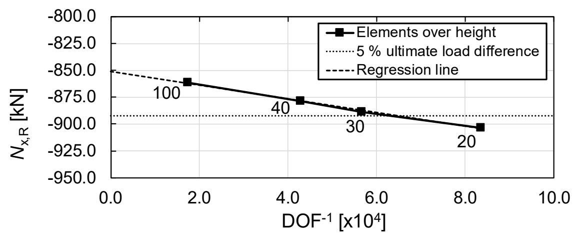

Figure 4: Numerically determined load-bearing capacity $N_{x,R}$ by varying the number of elements over the height.

3 – Results

The numerical model was used to calculate the stress and strain distribution over the beam height at the evaluation area according to Figure 1. For the calculation of the load-bearing capacities $N_{x,R}$ and $M_{y,R}$, the stress distribution (e.g. Figure 3) is integrated over the cross-section area according to Eq. (1) and (2).

$$N_{x,R} = b \cdot \int_{-h/2}^{h/2} \sigma(z)\, dz \quad (1)$$

$$M_{y,R} = b \cdot \int_{-h/2}^{h/2} \sigma(z) \cdot z\, dz \quad (2)$$

$\sigma(z)$	[N/mm²]	Stress distribution over beam height
b	[mm]	Beam width
h	[mm]	Beam height

Figure 5 displays the load-bearing capacity calculated from the numerical investigations under the assumption of tensile failure in bending at the lower edge of the beam. For an axial load up to F_x = – 730 kN, the non-linear and bilinear material behavior show similar load-bearing capacity $M_{y,R}$ with a difference up to 1.5 %. By surpassing F_x = – 730 kN, the strain value calculated with the non-linear material behavior at the top of the beam reaches $\varepsilon_{el+pl,3,0}$ and softening begins to occur. This leads to an increasing difference of $M_{y,R}$ between the non-linear and bilinear material behavior up to 35 %. When reaching the load-bearing capacity of $N_{x,R}$ without the resistance against bending ($M_{y,R}$ = 0), the difference between the axial $N_{x,R}$ of both material behaviors lies at 15 %. Therefore, $N_{x,R}$ of the bilinear material behavior corresponds with the compression strength $f_{c,0,2}$, while for the non-linear material behavior the calculated maximum $N_{x,R}$ results from the compression strength after softening $f_{c,0,3}$.

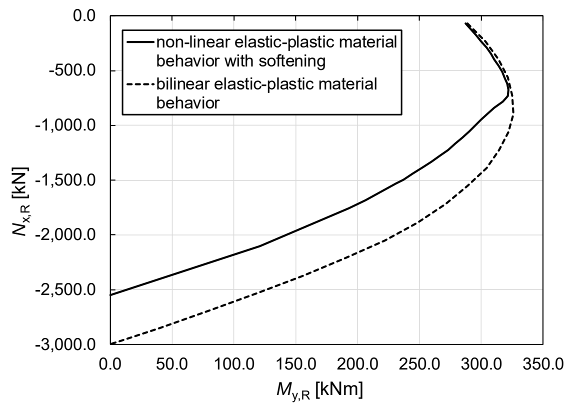

Figure 5: Load-bearing capacity of the numerical model with non-linear elastic-plastic material behavior with softening and bilinear elastic-plastic material behavior.

4 – Discussion

The load-bearing capacities for bilinear elastic-plastic material behavior show good agreement with the results from HÖRSTING [5]. As the form of the curve depends on the ratio $f_{c,0}/f_m$, the shape of the curve can differ for other hardwood species and/or engineered wood products.

The result of Figure 5 for a non-linear material behavior shows lower load-bearing capacities compared to the result of the bilinear material behavior when reaching tensile failure in bending. Reaching the beginning of softening in the cross-section, the discrepancy of $M_{y,R}$ increases with rising axial compression force. Buchanan [6] analyzed the load-bearing capacity for a bilinear material behavior with softening. After reaching the compressive strength $f_{c,0,2}$, a linear softening with constant slope is assumed. He suggests that the maximum load-bearing capacity for material behavior with softening is reached before tensile failure in bending occurs. This results in higher values for $M_{y,R}$ than those shown in Figure 5. Despite this, a higher load-bearing capacity prior to the tension failure in bending could not be replicated with the used numerical model. Nevertheless, the used numerical model underestimates the actual load-bearing capacity. Under full compression, the theoretical maximum load-bearing capacity $N_{x,R}$ is determined by the maximum compression strength $f_{c,0,2,}$ which the numerical model does not fully capture.

5 – Conclusions

A numerical model in SOFiSTiK FEA 2024 was created, considering two different material behaviors. The load-bearing capacity could be calculated for both material behaviors at the point of tension failure in bending. The following conclusions can be made regarding the applicability of the material behaviors:

1. The bilinear elastic-plastic material behavior is suitable for determining the load-bearing capacity under N_x-M_y interaction. However, plastification before reaching the compression strength $f_{c,0,2}$ and softening cannot be considered.

2. With the beginning of softening in the cross-section, the load-bearing capacity for a non-linear elastic-plastic material behavior is underestimated. All Effects of plastification can be modeled.

3. The bilinear and non-linear elastic-plastic material behavior are based on stress-strain relationships derived directly from experimental investigations under pure compression or pure bending. To accurately model the behavior of beam-columns under N_x-M_y interaction, the load-deformation behavior should be obtained directly from experiments.

6 – References

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Design of a new test configuration for in-plane shear of timber

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Abstract: The current in-plane shear test methods only apply to some variations of cross-laminated timber in development. This research aimed to design a test configuration to gauge a wide range of wood panel products. The chosen method is the picture frame test based on its potential to generate a pure shear field. Therefore, a connection is required to transmit uniform shear force to the edges of the timber specimen. Notches along all four edges were designed. By calculation, the number, arrangement, and size of those notches were chosen to maximise the load-bearing capacity. The performance of practical tests proved the functionality of this test configuration. Series of 3- and 5-layer CLT were tested with a total of eight specimens. Results show that this kind of picture frame is effective and provides plausible values for the shear modulus, which aligns with the literature. In addition, model-accurate shear stiffnesses can be determined and used in structural analysis. Furthermore, preliminary tests with mechanically laminated timber, including diagonal lamination, were performed, and an in-plane shear failure could be achieved. Further tests will be necessary for parameter studies and statements about the potential applicability of other wood-based materials.

Keywords: *in-plane shear, picture frame test, notches, cross-laminated timber, mechanically laminated timber*

1 – Introduction

Mass timber, in all its variations, especially cross-laminated timber (CLT), continues to be a research subject. New developments like the integration of hardwoods, the disintegration or diagonal alignment of layers, or the use of alternative bonding methods, such as mechanical jointing, also concern the mechanical load-bearing behaviour. Here, the in-plane shear properties as material parameters are of interest. However, the existing test methods, some standardised, do not apply to all types of mass timber elements. For example the diaphragm shear test, defined in EN 16351 [1], always generates shear in conjunction with compression due to the applied load. Therefore, this method is unsuitable for diagonal laminated timber (DLT) or other new wood-based materials.

In contrast, a picture frame test could create a perfect shear field. Björnfot et al. [2], Turesson et al. [3] and Kim et al. [4] have successfully conducted such tests with CLT. However, their connection with bolts would not be suitable for tests with mechanically laminated timber (MLT).

Consequently, this research aims to design a new test configuration that allows in-plane shear tests with all kinds and variations of CLT and other wooden panels, independently of the layers' disintegration, orientation, and jointing.

2 – Picture Frame Test

2.1 – General

The steel frame this test configuration is named after consists of four rigid legs hinged at the corners via single bolts, as Figure 1 illustrates. This results in a frame that is significantly stiffer than the test specimens, thus enabling a constant load introduction over the length of the legs. The upper and lower bolts are fixed, ensuring the frame can only deform along the centre axis. In an ideal model, the legs transfer the loads evenly over the precisely fitted test specimen edges, creating a pure shear stress state in the centre of the specimen.

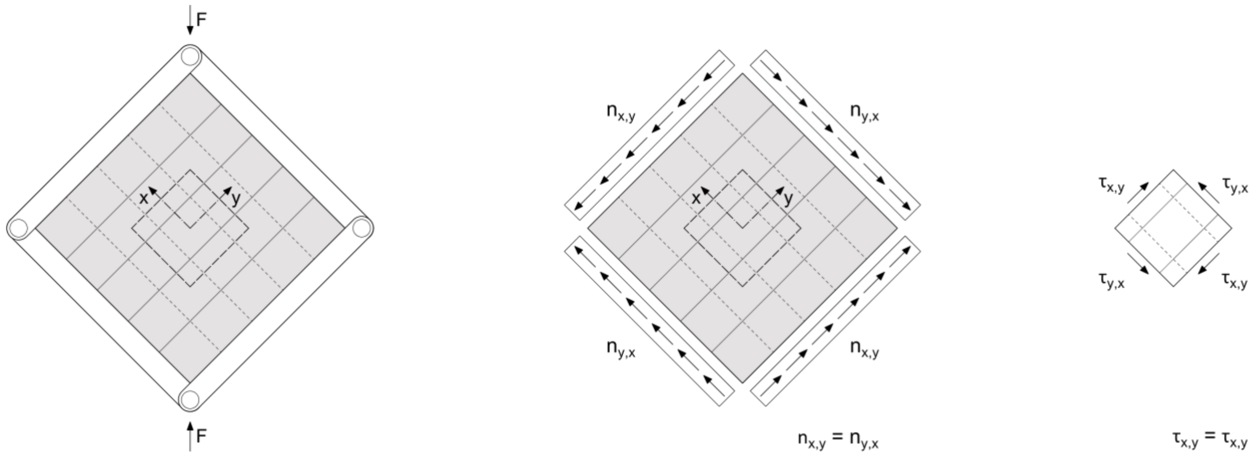


Figure 1: Principle of picture frame tests – left: picture frame under load with test specimen inside; middle: load on the test specimen; right: stresses on the differential element [5]

The shear stiffness k and the shear modulus G can be calculated according to (1). The derivation of this equation can be found in [5].

$$G = \frac{\tau}{\gamma} = k \cdot \frac{a}{2 \cdot l \cdot t_{CLT}} \qquad (1)$$

G	[N/mm²]	Shear modulus
τ	[N/mm²]	Shear stress
γ	[-]	Shear strain
$k = \frac{F}{\Delta}$	[N/mm]	Shear stiffness
F	[N]	Force
Δ	[mm]	Measured displacement
a	[mm]	Side length of measured area
l	[mm]	Load introduction length
t_{CLT}	[mm]	Total thickness of the CLT

2.2 – Load introduction

The most important aspect is the load transfer between the steel frame and the wooden test specimen. The method used here was the connection via a series of notches along the edge of the test specimen. The test frame was equipped with steel counterparts accordingly. Fricke [6] developed the final geometry of those notches. Considering the manufacturing process and the ease of installation, he selected the number, arrangement, and size to maximise the load-bearing capacity of the connection. Figure 2 illustrates the final test configuration.

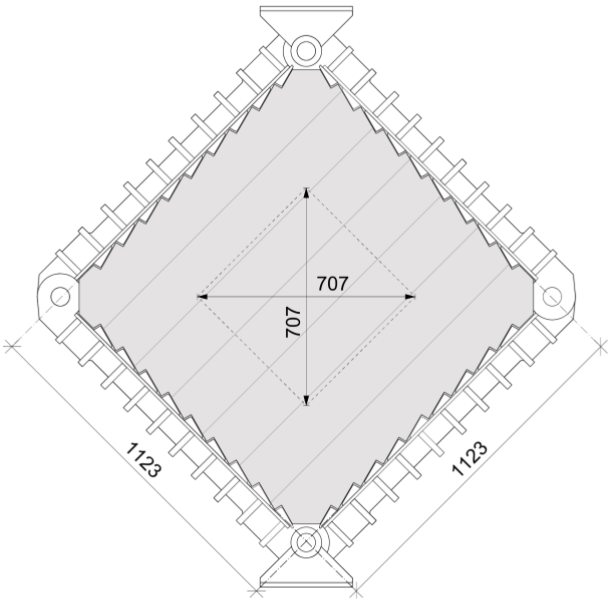


Figure 2: Picture frame test configuration with notches along the edges, all dimensions in millimetres [5]

3 – Experiments

In order to validate the effectiveness of this test configuration, three series of CLT were tested in practice. The first series consisted of five test specimens made of 3-layer CLT (20/20/20 [mm]), while the second consisted of three pieces of 5-layer CLT (40/20/20/20/40 [mm]). Thirdly, preliminary tests were conducted on eight 5-layered MLTs (20/20/20/20/20 [mm]), each comprising two diagonal layers (0/30/0/150/0 [°]). During the test, the shear strain was measured on side 1 using cable displacement transducers, while side 2 was recorded using a digital image correlation method. All measurements are available in the research data publication of Fochler and Schumacher [7].

4 – Results

4.1 – General observations

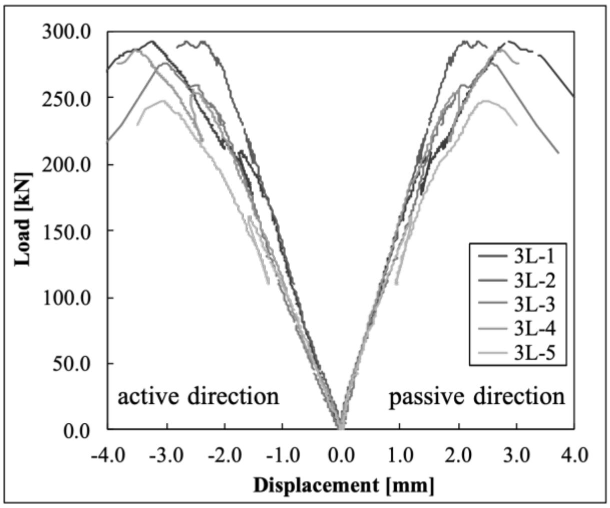
A linear elastic deformation occurs in the range of 10 to 40 % of the maximum load, which can be used to analyse the stiffness and shear modulus according to (1).
However, before in-plane shear failure occurs, the notches fail by shearing off. After that, it is impossible to maintain a uniform load transfer. This is evidenced by the frame legs losing contact with the edges of the test specimen. The following load situation is a compression between the upper and lower corner.

4.2 – Cross laminated timber

Figure 3 shows the load-displacement diagrams of the 3- and 5-layer CLT specimens. It can be observed that the stiffness of both CLT series is approximately 19 % higher in the passive direction than in the active direction. This divergence may be due to imperfections in the load transfer through the notches or an oversized measurement area.
The resulting mean shear modulus G_{mean} was 526.6 MPa for the 3-layer panels and 561.5 MPa for the 5-layer panels. These values are in the same range as those found in the literature and, therefore, appear plausible.
All 3-layer specimens showed net-shear failure, typical for non-edge glued CLT. No in-plane shear failure was observed in the 5-layer CLT elements at a maximum load of 600 kN. However, the deformations that occurred up to this point also indicate net shear behaviour.

4.3 – Mechanically Laminated Timber

A highly ductile load-bearing behaviour generally characterises the MLT elements. The mechanical connection via aluminium nails consistently resulted in torsion failure. With increasing loads, the large deformation caused the upright diagonal lamellas to get locked between the frame legs. The acting pressure led to the buckling of the diagonal layer and the entire element.
The mean shear modulus G_{mean}, calculated in the elastic range, is 100.5 MPa. However, the measured values for stiffness and strength are unreliable, as no comparative values are available in the literature.



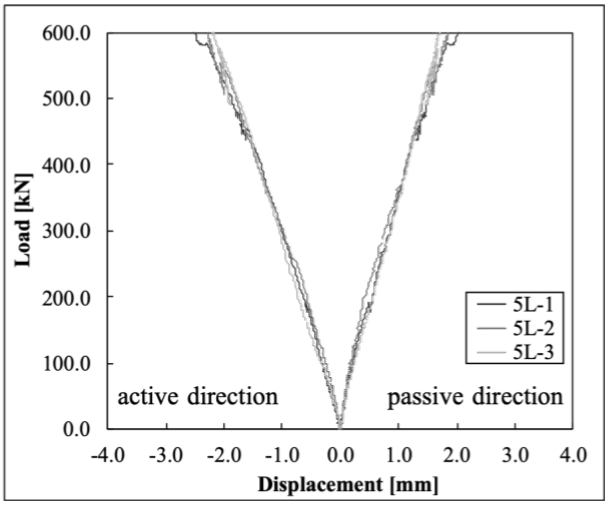


Figure 3: Mean values in active and passive direction in load-displacement diagrams, left: 3-layer CLT, right: 5-layer CLT [5]

4.4 – Further results and discussion

A more detailed description of the results and their discussion can be found in the publication of Fochler et al. [5].

5 – Conclusion

This study addresses the development of a modified picture frame test setup to determine the in-plane shear behaviour of various kinds of timber-based materials. The designed configuration incorporates notches for load transfer along the edges to accommodate CLT, DLT and MLT planes. The specific geometry of the notches was determined and implemented. The test specimen should be processed by machine to ensure a tight fit and load transfer. Tests carried out on 3- and 5-layer CLT panels showed that the resulting shear field and shear modulus were consistent with those reported in the literature. Despite the shear failure of the notches, in-plane shear failure was successfully achieved. Overall, this proves that this type of picture frame test setup can be used to determine the in-plane shear behaviour of CLT. With additional specimens tested, it has been demonstrated that MLT and DLT can also be tested using this method, which previously required complex, full-scale testing. However, further validation is necessary before this modified test can be widely adopted. Planned future tests include comparisons with the established EN 16351 method and investigations like the influence of edge board width. Finite element modelling will be used to carry out detailed parameter studies and assess the shear field's quality.

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Clay Boards as a fire protection layer – State of the art

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Abstract: This paper presents an overview of current research and knowledge when using clay as fire protection layers in timber structures and a comparison to the current standardisation regarding fire safety of timber structures. In Germany, fire safety requirements for load-bearing and separating elements in timber constructions consider standard fire resistance (REI) and for multi- storey timber buildings also additional criteria such as protection ability of linings for timber elements. Typically, gypsum boards are used to meet these requirements. However, industrially manufactured clay boards are emerging as a promising alternative or complement to conventional protection systems. This paper reviews current standards and regulations, showing that existing guidelines underestimate the fire protection performance of clay boards, as they are based on data derived from clay plasters. This leads to the necessity of further investigations to complement the current standardisation.

Keywords: clay boards, clay plaster, fire protection system, timber structures, fire design

1 – Introduction

Fire protection layers for timber structures typically consist of gypsum boards. The boards for enhanced fire protection consist primarily of a mixture of technical and natural gypsum and mineral fibres [1]. The most used technical Gypsum is the REA-gypsum, a byproduct of flue gas desulphurisation in coal combustion in power plants, which provides around half of the used gypsum in Germany [2]. Considering Germany's ongoing energy transition, which aims to reduce reliance on coal, a long-term reduction in the use of REA-gypsum can be expected [3]. One potential alternative is the use of clay boards, either alone or in combination with gypsum boards, to maintain adequate fire protection while reducing the environmental impact.

Therefore, this publication provides an overview of the regulatory background for the use and necessity of fire protection layers in Germany. It is followed by a summary of the current state of scientific research and standardisation concerning the application of clay as a fire protection material.

2 – Regulatory Background

To understand the necessity of fire protection systems it is crucial to differentiate between the classic fire resistance REI, including the criteria Load-bearing capacity (R), Integrity (E) and Insulation (I), and the additional regulatory requirements arising from building codes for multi-storey timber structures concerning the protection ability of linings and the start time of charring (t_{ch}).

Catalogues already list possible building elements using clay boards, ensuring 30, 60, or 90 minutes of Integrity and Insulation [4]. Elements with loadbearing and separating requirements lined with clay products under fire exposure can be designed using the next generation of EN 1995-1-2 [5].

In Germany, timber buildings in building classes 4 and 5 require a fire protection lining. This lining must delay the start time of charring by 30, 60, or 90 minutes, depending on the size of the fire compartment, the type of structural element, and the building class. Furthermore, material specifics concerning the fire protection linings requires the need to consist of non-combustible material (class A1/A2) [6]. From a purely building code perspective, this limits the use of clay boards to the four currently available board types listed in Table 1.

Table 1: Clay boards in fulfilling required reaction to fire classification

Clay board producer	Density ρ [kg/m³]	Class
LEMIX [7]	1450	A2-s1 d0
WEM [8]	1560	A2
Leipfinger-Bader	1850	-
Rapido Lehmplatte [9]	1413	A2

3 – Clay as fire protection material

3.1 – State of scientific knowledge

In [10] model scale furnace fire resistance tests were conducted using various plaster systems reinforced with natural fibres (hemp, cattail, and straw) applied on reed mat substrates. The plasters density ranged between 1600 – 1800 kg/m³. The tests were performed horizontally with an exposed area between 0.22 and 1.5 m² and under standard fire exposure. It can be derived that clay plaster thickness is a crucial factor, and protection time increases in proportion to the layer thickness. Among the fibre types, hemp and straw, hemp-reinforced clay plaster postponed the start time of charring 2.5 minutes longer than straw reinforced plaster. This corresponds to an increase of about 14 %. In [11], a comparison between horizontal (ceiling) and vertical (wall) orientations of the plaster system suggests that a vertical orientation improves the basic protection time. However, due to variations in plaster thickness and reinforcement configurations, further investigation is needed to confirm this effect.

Investigations presented in [12] examined various board materials, including hemp, wood and clay. The clay boards incorporate different additives. One consists of hemp and glass fibre, the other of perlite, reed stems, hemp, jute mesh, cellulose fibre, and starch, and the third one uses an inorganic binder. All clay boards had a density of around 700 kg/m^3. Small-scale fire experiments (100 × 100 mm) were conducted using a cone heater of a cone calorimeter, with 50 mm thick timber specimens as backing material and subjected to a predetermined heat flux of 50 kW/m^2 for 20 minutes followed by 20 minutes with a heat flux of 75 kW/m^2. Despite significantly lower density as clay plasters, the start time of charring occurred within a similar time range. The use of an inorganic binder enhanced the fire protection ability significantly.

In [13] large-scale fire tests were conducted on a vertically oriented timber frame backed with insulation (TF) and a solid timber (ST) construction with dimensions of 3 × 3 m. In both tests, the protection layer consisted of 22 mm Lemix clay boards. Temperature development was measured behind the clay boards. A temperature of 300°C was measured behind the clay boards after 32 minutes (timber frame) and 27 minutes (solid timber). This contradicts common findings, which suggest that fire protection linings backed by solid timber exhibit a later start time of charring compared to those backed by insulated timber frame constructions [14].

3.2 – State of the Art

The revision of Eurocode 5 includes design parameters for fire protection with clay plaster and boards. The approach for determining the basic protection time, now incorporated into the standard, was originally derived for clay plaster in [15] (see equation (1)).

$$\mathrm{t_{prot,0,i}} = 1{,}1 \cdot \mathrm{h_i} - 6{,}6 \qquad (1)$$

$t_{prot,0,i}$	[min]	basic protection time
h_i	[mm]	lining thickness

In the case of clay plaster and clay boards, the sum of the protection times of the different protection linings equals to the time of charring, as the time of failure is always higher than the time of charring, leading to equation (2) (see 5.4.2.3 (12) in [5]). Keeping in mind, this approach is only valid within specific material thickness limits, which are 40 mm for wall applications and 20 mm for ceilings and if the plaster/board is applied on solid timber or panelling. Additionally, as equation (1) was derived for clay plaster, it only applies to densities higher than 1600 kg/m^3. This excludes most clay boards currently on the market (see Table 1).

$$\mathrm{t}_{ch} = \sum t_{prot} \qquad (2)$$

t_{ch}	[min]	start time of charring
t_{prot}	[min]	protection time

3.3 – Comparison

Figure 1 compares the literature test results with the design equations given in [5]. As the formula was derived for clay plaster, there is a good fit with the provided data. Also, the clay boards with h=14 mm and a significantly lower density correlate well with the design equation. It must be noted that the test specimens in [12] were much smaller and heated from above with different test conditions, so no fall-off was possible. Nevertheless, it is notable that the results are comparable despite the density being far below 1600 kg/m^2. The 22 mm thick clay boards with low- and high-density, improve the protection time compared to lime plaster.

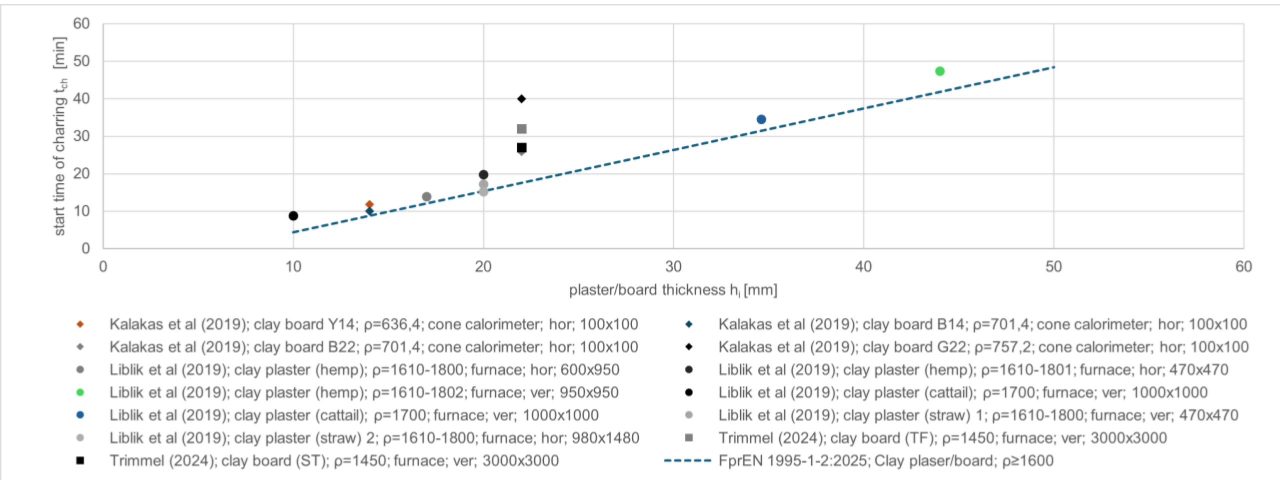

Figure 1: Start time of charring in reference to clay plaster/board thickness in literature and design parameters in [5] providing information about density (ρ), testing method (furnace, cone calorimeter), orientation (horizontal, vertical) and specimen size (mm)

4 – Outlook

The results indicate significant potential and a clear need for further research to establish clay boards as effective fire protection layers. Current standardized calculation methods—initially developed for clay plaster—are not directly applicable due to material density and composition differences. Fire tests have shown longer protection times for clay boards than predicted by the design equations in [5], presenting the need for complementary calculation approaches

In this context, the newly launched research project Be**clay**dung involves large-scale fire tests to improve the predictive accuracy of fire protection times for clay boards. The project's overarching objective is to facilitate the broader application of clay boards as fire protection system across all building classes in Germany, either as a standalone solution without additional linings or in combination with commonly used fire protection systems.

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Challenges and Opportunities in the Dissemination of Scientific Data: Insights from the 'TIMpuls Dissemination' Research Project

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Abstract: This article presents a report on the fire tests conducted as part of the *TIMpuls* [1] research project, along with the subsequent processing and preparation of the experimental data for publication. This research project aimed to establish fundamental insights through experimental and numerical studies. These studies aimed to advance German fire safety regulations in the context of an expanded use of timber construction. A part of the TIMpuls project investigated the influence of (initially) protected and exposed timber elements on the fire dynamics in the room. A comprehensive analysis was conducted on wall and ceiling components in light timber frame and solid timber construction. The *TIMpuls – Dissemination* [2] research initiative, started in 2022, built upon the findings of the *TIMpuls* project. Its objective was to further process the results and findings of the *TIMpuls* project and to make them freely accessible to all relevant parties. This also encompassed preparing and publishing the test data from the final full-scale fire tests for international exchange. The comprehensive results of these test series are currently accessible to the public via the website at www.timpuls-science.info [3]. This article describes the nature of the processed data, the intended applications thereof, and the challenges encountered during the preparation of the data set.

Keywords: Fire safety, Multi-storey timber buildings, Fire tests, Mass timber, Exposed timber surface

1 – Introduction

Regarding carbon storage, wood is one of the most significant building materials in the present and future. The increased use of wood in the construction of multi-storey residential and office buildings has the potential to significantly contribute to reducing greenhouse gas emissions and accelerating global decarbonization. The TIMpuls research project was carried out to prove the efficacy of fire protection measures in timber-framed construction up to the high-rise limit. The follow-up project 'TIMpuls - Dissemination' builds on this and ensures the further processing and publication of the results and findings. A key component of this effort was the preparation of the final full-scale fire tests and the international publication of the resulting research data in an accessible and comprehensible form.

2 – TIMpuls full-scale fire tests

2.1 – Test setup

The five full-scale compartment fire tests represent the culmination of the TIMpuls joint research project. They validate the knowledge from the preceding small-, medium-, and large-scale tests. The first test (T0) was designed as a reference scenario representing a non-combustible building construction. In the other four tests (T1-T4), different combinations of timber construction were used for the wall and ceiling components. The constructions included:

- cross-laminated timber (CLT),
- glue-laminated timber (GLT), and
- light timber frame (LTF),

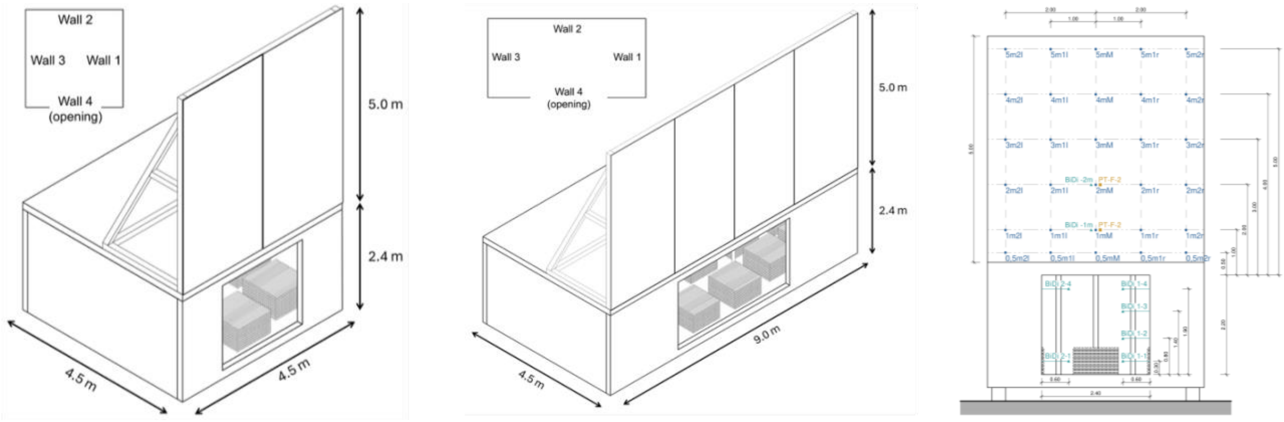
each combined with either type F gypsum plasterboard, gypsum fiberboard, or left exposed.

The fire tests were carried out in two different room sizes. T0-T2 had an internal floor area of 4.5 x 4.5 m², while T3 and T4 were twice that size (4.5 x 9.0 m²; see Figure 1). The room height was 2.4 m in each test.

All compartments have one opening. The opening factor is selected based on previous investigations and the natural fire curve used in the project, according to DIN EN 1991-1-2:2015-09 NA Annex AA [4], with a value of O = 0.094 $m^{(1/2)}$. This corresponds to an opening of 2.4 × 2.2 m² (width × height) in the small room (T0-T2) and 4.2 × 2.2 m² (width × height) in the large room (T3-T4). The air flow through the opening was always unhindered. This ensures comparability between the real fire tests and the preliminary basic tests.

Above the opening of the test room, a facade shield measuring 5 x 4.5 m (height x width) in the small room (T0-T2) or 5 x 9.0 m (height x width) in the large room (T3-T4) was installed. This allows for measuring and assessing the flame lengths and temperatures above the test stand in the vertical direction.

For the experiments, a fire load density of 1085 MJ/m² was selected, representing the 90% quantile for residential use given by the Eurocode [4]. This was implemented using evenly distributed wood cribs (1 x 1 m² base, 40 × 40 mm sticks). With 14% wood moisture, a bulk density of 580 kg/m³, and a heat of combustion of 17.28 MJ/kg, the corresponding values are estimated to be approximately 74 kg/m² of wood,



(a) (b) (c)

Figure 1: Test setup for the (a) small and (b) large test rooms, and exemplary (c) façade and opening for the small test room

which is equivalent to roughly 1.5 tons within the smaller room (4.5 × 4.5 m²) and 3 tons within the larger room (4.5 × 9 m²).

You can find a comprehensive account of the fire tests in the published literature [5], and on the new TIMpuls Science website (www.timpuls-science.info) [3].

2.2 – Measuring data

In each experiment, approximately 350 to 380 measurement points recorded the gas and material temperatures, gas flow velocities, and mass loss of the test specimen throughout the test duration and the subsequent observation period. A total of up to 350 type-K thermocouples, six plate thermometers, 12 bidirectional probes, and six cameras were used for each fire test. In addition, the water consumption for fire suppression was also measured.

The temperature was measured within the building components, behind the fire-protective cladding, on the facade, in the fire compartment, and in the area of element joints and component connections. The gas flow velocity was measured in the fire compartment, opening, and on the facade.

3 – TIMpuls Science – How to use it

A key objective was to present the complex and extensive test data in an intuitively understandable way. To achieve this, the website www.timpuls-science.info [3] was developed. It provides detailed descriptions of the experiments and access to all measurement points and data. The existing planning documents were supplemented with additional detail and location drawings to enhance clarity. Comprehensive visualizations are available for all components, connections, and measurement locations (walls, ceilings, façade, fire room, etc.), ensuring consistent and accurate orientation. The resulting menu navigation is designed to allow even first-time users to easily follow and understand the full-scale fire tests.

As demonstrated in Figure 2 and 3 the website and measurement data can be used effectively, and users can easily navigate the content. Under the menu item “Test setup”, the general objectives of the tests are described, and the test specimens used are presented – complementing the description provided in Chapter 2 of this article. An overview table facilitates the rapid acquisition of information regarding the component assemblies employed in each test. The “Components” section facilitates interactive exploration of the individual tests. The component structures and the joints between components and elements are illustrated in precise detail (Figure 2), using detailed graphics.

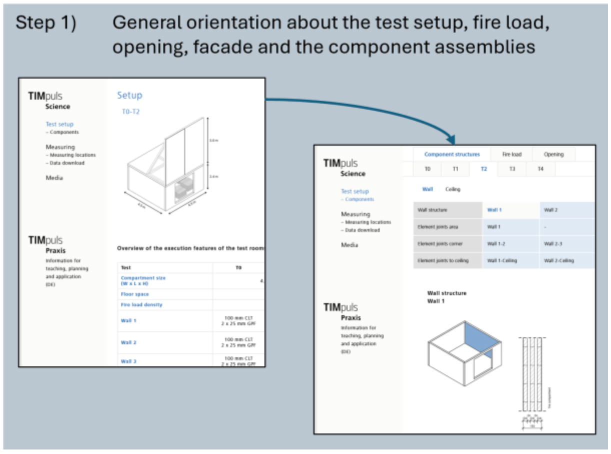


Figure 2: Step 1 for orientation on the test setup

The “Measuring” section provides a concise overview of the measured variables, and the instruments utilized for data collection. Within the section entitled “Measuring locations”, the position of all measurement points is displayed. The navigation system adheres to the same structural framework as the “Components” section, facilitating expeditious orientation. Steps 2 and 3 (see Figures 3 and 4) outline that the tabulated measurement results should be downloaded first when searching for specific data.

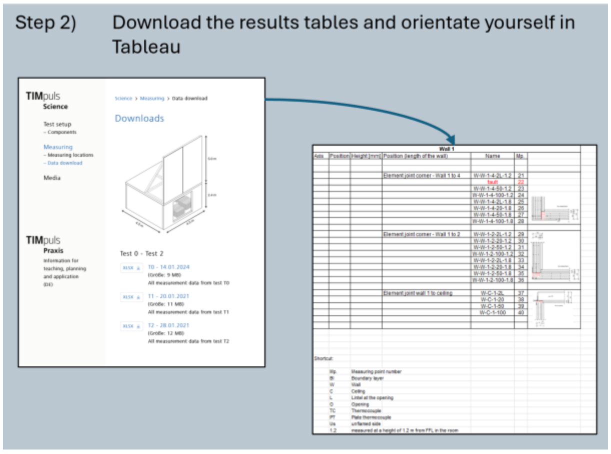


Figure 3: Step 2 for downloading the result tables and orientation

The tables presented herein contain all previously referenced measurement values, ranging from temperature readings to the quantity of extinguishing water utilized. The measurement point number enables the precise identification and tracking of all locations via the website. The nomenclature employed for each measurement point further substantiates the allocation of measurement locations within the test room or the corresponding building component.

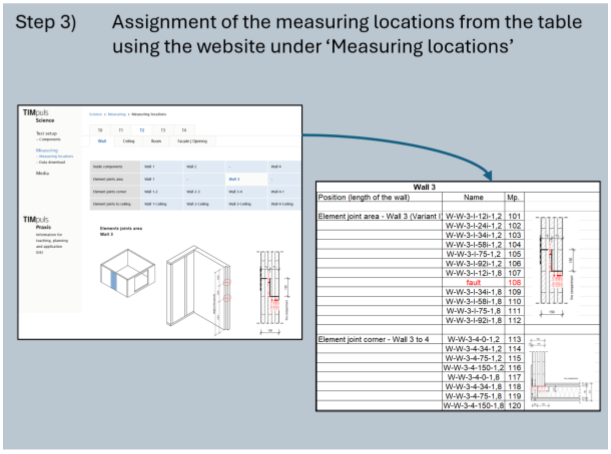


Figure 4: Step 3 for the assignment of the measurement points using the TIMpuls website

4 – Conclusion and learning

The website timpuls-science.info provides comprehensive and coherent access to all research data generated during the final TIMpuls full-scale fire tests, making them internationally available. Minor deviations in the execution of the planned experimental setups can never be entirely ruled out—whether in the form of altered sequencing in the designation of measurement equipment or modifications in joint constructions based on insights gained from previous trials. The greatest challenge in conducting and subsequently analyzing such large-scale fire tests lies in identifying and transparently documenting naturally occurring deviations during the experimental phase. Developing suitable concepts and strategies for this purpose is strongly recommended before conducting the experiments. This approach enhances the traceability of the results and thus ensures the reliability of the findings.

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Master thesis: Sustainability assessment of fire protection measures in timber construction

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Abstract: With the construction sector accounting for around 37% of global CO_2 emissions, adopting biogenic materials such as timber offers a significant substitution potential. However, due to its combustibility, timber requires specific fire safety measures. In Germany, the model regulations *Musterbauordnung* (MBO) and *Musterholzbaurichtlinie* (MHolzBauRL) enable the construction of multi-storey timber buildings. This study investigates the environmental sustainability of fire protection systems in multi-storey timber constructions, focusing on wall assemblies in German building classes (bc) 4 and 5, as defined in the *MHolzBauRL*. Life cycle assessments (LCAs) at the component and building levels show that, despite the necessary fire safety systems, timber buildings have a lower environmental impact than concrete buildings. Reducing fire protection cladding, such as OSB boards and gypsum boards, offers further environmental benefits.

Keywords: *life cycle assessment, fire protection systems, multi-storey timber construction*

1 – Introduction

The construction sector is responsible for 37 % of global CO_2 emissions [1] and is intensifying the anthropogenic climate change, which has already led to a global warming of 1.1 °C [2]. As the production processes for mineral building materials have already been optimized, further reducing their environmental impact is challenging. In contrast, biogenic materials can store carbon and cause low greenhouse gas (GHG) emissions. Their greater use could reduce construction-related GHG emissions and create a global carbon reservoir. [3]

A typical biogenic building material is timber, which is increasingly used in multi-storey building construction to reduce the climate impact of projects. As it is a combustible material, timber requires special fire protection. In Germany, since 2002, the regulatory framework *Musterbauordnung* (*MBO*) [4], specified by the *Musterholzbaurichtlinie* (*MHolzBauRL*) [5], has allowed the construction of multi-storey buildings with combustible building materials. The updated *MHolzBauRL* [6] from 2024 additionally enables the reduction of fire protection cladding. These federal model regulations are individually adopted into state law. The *HolzBauRL BW* [7] also allows biogenic insulating materials in load-bearing components in Baden-Württemberg.

This study aims to assess the environmental impact of fire protection systems in timber construction. The possible design variants for load-bearing interior walls in timber frame and cross-laminated timber (CLT) construction for bc 4 and 5 are considered. LCAs are carried out at a component and building level. The study explores whether adjustments to the thickness of fire protection cladding and the choice of insulation materials can improve environmental performance. The results are used to develop recommendations to support the ecological selection of fire protection systems. The study aims to ensure that timber construction projects, most of which strive for environmental sustainability, can meet these goals and that fire protection requirements do not undermine them.

2 – Methods

At the component level, a catalogue for load-bearing internal walls has been developed based on the building regulations for fire protection in timber construction for bc 4 and 5. It distinguishes between variants permitted nationwide according to the *MHolzBauRL* [6] and those only allowed in Baden-Württemberg. Figure 1 shows selected examples.

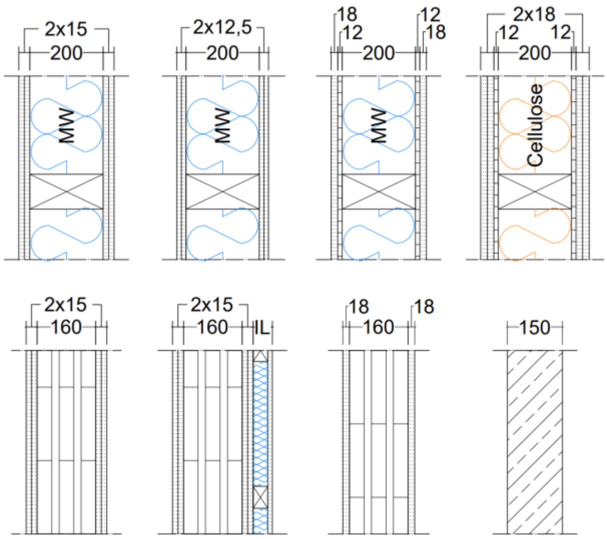

Figure 1: Selection of analysed interior walls in timber frame, CLT, and concrete

The study carried out LCAs according to DIN EN 15804+A2 [8] to evaluate the environmental impact. The functional unit is defined as 1 m² of wall area with equivalent load-bearing capacity and building authority approval, and the observation period is 50 years. The study framework follows the cradle to grave with options approach and includes the life cycle phases A1-A3 (product phase), B4 (replacement during use phase), and C1-C4 (end of life phase). The data source is the *Ökobaudat* database (version 2023-I). This paper examines two midpoint indicators: global warming potential (GWP) to characterize environmental impact, and non-renewable primary energy as an energy carrier (PENRE) to characterize resource use.

A subsequent building-level analysis validates and contextualizes the component-level findings through LCAs for a reference building classified under bc 4 and for variants with the same function and floor plan. The study includes a variant optimized according to the updated *MHolzBauRL*, a variant adapted to the specific regulations of Baden-Württemberg, and a variant made of concrete. The study compares the LCA results at the component and building levels and considers the disciplines responsible for the specific requirements of the components.

3 – Results

3.1 – Results on a Component Level

On the component level, the highest GWP values were found for variants with biogenic insulation materials, such as cellulose or wood fibre, and variants with an additional installation layer (IL). This is because an IL requires additional mineral materials, which increases the GWP and PENRE of the wall by around 15 % (Figure 2).

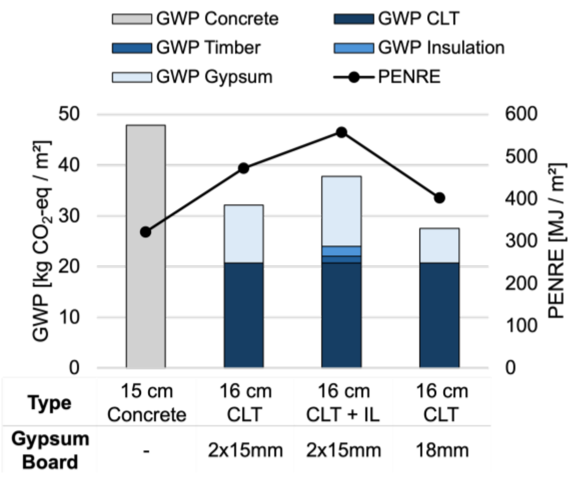

Figure 2: GWP and PENRE of concrete and CLT walls (phases A-C)

Variants with biogenic insulation materials, such as cellulose, show high environmental impacts because they require two additional layers of OSB per *MHolzBauRL BW* [7] (Figure 3). Additionally, the lifespan of biogenic insulation is shorter than that of mineral insulation materials, so replacement must be planned for over 50 years, resulting in a doubling of GWP and PENRE. However, biogenic insulation materials offer the benefit of high carbon storage within the walls.

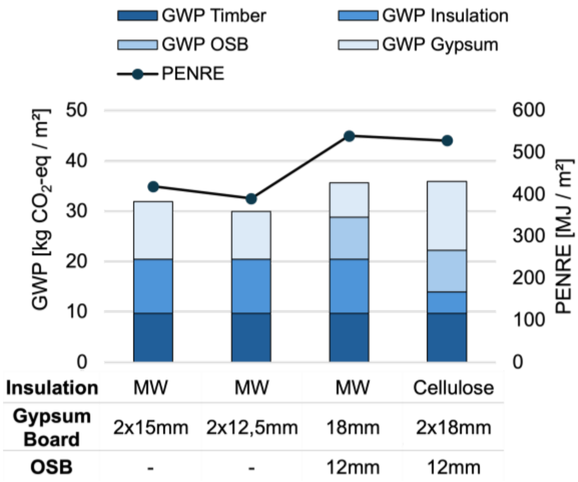

Figure 3: GWP and PENRE of timber frame walls (phases A-C)

The lowest GWP and PENRE are achieved by variants where the fire protection cladding is reduced - e.g., for CLT walls from 2 x 15 mm to 18 mm gypsum (Figure 2). This analysis considers gypsum plasterboard type F (GPF), which has a 40 % lower GWP and PENRE than gypsum fibreboard (GF). However, GF offers better load-bearing capacity and sound insulation, making its use necessary in some instances.

3.2 – Results on a Building Level

The results of the LCAs at the building level show the influence of fire protection requirements on the environmental impact, especially when biogenic insulation materials are used. The gypsum boards account for 12 % to 15 % of the total GWP of the timber construction variants analysed (excluding the foundation). Nevertheless, the results show a clear advantage of the timber construction variants over the concrete construction, especially for the fossil GWP.

Considering the PENRE in modules A to C, the concrete variant shows a slightly lower value than the timber buildings. This is mainly due to the high proportion of OSB and gypsum used in timber construction. However, the foundations were not included in the assessment, despite their typically larger dimensions in solid construction, which are likely to increase the environmental impact. In addition, the solid construction was only roughly dimensioned, meaning the results should be understood as approximate indications.

The reduction in the fossil GWP of the improved variants compared to the reference building is relatively low at 2 %. This is partly because around 50 % of the reference building's external walls must fulfil fire wall requirements due to its inner-city location. The reference building designs featured minimal fire-protection cladding for interior walls and exposed timber ceilings, further limiting the optimisation scope. Therefore, the only potential for optimisation was in the timber frame external wall, which accounts for about 53 % of the total external wall area and less than 8 % of the building mass (excluding foundations). Similar framework conditions typically also apply to other inner-city, multi-storey timber buildings, so it can be assumed that the optimizations based on the *MHolzBauRL* can only be implemented to a limited extent in practice.

3.3 – Recommendations for action

The following recommendations for action were developed based on the analysis:

1. From an ecological standpoint, a bc 4 timber construction is preferable to a solid construction building if the boundary conditions are suitable.
2. The fire protection cladding should be reduced to the required minimum.
3. Unless necessary for structural or building physics reasons, OSB boards should be avoided. If possible, GPF boards should be preferred to GF boards.
4. If the use of biogenic insulation materials requires the installation of additional OSB boards, the use of mineral wool is preferable from an ecological point of view.

4 – Conclusion and Discussion

The study demonstrates that, in bc 4 and 5, timber construction has a lower environmental impact than concrete construction, even when the necessary fire protection systems are considered. While the results for bc 5 are limited to the component level, similar trends are expected at the building scale. However, at the building level, optimisations are limited to specific wall areas as fire protection components, such as firewalls, cannot be modified under the updated *MHolzBauRL*. Consequently, the optimisation potential observed at the component level cannot be fully applied at the building level.

Overall, fire protection systems considerably influence the environmental impact of timber buildings, with gypsum boards accounting for 12 % to 15 % of the total GWP of the timber construction variants analysed. Consequently, complex wall constructions utilizing gypsum and OSB boards perform worse in the LCA than simple constructions with minimal material usage. Reducing gypsum and OSB boards under the updated *MHolzBauRL* can significantly improve the GWP and PENRE of wall constructions. Under prevailing building regulations, the use of biogenic insulation materials within load-bearing walls is not recommended. This is due to the necessity for additional OSB and gypsum panels, which offset the beneficial impacts on GWP and PENRE of the insulation.

Future studies are advised to improve LCA methodologies, focusing on biogenic carbon and material reuse, and to validate the *Ökobaudat* datasets, especially for gypsum products. Additionally, alternatives to OSB with lower GWP and PENRE should be investigated. This includes reassessing fire safety regulations that currently exclude options such as three-layer boards, which do not meet *MHolzBauRL* requirements. Moreover, the development of smoulder-resistant biogenic insulation materials that comply with fire safety standards has the potential to further enhance environmental performance.

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Sustainable Construction in Ghana: A comparative LCA analysis on mass timber and concrete.

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Abstract: Ghana has a growing population, and due to this, there is an increase in the construction of buildings, resulting in high carbon footprint levels. The primary building materials used in Ghana are concrete and steel, which have high carbon emissions. Timber has been recognized as an alternative building material with better environmental impacts than concrete and steel. This study used comparative life cycle assessment (LCA) between concrete and timber buildings in Ghana to show that timber had significantly lower Global warming potential than its counterpart, concrete.

Keywords: *comparative life cycle assessment, timber, concrete, sustainable construction, carbon footprint*

Introduction

The construction industry is a crucial sector in most economies, most especially in Ghana, and there are several reasons for its significance[1]. According to the Ghana Statistical Service, the construction industry in Ghana expanded by 10.7 percent (year-on-year) and 2.2 percent (quarter-on-quarter seasonally adjusted) in 2024 Q4 GDP of the country[2]. However, due to the massive population increase, Ghana's population is projected to move from 30.83 million in 2021 to 37.24 million and 52.47 million in 2030 and 2050, respectively[3]. There is a great demand for the construction of buildings and social amenities with little financial resources. Due to this demand, there has been a rise in different construction works, using materials available such as concrete with little regard to the topic of Sustainability[4]. The construction industry in Ghana has not kept pace with the increasing awareness of the adoption of sustainable practices, and the overall high carbon footprint detracts from the effectiveness of global sustainability efforts[5]. The choice of building materials used in construction has a significant impact on the carbon footprint, and using renewable and recyclable materials is one solution to this[6], [7]. Timber is a highly recommended sustainable building material because of its minimal amount of energy-based processing and low level of embodied energy relative to other building materials such as steel and concrete[8], [9]. Concrete is the primary building material used currently in Ghana, but due to increasing pressure from international role-players and climate mitigation commitments, there may be an increased interest and use of renewable materials such as timber[10].

Looking critically and evaluating the consumption of energy and greenhouse emissions is the starting point of assessing the impact of construction materials. Thus, an essential part of promoting energy efficiency and sustainable construction as a whole is the use of Life Cycle Assessment (LCA), most especially at the early stage in the design of buildings[11], [12]. However, LCA is generally low in capacity and interest from the industry and the governments of developing and emerging countries such as Ghana. LCA activities are usually only at a research or academic institution[10] even though it allows for a thorough assessment of environmental impacts associated with construction materials to help make informed decisions[13]. This study conducted a comparative LCA on concrete (the primary building material in Ghana) and timber (a renewable material) to assess the environmental impacts.

Methodology

This study followed the approach based on the ISO 14040 and ISO 14044 standards[14], [15]. This study aimed to evaluate the environmental impacts of a concrete building and its equivalent design timber building. The system boundary used for this assessment was from cradle to grave. That is, it included the following phases: A1-A3 (Production), A4 (transportation to building site), B1-B5 (use and maintenance), and C1-C4 (end of life).

The design of an already existing building was used for this assessment. The original design was a 3-storey conventional building in Ghana using concrete and steel as its primary material. An equivalent design in timber was created for this comparative analysis using Revit based on the CAD drawings of the original design. The foundation, doors, and windows were assumed to be identical for both designs; hence, this analysis excluded these. The timber building followed the exact shape and size of the original concrete structure, and the same location was used for this comparative analysis.

There was no extensive code analysis study on the original design, as it is an existing building. However, in designing the timber building, the following codes were utilized: Ghana building code, DIN EN 1990-1999, and data and designs from Dataholz. The Gross Floor area for both structures is 630m² with a life span of 50 years.

The quantities of both designs were taken from the drawings and used for the analysis. The Ecoinvent 3.1 database and the Activity browser software were used for the impact assessment. Due to a lack of specific LCI data for Ghana, the 'Row' (rest of the world) dataset was utilized[10]. Since the main objective of this comparative analysis was to compare the carbon footprint of the timber and concrete design, the impact categories analyzed in this study are the Embodied Carbon (Primary energy used) and Global Warming Potential.

Results

This section overviews the comparison of building materials between the two designs and the life cycle impact analysis. For the evaluation of this study, the following assumption was made: the materials used were sourced locally in Ghana. This is to help analyze the situation in Ghana if mass timber were locally sourced and used in building construction. The table below shows the materials used and quantities for both designs.

Table 1: Building materials and quantities in the concrete and timber buildings

Material	Unit	Concrete	Timber
Insitu concrete	m³	235	48
Steel bar	kg	31361	6604
Paint	kg	3255	1933
Glulam	m³	-	146
Plasterboard	kg	-	63520
Wool insulation	kg	-	11474
tiles	kg	18210	10605
mortar	kg	549736	77770
Timber formwork	m³	49	8
Aluminum sheet	m²	151	239
steel	kg	2373	6791
Wood cladding	m²	-	1093
OSB	m³	-	8
timber	m³	9	182
Waterproof plastic	kg	41	108
Masonry block	kg	475650	-

Table 2 represents the impacts of the buildings and the differences for each impact group. Timber has high values of renewable primary energy (PERE) used and in GWP biogenic. This is due to the biogenic nature of wood. In Figure 2, stage A1-A3 contributes the most to the values for PERE. This can be attributed to producing timber components mostly using renewable energy sources. The high PERE values of timber do not reflect a negative impact on the environment; timber still offers a favorable environmental profile due to its lower non-renewable energy use and GWP fossil.

Table 2: Impact assessment and differences per m² floor area

Impact category	Unit	Concrete	Timber	Diff %
Primary Energy (non-renewable)	MJ-Eq	7916	6354	22%
Primary Energy (renewable)	MJ-Eq	2859	12506	126%
GWP (biogenic)	kg CO2e	-198	-1034	135.7%
GWP (fossil)	kg CO2e	938	484	64%
GWP (land use)	kg CO2e	32	20	46%

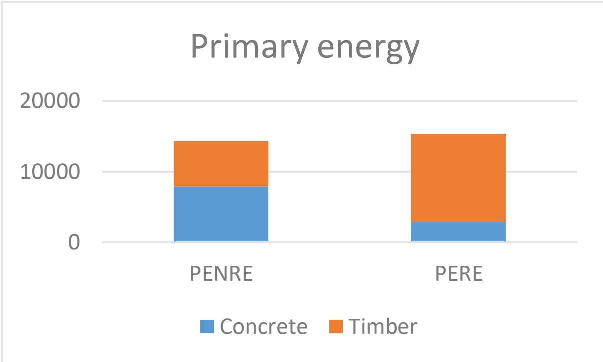

Figure 1: Bar chart of primary energy used in the concrete and timber building

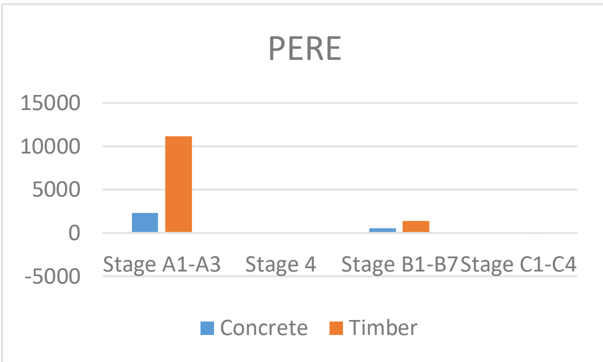

Figure 2: Renewable primary energy in the lifecycle stages

The values of the Global Warming Potential, which translates to carbon emissions, are mostly higher in concrete than in timber, apart from the Global Warming Potential biogenic. The higher GWP biogenic values in timber are caused by the release of stored carbon from incineration or decay at the end of life. The GWP land use in the concrete building is higher than the timber building because the extraction and processing of materials like limestone used in cement production significantly alter natural landscapes and deplete carbon stocks. Timber on the other hand when harvested from a sustainable forest is regrown and improves the land carbon balance.

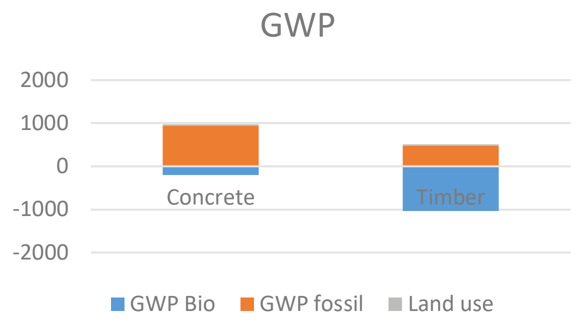

Figure 3: Global warming potential of the concrete and timber buildings

Discussion and Conclusion

As already indicated from other literature, [8], [9] the results from this study show that concrete has a higher carbon footprint than timber. Historically, before the topic of sustainable construction was a prioritized issue, a significant number of buildings were constructed using readily available materials such as timber [16] but after the use of gravel and concrete began to spread, timber construction was increasingly disregarded. Now, with the spread of knowledge on sustainable construction, the Ghanaian construction industry and its stakeholders must revisit traditional materials such as timber because they reflect sustainable construction[17].

As stated by [18], an increased timber construction quota offers high potential for carbon storage and a significant reduction potential for carbon emissions. This will prove a challenge in Ghana, as public organization workers and stakeholders in the construction industry have little knowledge or interest in sustainable construction.[19]. For this study to significantly impact the construction industry in Ghana and Africa by extension, further studies should be carried out on addressing the challenges of using timber as a primary construction material in Ghana.

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Additive Manufacturing of Wood via Individual Layer Fabrication

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Abstract: Additive Manufacturing (AM) offers new possibilities for the individualized production of building components. While AM for construction has so far been dominated by mineral-based materials, wood presents a sustainable, lightweight, and renewable alternative. However, current wood-AM approaches are largely limited to decorative or small-scale applications, with low wood content and poor mechanical performance. To overcome these limitations, the Individual Layer Fabrication (ILF) process was developed as a novel method for additively manufacturing structurally viable wood composites. ILF combines selective adhesive application, mechanical pressing, and layer-wise lamination to create large-scale components with up to 90 wt% wood content. Experimental results show that ILF elements can achieve bending strengths exceeding 50 MPa and stiffness values over 5 GPa, comparable to conventional engineered wood products. Demonstrator objects such as acoustic panels and topology-optimized elements illustrate the geometric and functional versatility of the process. ILF may help bridge the gap between digital fabrication and sustainable construction materials, with potential to advance wood-based additive manufacturing toward architectural applications.

Keywords: *Additive Manufacturing, 3D Printing, Wood Composites, Binder Jetting, Sheet Lamination*

1 – Introduction

Additive manufacturing (AM) enables the direct fabrication of complex, customized geometries based on digital design models. Its tool-free nature and capacity for individualization make it particularly attractive in fields where variation and freedom of form are valuable. Accordingly, AM holds significant potential for the construction industry, where bespoke components and small-batch production are the norm.

This potential has led to the emergence of Additive Manufacturing for Construction (AMC) as a rapidly growing area of research and development. However, most AMC efforts to date have focused on mineral-based materials, especially concrete [1]. While these materials are well-suited for large-scale applications, they lack the ecological advantages and lightweight characteristics of wood.

Wood is a renewable, well-understood building material with long-standing use in structural applications. Its integration into AM could contribute to more sustainable and resource-efficient construction practices. Yet, the use of wood as a feedstock in AM remains relatively rare. Existing approaches often involve small-scale decorative objects, or wood plastic composites processed by conventional filament-based printers. These methods rarely exploit wood as the primary structural material.

To bridge this gap, new processes are needed that combine a high proportion of wood content with both mechanical performance and scalability. This can be achieved with Individual Layer Fabrication (ILF), a novel process designed to manufacture large-scale, structurally viable wood composite elements, pointing toward new possibilities for sustainable construction.

2 – AM with wood

Wood has been integrated into various additive manufacturing processes, typically as wood-plastic composites or fine particles bound by synthetic or bio-based adhesives [2]. These processes differ widely in material composition, scale, and application domain, ranging from decorative consumer products to experimental construction components.

One of the most commercially established approaches is Material Extrusion, particularly Fused Filament Fabrication (FFF) using wood–plastic composites. Here, wood flour is combined with thermoplastic polymers to form printable filaments. These materials are widely available and processable on desktop 3D printers, though the wood content is typically limited to 20–30 wt%, as higher concentrations compromise flowability and mechanical stability. While primarily used for decorative applications and consumer goods [3], notable examples of architectural use include the 3D-printed house by the University of Maine [4] and a shape-adaptive skylight used in the livMatS research building [5].

Binder Jetting offers another approach. Early work used wood powder as a filler to reduce the cost of proprietary binder systems [6]. More recent applications are motivated by aesthetics and environmental considerations [7]. In a typical approach, a mixture of wood flour and powdered binder is selectively solidified using an activator, then infiltrated with epoxy resin to enhance mechanical performance. However, due to limited resin penetration, the resulting components are generally restricted to thin-walled or small-scale applications, such as decorative objects[8].

Sheet Lamination, while subtractive in nature, is occasionally marketed as additive manufacturing when used with wooden feedstocks. In this method, sheet materials, often plywood or veneer, are CNC-cut and bonded to form three-dimensional objects. Applications include customized connectors [9] and full-scale models as shown in Figure 1 [10]. However, the material waste constrains its broader use.

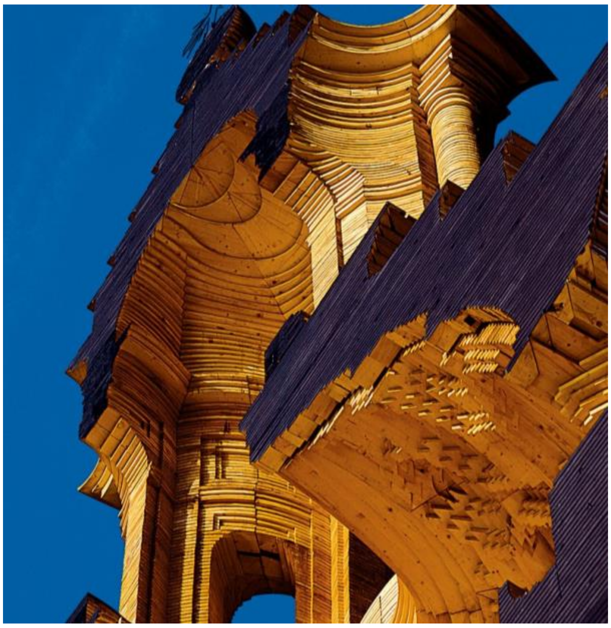

Figure 1: „Borromini in Holz" a life-size wooden replica of the San Carlo alle Quattro Fontane church from [10]

More experimental processes seek to increase the wood content or the scale of printed elements. Liquid Deposition Modeling uses a paste of wood particles, binder, and a liquefier, which solidifies as the liquid evaporates [11]. Depending on the binder system (e.g. urea formaldehyde, methylcellulose, mycelium), wood contents of up to 85 wt% are achievable [12]. However, the resulting structures are typically porous and mechanically weak, with flexural strengths in the range of 1–5 MPa [12]. Despite these limitations, applications such as furniture [13], or even tiny houses [14] are under development.

Other noteworthy approaches include the 3DP Biowall, which produces fully biodegradable wall elements from wood particles and starch-based binders through thermal pressing (~50 wt% wood) [15], and Additive Timber Manufacturing, which uses robotic lamination of veneer strips but requires counterforms and offers limited design freedom due to anisotropic properties[16].

3 – Individual Layer Fabrication

3.1 – The Process

While most additive manufacturing processes involving wood focus on decorative applications or small-scale elements, Individual Layer Fabrication (ILF) was developed specifically to enable the production of large-scale, structurally relevant wood composites [17]. The process aims to maximize wood content while minimizing binder use and achieving mechanical performance comparable to established engineered wood products such as particleboard or plywood.

The ILF process combines aspects of Binder Jetting, Sheet Lamination, and hot pressing into a four-step additive workflow as seen in Figure 2.

a) A thin layer of wood particles is evenly scattered over a build surface.
b) An adhesive is selectively applied according to the target geometry using a dispensing system.
c) The layer is mechanically pressed, compacting the material and bonding the particles with reduced binder usage.
d) The unbound material is removed, and the contoured panel is laminated onto the previously fabricated stack.

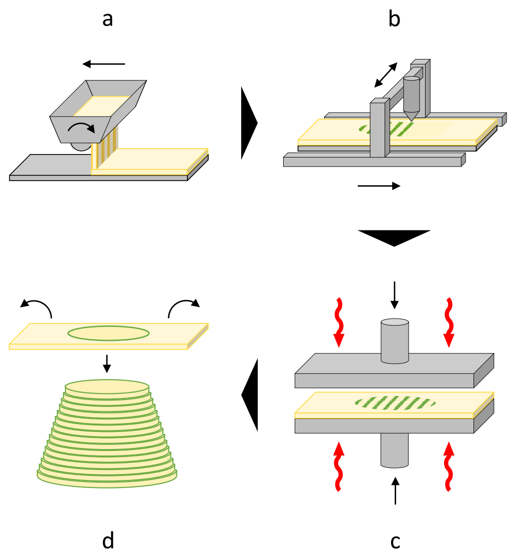

Figure 2: General scheme of the ILF process; adapted from [18]

By adjusting adhesive dosage and pressing pressure, the ILF process achieves densities and strengths previously unattainable in wood-based AM. In experimental testing, ILF panels exhibited bending strengths exceeding 30 MPa and moduli of elasticity over 3 GPa, fulfilling the requirements of plywood class F20/E30 [19]. With optimized wood particles, even higher values exceeding 50 MPa bending strength and 5 GPa stiffness could be reached [18].

The wood content in ILF parts ranges between 83 and 90 wt%, placing it on par with conventional engineered wood products. Moreover, the use of commercially available wood residues as feedstock adds ecological and economic advantages. [19]

3.2 – Application of ILF

Initial applications of the ILF process have focused on demonstrating the feasibility of producing wood composite components with non-standard geometries. One example is an Enneper minimal surface (see Figure 3), fabricated to test geometric limits and showcase the possibilities of the process.

Figure 3: A demonstrator object made with the ILF process [20].

Other demonstrators were produced to explore functional use cases. A Helmholtz resonator, for instance, was fabricated to investigate acoustic properties. Such elements may be applicable in interior construction where integrated sound absorption is desired. Additionally, a section of a topology-optimized ceiling element was manufactured to evaluate material efficiency and form fidelity [20].

More complex applications, including structurally optimized components or elements with multiple integrated functions, remain topics for further development. Their feasibility depends on ongoing improvements in process reliability, automation, and material control.

4 – Conclusion and Outlook

This paper presented the ILF process as a novel approach to additive manufacturing with wood. Unlike existing methods, ILF enables the production of customized components with high wood content and mechanical properties comparable to conventional wood-based materials. Initial demonstrators have shown the feasibility of manufacturing complex geometries and integrating basic functionality, such as acoustic behavior.

However, several questions remain before the process can be applied in structural or architectural contexts. Future research should address the long-term behavior of ILF composites under varying environmental conditions, including moisture resistance, dimensional stability, and creep performance.

From a production perspective, key development steps include the automation of the lamination process, and improved material handling. Additionally, the definition of joining strategies, especially for integrating ILF components into existing timber systems, will be crucial for practical applications.

With continued development, ILF may offer a path toward producing individualized, load-bearing components from renewable materials using additive manufacturing. Its ability to process wood as a primary feedstock and reduce the use of binder positions it as a potentially sustainable addition to the AMC field.

5 – Acknowledgment

The project was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) project number 414265976–TRR 277.

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The future potential of admixtures of beech with silver fir or Douglas fir

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Abstract: To address the challenges posed by climate change in silviculture, the establishment of mixed forests and the integration of drought-tolerant tree species such as Douglas fir and silver fir represent effective adaptive strategies. In our project we examine the impact of mixing Douglas fir or silver fir with European beech, with a focus on stand structure, growth dynamics, and their influence on both above- and below-ground biodiversity. A review of existing literature indicated that the effects of Douglas fir on native biodiversity are generally non-significant, though it underscores the need for further research in this area. Study sites were established in the Spessart region of northwestern Bavaria, an area recently affected by drought. The experimental design included Douglas fir/beech and silver fir/beech mixed stands, with pure beech stands serving as references. We investigated radial growth of trees in our study area, finding significant differences in growth between species, but not within beech in different mixtures. The findings underscore the need for further research into the effects of Douglas fir on native biodiversity, as well as the factors influencing tree species' responses to drought.

Keywords: *climate change, tree species mixture, biodiversity, central Europe, Douglas fir, silver fir*

1 – Introduction

1.1 – Background

Currently, Bavaria's forests are made up of a high proportion of spruce at 38 % [1]. Due to the prolonged periods of drought caused by climate change, spruce is increasingly losing its competitive strength and growth in lower altitudes in Central Europe [2], [3]. The most recent summer drought events between 2018 and 2020 led to an average 41.3 % decline in the growth of all tree species in Bavaria - with long-term negative ecological and economic consequences [4], [5].

European beech is one of the most important deciduous tree species in Germany, not only economically as a valuable timber resource but also for local biodiversity. However, it is a known climate sensitive species, which may suffer in view of increasingly frequent and intense droughts in central Europe. The admixture of more drought tolerant species like the non-native Douglas fir or the native silver fir with beech could mitigate effects of drought, due to complementary effects like facilitation or the competition for different resources.

1.2 – Alternative tree species

Douglas fir, which has its natural range on the west coast of North America, has been discussed as a drought-tolerant conifer species, as it is adapted to dry summers in its natural range [6], [7]. Due to its expected resistance to the climate changes predicted in the medium term, but also because of its wood quality characteristics which are comparable to spruce, the cultivation of Douglas fir in a mixture with other tree species offers a promising option for future-oriented silviculture [7].

Silver fir is a native tree species, with its range in Alpine regions of Central and Southern Europe. It has comparative growth characteristics to Douglas fir and is a native alternative for tree species mixing. As its natural range lies at higher altitudes, its projections for future survival at lower altitudes are uncertain [8].

1.3 – The project

Since 2022, the cooperation project "Future potential of Douglas fir and silver fir admixtures" of the Technical University of Munich and the Georg-August-University Göttingen has been investigating various ecological, structural and physiological aspects of mixed beech-conifer forests in northern Bavaria. The overarching aim of this project is to determine investigate admixtures of Douglas fir or silver fir with beech as suitable alternative species in managed forests.

From a biodiversity perspective, we asked ourselves if the addition of Douglas fir or silver fir to beech stands leads to an increase in biodiversity, both above and below ground. If this is the case, then does a threshold of mixing exist, below which any changes are not detectable? We also looked at the growth and structural properties of these mixed forests. Here we asked: Can different reactions of tree species to recent drought events be identified in their radial growth and is the reaction of the trees influenced by their surrounding neighborhood or individual tree morphology? The results of this project aim to help in developing strategies for ensuring the sustainability of the economic sector, which should also increase the stability of the forests in the long term.

2 – Study site

Our study sites are located in the Spessart region in northwestern Bavaria (Figure 1). A cool and precipitation-rich climate characterizes the region, ideal conditions for forest growth. However, the region was affected by the severe summer droughts of 2018/19 [9]. This allowed us to investigate potential effects of drought on trees in our forest plots. We selected 38 Beech/Douglas fir mixed plots, 31 beech/silver fir mixed plots and 25 pure beech plots as a reference. The proportion of Douglas fir in mixed beech plots was between 14 % and 88 %. The proportion of silver fir in mixed beech forests was between 8 % and 78 %. Having plots with differing gradients of mixtures allowed us to investigate potential thresholds of biodiversity in mixtures as well as effects of tree species composition on growth and structure of trees.

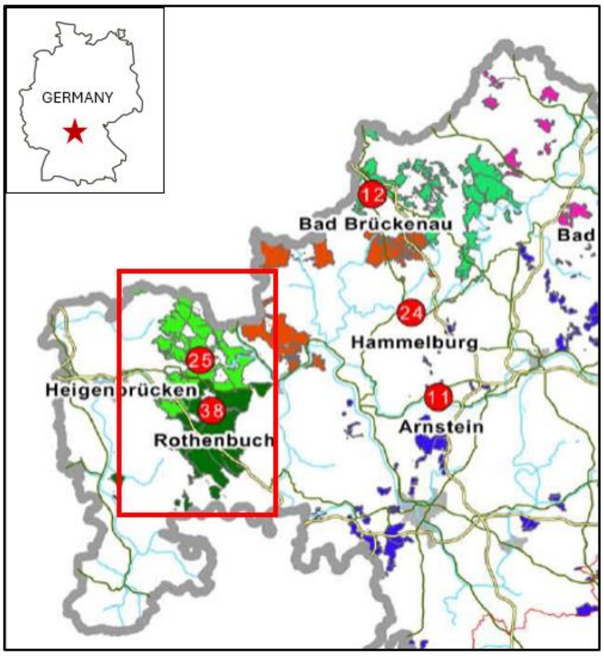

Figure 1: Map of the Spessart region forests, with two Forest Enterprises Heigenbrücken and Rothenbuch [11]

3 – The effect of Douglas fir on native biodiversity

To determine the impact of the introduction of the non-native Douglas fir on native biodiversity, we carried out a systematic literature review. Research into the impact of the non-native Douglas fir on different native species groups is crucial, as this tree species is increasingly used in managed forests. A comprehensive understanding of its impact on flora and fauna is essential to assess the long-term ecological consequences of its involvement in native forests. There are significant gaps in knowledge regarding the response of birds and arthropods, and little information is available on the effects of Douglas fir on soil fauna [10].

Out of 32 relevant studies, the effects of Douglas fir on native biodiversity in comparison to native tree species were largely non-significant (78.6%). Only 12 % positive effects were observed, while negative effects made up 9.4 % [10]. Douglas fir impacted above and below-ground biodiversity through changes in abiotic factors such as the light regime or soil characteristics and biotic factors like ground cover and food availability. These effects are mediated by moderating factors like management or surrounding forest. The review emphasizes the limited studies available on this topic and that further research is needed[10].

4 – Radial growth of trees during drought and normal years

To investigate the effects of growth of Douglas fir, silver fir and beech in different mixtures across our study area were cored and their ring widths measured from the years 2000- 2022. The ring widths were then converted into basal area increment (BAI), which quantifies tree growth in relation to their diameter at breast height.

We find that in general, BAI of the conifer species is significantly higher than beech (Figure 2a). We identified 2003, 2018 and 2019 as drought years in our study area, with the expectation that radial growth would decrease in these years [12]. We observed that Douglas fir and silver fir basal area increment was lower than in normal years (average of years 2014/15). In contrast, beech growth during drought in 2018 and 2019 was slightly higher than in normal years [12]. This could be due to a variety of factors, such as the anisohydric characteristics of beech allowing it to continue taking up water in dry conditions [12]. Previous studies also state that beech could display a lagged reaction in its radial growth to drought, decreasing BAI in the following years after drought [13]. In figure 2b we see that beech growing in Douglas fir or silver fir mixtures do not differ significantly in their BAI from beech in pure stands. Further research is needed into factors potentially influencing radial growth of beech.

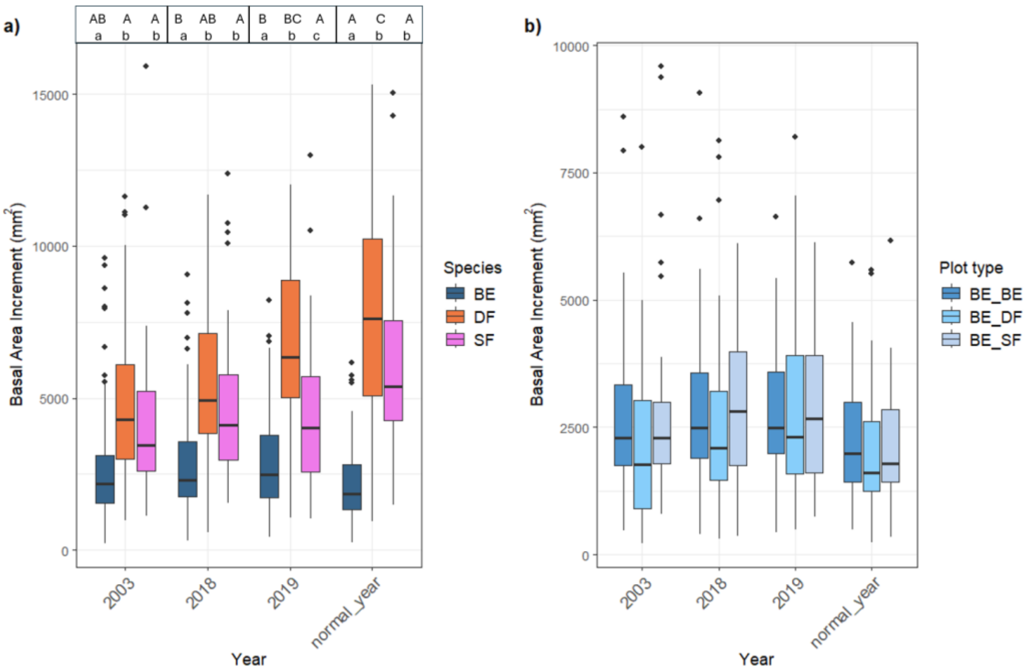

Figure 2: Distribution of annual basal area increment (BAI) in mm^2 in drought years 2003, 2018 and 2019 compared to normal year average (years 2014 and 2015) compared between a) investigated species beech, Douglas fir and silver fir and b) beech mixed with Douglas fir (BE_DF), beech mixed with silver fir (BE_SF) and pure beech (BE_BE). Capital letters show significance levels between years within one species group, and lower-case letters show significance levels between species with a year (pairwise Wilcoxon test). Data from [12]

5 – Conclusion

Mixed forests and the introduction of drought-tolerant tree species such as Douglas fir and silver fir are one way of meeting the challenges of climate change in silviculture. In this project, we investigate the effects of mixing Douglas fir with beech and silver fir with beech. We focus on the stand structure and growth of mixed stands and their effects on above- and below-ground biodiversity. A literature review revealed that effects of Douglas fir on native biodiversity was mostly non-significant, although it highlighted a need for further relevant studies. We established our study sites in Spessart, northwestern Bavaria, which was affected by recent droughts. Our plots consisted of Douglas fir/beech mixtures, silver fir/beech mixtures and pure beech stands as reference. Radial growth analyses revealed significant interspecific differences, while beech exhibited no notable variation in growth across different stand compositions. Our results highlight a need for further study into the effect of Douglas fir on native biodiversity as well as factors influencing the reaction of tree species to drought.

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A Robotic Fabrication Strategy for Hybrid Timber-Earth Slabs (TES)

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Abstract: The Timber-Earth Slab (TES) is a hybrid modular ceiling system that merges the structural performance of timber with the thermal, acoustic, and fire-resistant properties of earth. At the core of the system is a lightweight, spaced timber grid that serves as the primary load-bearing structure while also acting as reinforcement for the earth infill. This grid is robotically fabricated from small timber cross-sections using an integrated digital workflow. A custom digital configurator translates design parameters—such as slab geometry, structural loads, and fabrication constraints—into robotic assembly instructions, enabling design flexibility and adaptive optimization. The fabrication process includes automated positioning, adhesive application, and wood nailing with controlled pressure, all carried out by a robotic arm to ensure precision, repeatability, and consistent press force during insertion. After assembly, the timber grid is filled with a flowable, additive-enhanced earth mixture that cures to form visible interior surfaces, contributing to indoor climate regulation. TES exemplifies a scalable approach to combining regenerative materials with digital construction technologies and holds promise for applications in multi-story buildings. Its design and fabrication methodology may also be extended to other hybrid building components, opening new avenues for sustainable and automated construction.

Keywords: *timber-earth construction, digital fabrication workflow, robotic timber assembly, hybrid ceiling system, reversible construction*

1 – Introduction

The Timber Earth Slab (TES) is an innovative construction system that deliberately combines the structural advantages of wood with the physical advantages of earth. The interaction of these two regenerative materials creates a unified and resource-efficient system that is intended for use in multi-story timber construction (Fig 1) [1,2]. TES advances digital planning processes and robotic manufacturing methods to ensure high precision, individual adaptability and customization, and efficient use of materials.

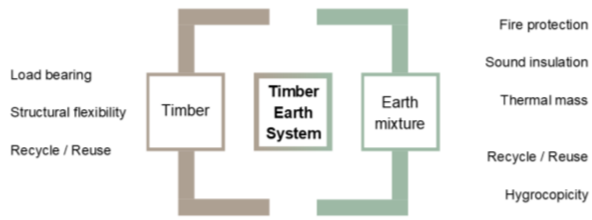

Figure 1: Combined characteristics of a timber earth slab

At the core of the system is a spaced timber grid fabricated from small cross-sections, forming a lightweight yet structurally robust framework. This grid is robotically assembled using a custom digital configurator, which translates design parameters—such as slab geometry, structural loads, and fabrication constraints—into robotic instructions for precise and adaptable fabrication. The robotic process includes automated positioning, adhesive application, and wood nailing with controlled pressure, ensuring a consistent and repeatable workflow. Following assembly, the timber structure is filled with a flowable, additive-enhanced earth mixture that cures in place, contributing to sound insulation, fire resistance, and indoor climate regulation (Fig. 2).

This paper focuses on the development and implementation of the robotic fabrication workflow for the TES system, detailing the digital-to-physical integration process. It aims at showing how the combination of digital tools with robotic manufacturing cannot only improve productivity and construction quality but also open new design possibilities for modular timber construction.

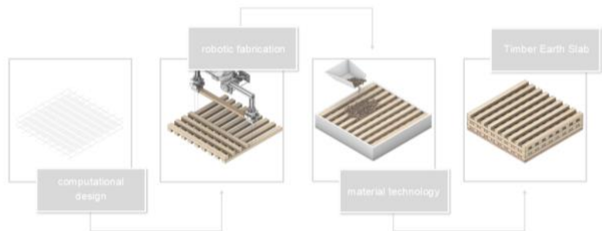

Figure 2: TES = computational design + robotic fabrication + material technology

2 – Method

2.1 – System Overview

The Timber-Earth Slab (TES) is a hybrid construction method that combines the structural strength of timber with the thermal, acoustic, and fire-resistant properties of earth, creating a multifunctional system [2].

The structural concept of TES is based on an innovative lightweight system derived from cross-laminated timber (CLT). Unlike traditional CLT, in which timber layers are fully surface-glued, the TES system forms a spaced grid by selectively bonding the layers only at the connection points. In TES, this timber grid fulfils a dual role. It serves as the primary load-bearing component by providing high tensile strength and structural adaptability. The use of small cross-sections promotes resource efficiency, minimises production waste and enables the production of different panel layouts, including non-standard geometries or slabs with openings. This approach supports scalable, flexible production and enables fully robotic prefabrication of the timber structure (Fig 3).

Once the timber grid is complete, its cavities are filled with a specially developed earth-based mixture. Formulated by ETH spin-off Oxara, the mix incorporates Oxacrete® Care, an additive that

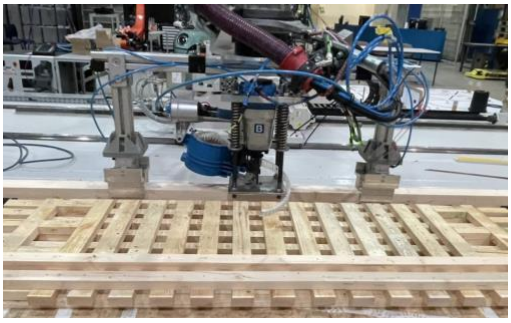

Figure 3: Robotic fabrication of the timber grid

enhances flowability with minimal water content [3]. This allows the earth material to be poured into the wooden structure. During the pouring process, the structure is continuously vibrated to ensure even distribution, avoid air pockets and ensure sufficient compaction. Depending on the ambient conditions, the drying phase takes around two to four weeks until the structural strength required for transportation and installation is achieved.

Figure 4: Earth mixing process by Leipfinger Bader Ziegelwerke and Oxara

In contrast to traditional timber-concrete composite slabs—where concrete is poured onto the timber—TES integrates the earth within the timber grid. This produces a monolithic, composite system where the earth remains exposed on the soffit, allowing it to unfold its full functional potential. The visible earth surface enhances passive thermal regulation, contributes to fire resistance, and improves acoustic insulation. Moreover, the slab can be thermally activated, forming a foundation for integrating passive heating and cooling technologies.

2.2 – Design Configurator

The configuration of the horizontally layered timber structure is achieved using a parametric design methodology developed as part of the research. This method integrates the architectural design, the structural analysis and the parameters for robotic manufacturing into an automated design workflow. As a central component in the chain from design to production, the configurator determines the optimal arrangement of timber layers based on the overall geometry.

Based on the input parameters for the dimensions of the lamellas, the number and orientation of the layers, and, if required, the positioning of openings, the configurator creates a flexible system adapted to varied geometric layouts and structural requirements. In addition, it is possible to condense or expand individual areas to precisely adapt to the load-bearing structure and at the same time reduce the amount of material. This differentiated design methodology prioritises material efficiency by arranging the lamellas specifically in accordance with the requirements of the earth infill. In addition, all the necessary parameters for robot production are calculated automatically by the configurator.

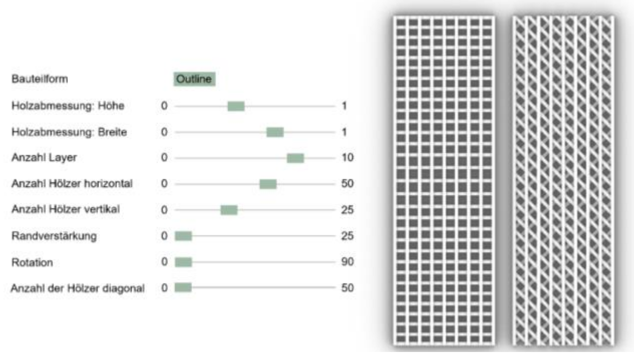

Figure 5: Digital design configurator that integrates architectural design, structural calculations, and the manufacturing workflow.

2.3 – Robotic manufacturing

The timber grid is assembled robotically, using a digital model to guide the customised placement and joining. The robot positions each lamella with high precision, bonding them at defined contact points to form a structurally effective lattice. This method combines the material efficiency and reduced adhesive demand of traditional beam slab systems with the load-bearing capability, high dimensional accuracy, and prefabrication advantages of modern CLT construction.

Currently, the fabrication workflow is partially automated and comprises four main steps, carried out at or in conjunction with a single robotic workstation.

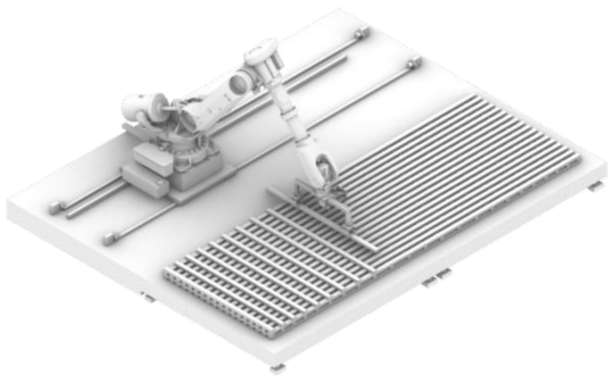

Figure 6: Robotic fabrication of the load-bearing grid structure made of wood.

1 Preparation and cutting of the lamellas. At present, timber lamellas are cut, ground, and prepared separately according to the geometric layout specified in the digital model. These pre-processed lamellas are then supplied to the robotic station. In future iterations of the workflow, this preparatory phase is intended to be integrated into the robotic system, enabling fully automated shaping and feeding of the lamellas directly from raw stock.

2 Positioning of the lamellas. Guided by the digital model, the robot grips and places each lamella with high accuracy. At this stage, the process operates in a feed-forward manner, relying solely on pre-defined positions and geometries. However, natural variability and deformation in the timber elements (e.g., bowing or twisting) can compromise alignment and bonding quality. To address this, future implementations will incorporate real-time sensor feedback —such as vision or tactile systems— to detect deviations and enable adaptive correction during assembly, ensuring robust structural performance despite material inconsistencies.

3 Applying the adhesive. Currently, adhesive is applied manually at specific bonding points before robotic layer placement. While functional, this manual intervention limits process speed and continuity. Future developments aim to integrate robotic adhesive dispensing, synchronised with lamella positioning, to enable precise, on-demand application within the adhesive’s open time and reduce waste.

4 Insertion of wood nails. After adhesive placement, the robot positions the next lamella layer and inserts nails under controlled pressure to locally secure the joint during adhesive curing. This strategy circumvents the need for large-surface pressing methods, such as vacuum pressing, making the process well-suited for complex or perforated slab geometries.

3 – Conclusion and Outlook

Initial tests confirm that the robotic assembly of the Timber-Earth Slab (TES) is both feasible and structurally effective. The automated positioning, nailing, and bonding process performs reliably, with a first structural assessment indicating that nail bonding under controlled pressure shows sufficient joint strength. Due to the controlled pressurised nailing, even with narrow timber cross-sections (6–8 cm), the nailing pattern has remained consistent, and little to no splitting of the wood has been observed—demonstrating a promising balance between precision handling and material robustness.

While these outcomes validate the core assembly concept, several areas require further development to achieve a fully integrated and scalable system. The current robotic workflow operates in a feed-forward manner, without real-time correction for material variability. Thus, future iterations must incorporate sensor-based feedback for positional accuracy, deformation detection, and process monitoring. In parallel, the manual adhesive application step should be replaced with a robotic dispensing solution to enable continuous, targeted, and synchronised bonding. Additionally, parallelisation of fabrication tasks could significantly enhance production throughput and system scalability.

Beyond the timber assembly, the earth infill process remains an essential focus for future research. Although the pouring method has been successfully implemented at a preliminary stage, further testing is needed to assess aspects such as fill consistency, surface quality, dimensional accuracy, and drying behaviour under variable environmental conditions. The interaction between the earth material and timber structure—especially in terms of shrinkage, bonding, and performance over time—must also be critically evaluated.

Ultimately, achieving a robust and versatile TES system will require not only the refinement of individual fabrication steps, but also their seamless integration into a coherent, automated workflow. Advancing these aspects will be key to positioning TES as a sustainable, adaptable, and industrially viable solution for future-oriented multi-storey timber building construction.

4 – Acknowledges

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Potential of Timber Construction in Tanzania

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Abstract: This paper provides an overview of the key aspects discussed during a workshop on timber construction in Dar es Salaam, Tanzania. East Africa is a rapidly growing region with high population growth and a substantial demand for housing. Given that forests and woodlands broadly cover the country, standardised timber construction with high prefabrication could present valuable chances. Despite the region's high potential for timber construction, modern timber construction is almost non-existent. Therefore, numerous political, socio-economic, educational and technical developments are still necessary. This situation presents plenty of opportunities for research cooperation, ranging from the fields of forestry, wood science and technology to architecture and social sciences.

Keywords: *Tanzania, forestry, timber construction, housing, value chain of wood*

In April 2025, the workshop "The Beauty of Building with Timber" took place in Dar es Salaam. Researchers from Germany and Tanzania, as well as students, government representatives and industry partners from Tanzania, participated. Topics discussed included the current state of housing, the role of timber construction in East Africa, and opportunities for research and development.

1 – Building sector and housing

1.1 – Population growth and housing shortage

The population in the United Republic of Tanzania is growing rapidly. According to current predictions, the population of over 61 million (as of 2022) will almost double by 2050 [1]. If the population growth rate remains that high and people continue to migrate to cities in search of work, Dar es Salaam could be among the 10 largest cities in the world by 2100 [2]. This rapid development also entails a significant demand for housing. Currently, there is an estimated housing deficit of approximately three million units, and the demand grows annually by around 200,000 units [3].
Due to these developments, it is estimated that by 2040, 70 % of Africa's building stock will have yet to be constructed. A high proportion of these additional residential buildings are projected to occur in urban areas and existing informal settlements. [4]

Another issue is that approximately 25-30 % of Tanzania's inhabitants live in poverty and lack access to education. With a median income of about 1,000 USD per person per year, many residents cannot afford appropriate formal housing. [5]

1.2 – Residential construction

Multi-story residential buildings make up only a small portion of the building stock in Tanzania. In fact, 94.4 % of all residential buildings are single-story, and 98.2 % contain only a single residential unit [6]. These buildings are usually self-constructed by the owners on purchased land or land owned by the state. However, these areas are frequently characterised as informal settlements, meaning areas without access to infrastructure such as wastewater management systems. As a result, only 72.6 % of all buildings have road access, 51.6 % are supplied with electricity, and only 24.9 % have access to fresh water [6].

Due to self-construction, buildings in informal settlements are often constructed without planning by educated engineers or architects. Primarily, clay bricks (burnt or sun-dried), stone blocks, and sand-cement blocks are used as building materials. The roofing is typically made of iron sheets. Timber planks, along with bamboo poles, are used as construction materials in 16.4 % of walls or as substructures for roofs [6].

2 – Wood and Timber in Tanzania

2.1 – Wood production

Forest and woodlands cover 55 % of Tanzania's total land area. National parks protect some of these ecosystems. The total area of plantation forests, including state-owned and private plantations, is estimated at approximately 325,000 hectares. About 65 % of these are planted with pine (*Pinus patula*), 20 % by eucalyptus (*Eucalyptus grandis*) and smaller areas of teak and black wattle. [7]

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Figure 1: Pine plantation in Tanzania (Photo: Stephan Birk)

A typical pine plantation can be seen in Figure 1. However, the forest sector is under pressure. For small forest owners, using their land for agriculture or fruit cultivation is often more economically viable.

2.2 – Wood utilisation

Of the wood harvested annually, around 85 % is processed into firewood and charcoal. This is primarily due to the fact that over 80 % of the local population uses wood and charcoal as their primary source of energy for cooking [5]. The remaining harvested wood is mainly used for furniture manufacturing, construction materials, packaging and paper industry or is exported. [8]

2.3 – Wood quality

Under tropical conditions in Tanzania, pine trees grow with an annual ring width of up to 1 cm. This means that the trunks reach maturity earlier, but it also results in a higher proportion of less dense earlywood. Therefore, Tanzanian pine (*Pinus patula*) was studied at the Technical University of Munich for use in construction. The wood was graded according to German and European standards and tested for properties such as tensile strength, bending strength (see Figure 2), delamination, finger jointing, fire resistance, and moisture behaviour [9]. The results show that the mechanical properties are sufficient for use in construction, even though they are lower than those of Central European softwoods. A more detailed report on the mechanical properties can be found in [9]. Possible applications include light frame walls or Brettstapel ceilings. Further studies are necessary.

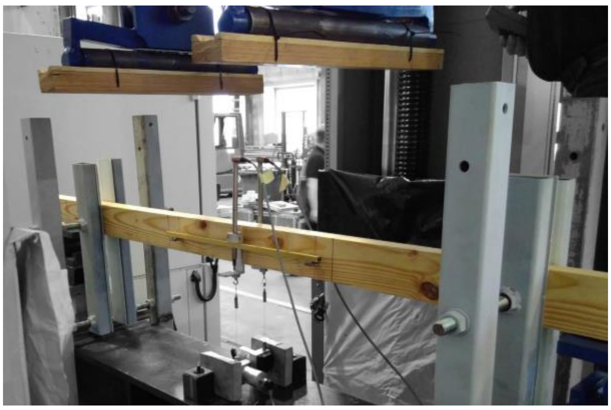

Figure 2: Four-point bending test of Tanzanian pine [9]
(Photo: Lucas Viereck)

2.4 – Engineered Wood Products

Currently, only a small proportion of engineered wood products (EWP) is manufactured from indigenous Tanzanian woods. Across Tanzania, approximately 20 factories produce veneer sheets, plywood and marine boards, manufacturing block boards, finger-jointed boards and fiber boards [10]. MDF factories are presently established. However, there is no production of other essential EWPs for timber construction, such as finger-jointed solid wood, glued laminated timber, or cross laminated timber. Consequently, the current demand for EWPs is met through imports. [8]

3 – Timber construction

3.1 – Current status in Tanzania

Multi-story timber construction is almost non-existent in East Africa. So far, there are only a few pilot projects driven by private investors in Tanzania and Kenya. The cross laminated timber and glue laminated timber used in these projects mostly come from Europe or, in some cases, South Africa. As a result, the housing units created are not affordable to the average Tanzanian citizen.

3.2 – Potential of Timber Construction

Wood resources are already available locally in Tanzania and have the potential for further development. If the means are available to reduce the amount of wood that is burned directly, these resources could be utilised as timber for the building sector. With its high degree of prefabrication, multi-story timber construction can significantly contribute to creating many housing units in a short period of time. Therefore, the EWPs as construction material must be available locally. If EWPs made from local wood could be used in standardised processes, housing can be created quickly and, above all, affordably for the average residents of Tanzania.

4 – Research and Development

For these developments to occur, extensive research and development are necessary. Political and socio-economic advancements are required to lead to long-term improvements in living standards, which would decrease informal housing and wood utilisation through burning.
Architecture must address questions in various areas such as affordability, social dynamics, urban planning, housing typologies, climate adaptability, energy efficiency, and more. In addition, concepts for the financing of housing must be developed. The provision of affordable housing and the preservation

of social infrastructure must be prioritised. The goal must be to create a fundamental social desirability and demand for timber buildings. This would also drive the demand for wood materials, leading to the emergence of a new local timber value chain. The development of a commercial forestry sector and EWP industry has the potential to generate new jobs and provide economic benefits through increased exports.
A sustainable forestry management system is essential to provide ecologically and economically the required resources. Establishing this industry requires research in the field of wood science and technology.

Knowledge and skills must be developed at all levels, and misconceptions and doubts about timber construction must be overcome. The relevance must be recognised as a political interest, initiating support measures and development steps. Forestry, sawmills, carpentry, and timber construction companies are necessary to enable production and disseminate knowledge by training new skilled workers. At the same time, training professionals such as planners, architects, engineers, foresters, and craftsmen is of great importance. Consequently, study programmes and courses must be established at schools and universities to impart knowledge about wood and timber. At the same time, research institutions must continue to collaborate, develop, and improve timber products made from native Tanzanian wood.

5 – Conclusion

The workshop held in Dar es Salaam was an important step towards a sustainable timber value chain in Tanzania. It facilitated the establishment of national and international contacts, the exchange of knowledge, and the development of a comprehensive understanding of the current state. It became clear that the potential is fundamentally present. However, large-scale developments are necessary and require time and effort.

This opens a multitude of research fields and questions. Their exploration can be carried out in close cooperation between European and East African universities, research institutions, and industry partners, bringing together different perspectives and experiences on housing and timber construction.

6 – Acknowledgement

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