INNOCROSSLAM – ADDING KNOWLEDGE TOWARDS INCREASED USE OF CROSS LAMINATED TIMBER (CLT)

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ABSTRACT: The research project *Innovative Solutions for Cross Laminated Timber Structures* (InnoCrossLam) was recently finished. The project aimed at increasing the competitiveness of CLT as a versatile engineered product, by increasing its predictability in demanding design situations not covered by the guidelines of today, or standards and codes foreseeable in the near future (*e.g.,* second generation of European design standards). This paper summarises the main project findings in the context of innovative CLT structures, such as: *i*. contemporary design approaches *ii.* the use of (non)linear FE modelling *iii.* experimental investigation of complex details for CLT structures, *iv*. investigation of multifunctional CLT. In this paper, the motivation behind the research topics within the project InnoCrossLam is explained and backed-up by exemplary results and discussion on future work.

KEYWORDS: mass timber, cross laminated timber, CLT properties, structural design, FE modelling, experimental investigation, multifunctional CLT, diagonal laminated timber, DLT

1 INTRODUCTION

1.1 BACKGROUND AND AIMS

Multi-storey timber construction has seen an important development over the last two decades, especially due to the introduction of cross laminated timber (CLT). Although the introduction of CLT to the market must be described as a success story, from a European perspective, the increased use of CLT is still slowed down by the lack of supporting provisions for design. Thus, there is still a lack of harmonised standard and unified design approaches in structural design codes. In addition, other complementing engineering tools such as handbooks are fragmented, national and, as a result, there is a risk of such documents leading to diverging recommendations. Finally, several common design situations are not covered [1].

1.2 OVERVIEW OF PRESENT WORK

Within InnoCrossLam, both basic research efforts and applied studies of innovative concepts have been performed. The work has covered studies to gain in-depth and basic knowledge of the mechanical behaviour of CLT, including joints and moisture related behaviour. Furthermore, the work has addressed more applied research by including investigations on prototypes of innovative concepts related to CLT with embedded functionality in terms of heating and ventilation (known as thermal activation). Finally, the project InnoCrossLam has aimed at proposing practical design approaches and formulae, for inclusion in future structural codes and standards.

2 PROJECT TOPICS AND RESULTS

2.1 SURVEY OF CURRENT CLT PRACTICE

Due to the crosswise arrangement of layers, CLT requires special approaches in the calculation of its mechanical properties and the evaluation of its structural performance compared to typical timber products such as solid structural timber or glulam (GLT). Therefore, as part of the project, it was deemed necessary to conduct a global survey of current practices. The results of the survey can be found in [2]. The questionnaire was distributed digitally worldwide to those who can produce, process, design or install CLT (i.e., CLT manufacturers, suppliers, engineers in construction companies, structural engineers, and researchers in institutions). A large part of the participants came from the main area of the CLT industry, i.e., Germany and Austria.

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More than 70% of the respondents are involved in practice, either in a design office or in a construction company. About 20% of the participants was from research and the remaining from construction companies.

Respondents proved to be quite experienced, most of them having worked in the field for more than 11 years (52.5%). Considering the recent introduction of CLT in practice and the experience of the respondents, it is possible that most of the respondents are self-taught on CLT design. Although most of them, 85%, consider that they have a reasonable knowledge of cross laminated timber structures, the obtained results show a very diverse level of knowledge. The design practice is also very different. While material parameters are uniformly applied to some extent, the approach to design is documented in a very heterogeneous manner, as shown by the wide range of literature used for design practice. No uniformly used background document could be identified.

Regarding the type of software or tools used for CLT verification, practice-oriented finite element (FE) modeling software is most commonly used, especially by designers and constructors in practice (about 70%). CLT-oriented software is used comparatively often, especially in the construction sector. In most cases, however, designers must additionally develop their own tools for certain analyses and verifications.

The most challenging design aspects in practice were openings in walls/floors (cca. 18% and 15%), point supports, and concentrated loads (23%). The majority pointed out the lack of design provisions as the main reason. In addition, connections, vibration, and fire measurements were also reported, again due to the lack of existing design regulations. The results of the survey mainly point to the lack of standardization and incomplete regulations as the main problems for practitioners. This unclear situation leads to the fact that the design of a structure in solid timber construction requires experience and further qualification and can therefore be performed only by some well-trained engineers. There is a need for the development of appropriate tools and models for the product, as well as simple design rules.

2.2 CLT AND MOISTURE

CLT is commonly used as a base for Timber Concrete Composites (TCC), and in this application the issues of moisture transport, drying and moisture-induced deformation are of interest. These were investigated with the help of accurate 3D FE models.

In general, wood moisture plays a major role in the design of timber structures, as wood is a highly hygroscopic material in which changes in moisture lead to changes in almost all physical properties. Due to its directionally dependent material properties, this can lead to cracking. However, the determination of the moisture condition in a timber member is relatively complex and the condition is variable both spatially and temporally, which is why only a very simplified consideration is used in the current version of the standard for the design and construction of timber structures. Water can occur in wood as bound water in the cell walls and as water vapor or free water in the cell lumen. Transport in the respective phases can be described by diffusion (bound water and water vapor) or capillary transport (free water). The phases are also connected by sorption (between water vapor or free water and bound water) and evaporation/condensation (between water vapor and free water). These mechanisms can be described with a so-called multi-Fickian transport model, which was previously implemented and validated with the finite element method and the commercial software Abaqus within a user element subroutine [3].

Next, this simulation tool was used to study the moisture loads that can occur in buildings. The first winter (heating phase) after the installation of the wood component is particularly critical when using timber elements indoors. To simulate such changes in humidity, moisture loads were applied to different wood elements in [4]. Starting from different initial wood moisture contents, fictitious reductions in relative humidity were applied to all exterior surfaces of the cross-sections and held for 720 h. The results were then used to simulate the moisture content of the cross-sections. Depending on the applied difference in relative humidity, the moisture content (MC) differed between 1% and 15% between the outside and inside of the cross-section. Based on the moisture simulations, the stresses can be calculated using expansion coefficients and the stiffness tensor. In unfavourable cases, these stresses can exceed the strength of the wood, causing plastic deformations and cracks [5]. Based on simulation results at the level of individual wood cells, a multisurface failure criterion was developed [6-8] that can reveal ductile (plastic) and brittle (cracking) failure mechanisms that can be used in commercial finite element software to predict the nonlinear behaviour of timber elements under moisture loading. The resulting crack patterns were analysed, and the maximum crack depths at specific time points are shown in Figure 1 for an initial wood moisture content of 15.3%.

From this figure, it can be seen, that the cracking is completed at different times depending on the cross-section width. In the case of the smallest cross-section with a width of 6 cm, this is already the case after 72 h, while in the case of the largest cross-section (GLT 20/40) an increase is already evident after 720 h. This is due to the difference in the cross-section widths: the difference in wood MC (and thus the wood moisture gradient) between the surface and the centre decreases as soon as the moisture flow from the surface reaches the centre of the cross-section. This is also roughly the time when cracking is complete. It is also easy to see that short-term changes of less than 8 hours cause only very small cracks, as a significant wood moisture gradient develops only near the edge. It can also be seen that small moisture differences in small cross-sections still lead to no or only small crack depths, while cracks or significantly deeper cracks can already occur in larger cross-sections. According to [9], cracks up to a depth of 15 mm per side are considered harmless.

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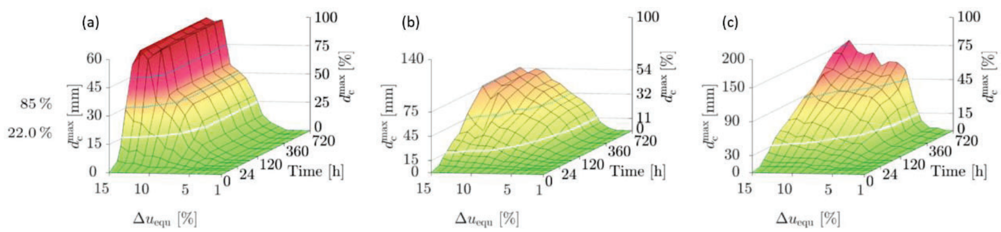

Figure 1: *Development of the maximum crack depth (sum of maximum crack depths of both cross-section sides), given in absolute and relative crack depth, for the cross-sections (a) solid timber 6/8, (b) solid timber 14/28 and (c) GLT 20/40 with an initial wood MC = 15.3% at different moisture content (MC) differences during 30 days (720 h) [9,10].*

The ultimate and serviceability limit states must be respected in the design of a timber structure according to EC 5. Changing climatic conditions and associated moisture-induced stresses are not taken into account directly in the current version of this standard, but via adjusted material parameters [10]. Compared to other environmental effects on the structure, such as wind and snow, no similar site-specific data are available for wood.

The following application of the models to a timber concrete composite demonstrates the capability of such an approach in studying critical conditions. Nowadays, the common method of manufacturing TCC elements with notches as shear connections is to apply fresh concrete directly to the CLT element. However, the fresh concrete releases moisture after application, which is absorbed by the highly hygroscopic wood and may lead to critical reduction of mechanical properties or problematic situations due to different expansion behaviour. Therefore, we used the moisture simulation tool to investigate the influence of the fictitious application of fresh concrete and then a realistic indoor climate applied to the bottom of the CLT element on the moisture behaviour of the timber parts [11]. Figure 3 shows the model of the CLT element and the path along which the wood MC is evaluated over the simulation period.

The resulting wood MC along the path over the simulated period are first shown in Figure 2 (below) for the original model without sealing. Moisture peaks above 70% occur in the uppermost lamella, corresponding to a value above the fibre saturation point and thus free water in the wood cells. Approximately the top half of the slab is affected in wood MC by the application of the fresh concrete. Depending on the indoor climate, the additional moisture introduced is removed over the course of nine to ten months before the entire slab dries out and an equilibrium MC of between 8% and 9% is reached. After that, only the lowest two lamellas are affected by the indoor climate. In addition, local sealing in the area of the end faces of the notches effectively reduces the moisture peak that occurs (see Figure 2). This means that such a sealing could possibly replace commonly used separating foils, which cause a high labour input or can reduce the load transfer.

In the next step, the implementation of more advanced crack modelling techniques [11,13] will also allow to represent in more detail the variability of, e.g., the strength properties of such timber products, leading to even better performance predictions, which have already successfully been shown for studying the so-called size effect of glulam [14,15].

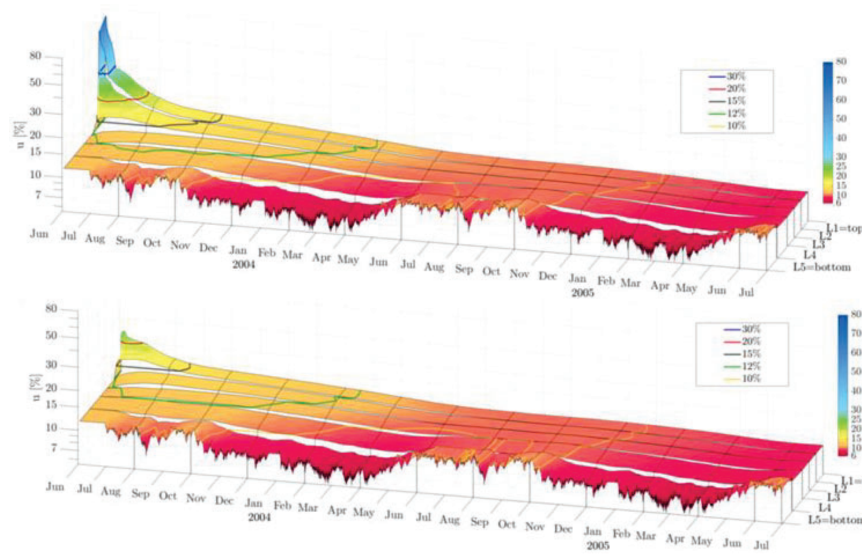

Figure 2: *Course of wood moisture content (MC) along the CLT plate thickness (from L1=top lamella to L5=bottom lamella), plotted over two years for the unsealed model (top) and the model with sealed end faces in the area of the notches (bottom) [11].*

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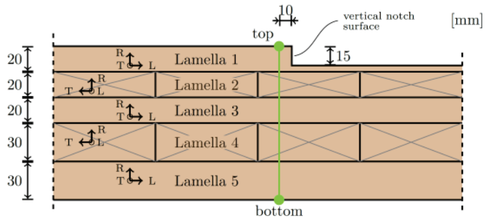

Figure 3: *Sketch showing the structure of the CLT element with local coordinate systems and path (green) for the evaluation of the MC curves over the simulation time [12].*

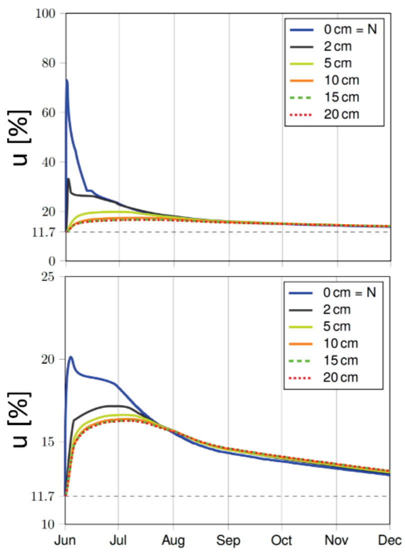

Figure 4: *Course of moisture content (MC) in the shear plane for the unsealed model (top) and the model with sealed end-grain surfaces (bottom) [12].*

2.3 CLT IN-PLANE SHEAR

For in-plane shear loading of CLT, two types of loading situations may be considered: pure in-plane shear loading and in-plane beam loading. The pure in-plane shear loading case is relevant for the loading situation in a shear wall or in a floor diaphragm, while the in-plane beam loading case would represent the loading situation for a lintel, or a pointsupported wall element.

For shear, three possible failure modes - gross shear failure (I), net shear failure (FM II), and shear failure in the crossing areas (FM III) - must generally be considered in the design. The methods proposed for verifying the ultimate capacity with respect to these three shear failure modes vary considerably among the design codes, design manuals, and ETAs of CLT manufacturers. The differences mainly relate to the determination of the design relevant stress components for FM II and FM III and the underlying mechanical models for stress analysis.

Within InnoCrossLam, investigations of the in-plane shear behaviour of CLT focused on the development of rational and unified design approaches for the cases of pure in-plane shear and in-plane beam loading conditions, considering design with respect to FM III.

An analytical model for prediction of internal forces and stresses acting in crossing areas between laminations of adjacent layers has been developed. The model is derived by considering the static equilibrium of individual laminations in CLT without narrow face bonding and loaded in pure in-plane shear. Stress predictions from the developed analytical model, predictions of design-relevant stresses from methods found in codes and handbooks and results from full 3D finite element simulations are compared for 3- and 5-layer CLT in [16] and for 7-layer CLT in [17]. The modelling approaches are limited to consideration of linear elastic behaviour, and the studies focused on the influence of CLT layup (i.e., individual layer thicknesses) on the magnitude and distribution of shear stresses acting on the crossing areas between adjacent layers. The results reported in [16] and [17] show large discrepancies between the considered models in terms of the magnitude of the stresses relevant for shear FM III.

An analytical model for stress analysis of CLT at in-plane beam loading was previously developed by Flaig & Blass, see e.g. [18]. This approach formed the basis for the design equations which were included in previous draft-versions of the new Eurocode 5 and the design equations suggested in the Canadian CLT Handbook. Modifications of the original model by Flaig & Blass have been suggested in [19], aimed at improving predictions of the stress state at loading (compared to the results of finite element simulations). A unified design approach, covering both the case of pure in-plane shear loading and in-plane beam loading, has been developed and is presented in [20]. This approach is based on the analytical model for pure shear loading and the modified model for the beam loading case, with some simplifications and approximations to arrive at rather simple and compact design equations.

In addition, experimental tests of CLT beams have been carried out at ZAG, Slovenia, using a 4-point bending test setup as shown in Figure 5. Six test series with a total of 36 individual tests were performed on beams with a gross cross section b×h = 140×600 mm^2. The study included investigations of three parameters: the individual lamination width, the cross-section lay-up in terms of thickness of each longitudinal layer, and the beam overhang at the supports. The general load versus displacement response was similar in all tests: after an initial linear response, a gradual decrease in stiffness was observed before reaching the maximum load and final failure. At the ultimate limit state, the beam failed due to bending (combined bending and tension) of the individual longitudinal laminations. Digital Image Correlation (DIC) measurements of surface strains and measurements of relative displacement between adjacent longitudinal laminations in the external layers showed significant sliding between the laminations. Sliding between laminations could also be observed at the end faces of the beams, as shown in Figure 6. The gradual decrease in stiffness - before reaching the maximum load - indicates damage and loss of stiffness of the bonding over the crossing areas.

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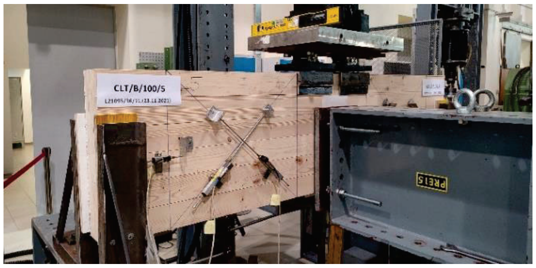

Figure 5: *Test setup for CLT at in-plane beam loading.*

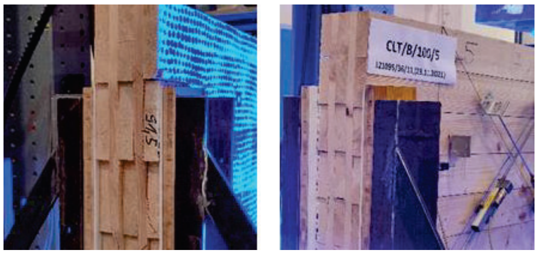

Figure 6: *Shear failure in crossing areas at beam ends.*

The test results are yet to be fully analysed and published. However, the results indicate very little or no effect of the lamination width or of the element layup on load-bearing capacity. These two findings are not consistent with the predictions of the proposed design equations. There are several plausible reasons that could explain the differences between the model predictions and the experimental results for the load-bearing capacity. The models and the failure criterion are based on the assumption of linear elastic behaviour. There appears to be gradual damage of the bonding over the crossing areas between the laminations of adjacent layers appear to take place, before the maximum load is reached. This damage and the corresponding local stiffness reduction could lead to stress redistribution effects and a stress state that deviates significantly from the model assumptions.

Moreover, the failure criterion itself, which is based on consideration of rolling shear stress and a torsional shear stress acting in the crossing areas, may not be suitable for accurate prediction of the load-bearing capacity. Failure criteria for FM III and test setups for determining the relevant strength parameters are further investigated and discussed in [21].

2.4 CLT WITH OPENINGS

An often-faced challenge relates to the design of CLT floors with openings. Within the project this situation has been studied both numerically and experimentally at Technical University of Munich (Figure 7) to find practical design recommendations. Two sets of specimens were designed to understand the different contribution of bending and shear to the overall deformation. Different types of holes were used for each set: a central hole for the bending specimens and holes on the supported edges for the shear specimens. For comparison purposes, three different hole sizes were tested: no holes, a 300x300 mm^2 hole for bending specimens, and 200x300 mm^2 holes for the shear specimens, both of which were eventually enlarged to 600 mm. The different holes were applied sequentially to each specimen, which were therefore tested only in the elastic region. As expected, in both cases the deformation increases with increasing hole size (and thus the stiffness decreases).

As can be seen from the survey [2], FE modelling based on shell elements is the most widely used approach. In the case of holes, the Beam Grillage Model (BGM) was proposed in [22], which simplifies the slab to a beam grid with effective stiffness. These two modelling approaches were compared with the obtained experimental results. Both show poor accuracy compared to the test results, especially in the case of shear dominated configurations. The FE model appears to be more accurate than the BGM for both bending and shear configurations. Although the BGM model is less accurate, it is shown to be conservative for the bending cases (which could be the main case in realistic applications). Both models need to be improved to be considered adequate approaches for this design challenge. For more information, see the companion paper [23,24].

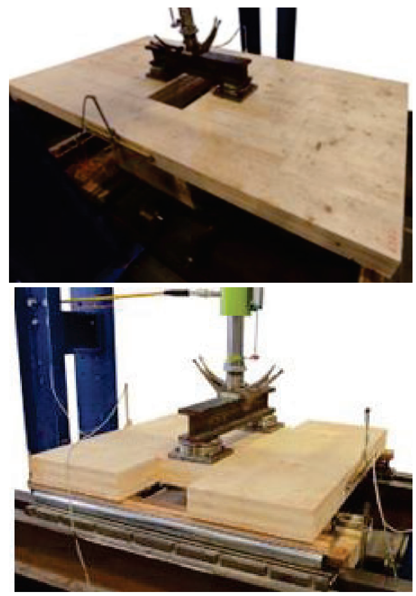

Figure 7: *Experiments on CLT floors with centred openings (bending series, top) and in the supports (shear series, bottom).*

2.5 CLT JOINTS

As with all structural timber elements, understanding the behaviour of joints is crucial also in CLT. As part of InnoCrossLam, particular emphasis was placed on quantifying brittle fracture through an experimental investigation (Figure 8) and reviewing previously available design approaches for their applicability to CLT. Currently existing brittle failure models have been developed mainly for timber products such as glulam and LVL [25-27]. Due to the load distribution between adjacent layers within a CLT element, i.e., due to cross-layer reinforcements, these models cannot be directly applied to CLT. Zarnani and Quenneville [28] made some modifications to their original model [29] to adapt it for CLT and verified the new approach for riveted CLT connections. Within the project, an experimental campaign was conducted at ZAG (the Laboratory for Structures) on connections with self-tapping screws subjected to tensile loads parallel to the outer layer of the CLT. The experimental campaign, the obtained results and the observed failure modes are described in [30], while the explanation of the existing model, its application to the performed experiments and the obtained results can be found in [31].

The experimental results described in [30] indicate that the load-bearing capacity of the connection increases with the width of the CLT specimen; for example, a 45% increase was observed between the width w = 250 mm and w = 750 mm. However, the increase in specimen width does not seem to affect the resulting elastic stiffness. The length of the screws was found to have a large effect on the elastic stiffness; for example, an increase of more than 70% was observed between 40 mm and 100 mm fastener lengths. The CLT layup does not seem to have a significant influence on the elastic stiffness, while it has an effect on the resulting load-bearing capacity, especially in relation to the penetration of the fastener into the different layers.

Figure 8: *Example of brittle CLT connection failure.*

It was also found that brittle failure typically occurs after the yielding of the fastener has already begun. Quite low ductility values are typically observed, in the range of 1.5-2.5, making these types of connections unsuitable for use in earthquake-prone areas where higher local ductility would be desirable. The existing model developed by Zarnani and Quenneville [28] has given rather inconsistent results compared to the experimental values of the connections performed in [30]. A major reason for this is the significant difference between the reported material properties. It must be emphasised that the need for reliable material properties is (as always) an important task. Moreover, they should be obtained from tests under conditions comparable to those assumed in the model. In addition, the trends presented for moisture may be affected by the reliability of the characteristic level due to the small number of replicates.

2.6 INNOVATIVE CLT

2.6.1 Multifunctional CLT in terms of thermal activation

Introduction and definitions

As part of the work on specific CLT panels, the InnoCrossLam project addressed the properties of application-optimised, multifunctional CLT wall elements. The objective of the presented research was to further develop a previously proposed CLT element (proof-of-concept [32,33]), which is multifunctional in terms of its thermal activation, to application maturity.

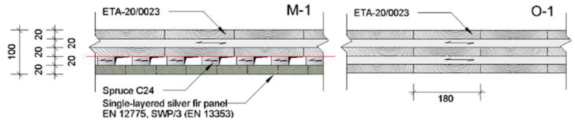

Figure 9: *Exemplary layup of a multifunctional CLT series (left) and a reference series (right) [mm].*

CLT wall elements with channels in which conditioned air circulates (Figure 9), enable the conditioning of massive timber buildings that meet the energy standards currently required in Central Europe [29]. The Construction Product Regulation (CPR) defines the essential requirements and key deliverables for the development and introduction of new construction products on the European market. By determining several essential properties of the multifunctional CLT, the relevant requirements covered in the CPR were answered.

Experimental investigations on the mechanical resistance and moisture changes in the cross section

The experimental investigations have proven that the reduction of the cross-sectional area by the channels does not necessarily have a significant effect on the compressive strength and stiffness of the elements [34]. On the other hand, the climatic tests clearly show that the quality of the front layer is of crucial importance for the deformation behaviour and the cracking pattern under thermal loading. It is therefore advisable to use high-quality 1-layered or better 3-layered solid wood panels for the outer layer [35].

Experimental and analytical investigations on the fire resistance

Safety in case of fire is a key issue in mass timber construction; such as the determination of mass burning rates and the fire protection closure. In large-scale fire tests, the time-temperature curves, the mass burning rate, and fire protection closure were investigated with and without cladding (Figure 10). Additional studies were conducted to analyse the effects of the fire within the channels. For the cavity fire studies, test specimens were moved inside the furnace (Figure 11, right). The specimens had the dimension $w/l = 0.5\ m\ /\ 0.5\ m$.

Figure 10: *Test specimen in the climate chamber.*

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The charts in Figure 11 show examples of the time-temperature curves behind each layer of test specimens (i.e., at a depth of 20, 40, 60, and 80 mm) for a fire event following the ISO 834 [33] curve. Compared to a standard CLT (O-1 series), the discrepancy between the curves measured at 40 mm depth with and without channels differs significantly. For the M-1 series, the flash point of 300 degrees is reached about 15 minutes earlier than for the O-1 series within the middle layer. Smoke and heat passage for M-1 is reached after 60 minutes. A burn-through after 90 minutes. Comparing the M-1 series without additional cavity fire to the M-1 series with additional cavity fire it is clear that the additional cavity fire leads to a reduction in fire resistance of an additional 10 minutes. The question of how to limit or extinguish cavity fires is a question of causality of a fire event that can only be answered analytically: Either a burning-in must be prevented by fire bulkheads or intumescent stripes must be introduced into the cavities during production [35].

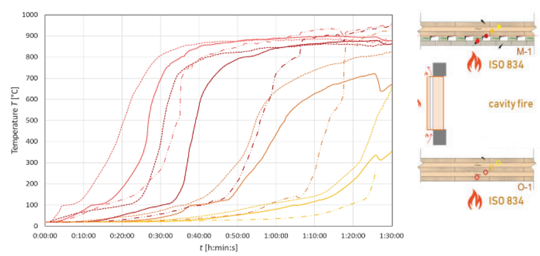

Figure 11: *Time-temperature curves of O-1 and M-1 series with and without cavity fire.*

2.6.2 CLT with diagonal layer arrangements

Introduction and definitions

In addition to research on multifunctional CLT, the mechanical properties of innovative Diagonal Laminated Timber (DLT) were investigated. DLT is a massive timber element, which is innovative in terms of its out-of-plane load-bearing capacity under biaxial bending and homogenization effects of stress distribution. DLT represents an application-optimised evolution of CLT. Conventional CLT consists of individual layers made from softwood laminations which are glued together in crosswise arrangement; this is done at angles of 90°. In DLT, on the other hand, 5 to 9 layers are glued together at specific angles Θ. For each –Θ layer, there is a +Θ layer within the laminate (Figure 12). In this context, DLT can be considered as a standard counterpart to CLT, offering improved mechanical properties when using the same material properties and layer thicknesses.

The diagonal arrangement of the individual layers promises increased in-plane and out-of-plane stiffness properties. Thus, for DLT, smaller deformations compared to conventional CLT are to be expected. In addition, the diagonal arrangement of the layers promises further homogenization of the orthotropic stiffness and strength properties. This can have a positive effect on the stress distribution due to the introduction of concentrated loads.

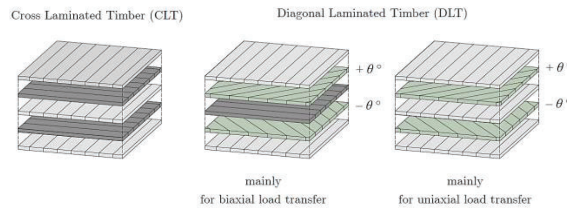

Figure 12: *Exemplary layup of a CLT series and DLT series*

Analytical, experimental and numerical investigations

The aim of this research was to determine the stiffness properties of DLT in terms of number and orientation of the layers. Therefore, the stiffness properties (out-of-plane shear stiffness, torsional stiffness, bending stiffness) have been determined by means of analytical, numerical, and unique experimental investigations (Figure 13). Parts of the results of this research have already been published in [36] and form the basis of further publications [36] and a future dissertation [38].

Following the studies on out-of-plane stiffness properties, a quantitative statement was made on the increase of the in-plane stiffness properties of DLT compared to CLT. This is particularly relevant to the use of DLT for stiffening wall and slab elements and for deep beams with large openings and notches. In addition, the objective was to implement the stiffness parameters in 2D FE models used for deformation analysis related to different static systems of mass timber slabs. The stress distribution in the load application region of point-supported CLT and DLT panels was investigated using large-scale 3D FE models.

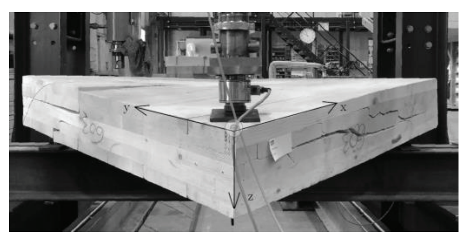

Figure 13: *Experimental investigations on the torsional stiffness of DLT.*

Ratio of homogenization

The terminology "ratio of homogenization" in terms of the number of diagonally or transversely oriented layers relative to the total number of layers oriented in the global x-direction was introduced. By the ratio of the sum of the thicknesses of diagonally and orthogonally oriented layers $t_{d,i}$ to the total thickness t_i, this terminology is quantified. Here, diagonally or transversely arranged layers are accounted for by the square of the cosine function of the respective angle Θi ($cos^2 \Theta i$). For a 5-layered DLT element with two layers arranged at 45° - as shown in Figure 12, centre - the ratio is ξ=0.600 (equation (1)).

$$\xi = \frac{\sum t_{d,i}}{t} = \frac{(cos\,45°)^2 \cdot 30 \cdot 2 + (cos\,45°)^2 \cdot 30 \cdot 2 + (cos\,90°)^2 \cdot 30}{150} \qquad (1)$$

Therefore, an isotropic plate element could be given as an extreme value that gives the ratio ξ=1.000. A 5-layered CLT of series O-1 has a homogenization ratio of ξ=0.429. The homogenization ratio serves as an indicator of the applicability of the chosen layup, regarding structures governed by uniaxial or biaxial bending in the serviceability limit state (SLS).

2.7 SEISMIC DESIGN OF CLT STRUCTURES

Extending the use of CLT structures to earthquake-prone areas and/or the architecturally driven development of asymmetrical and tall CLT structures requires more accurate numerical models and engineering design tools. The use of (non)linear FE models was investigated and evaluated from an engineering perspective.

The seismic force-resisting system (SFRS) in CLT structures consists of shear walls connected to the foundation or floors through various types of connectors to resist uplift and shear forces [39]. In general, CLT panels exhibit in-plane elastic deformation, while the desired seismic behaviour is achieved with sufficient overstrength design for possible brittle failures, such as splitting, and dissipative zone yielding of predefined ductile connections [40]. The decision on the type of FE analysis, linear and/or nonlinear, is mainly determined by the height and complexity of the structure and by the design approach chosen - Force-Based Design (FBD) or Displacement-Based Design (DBD).

Force-Based Design (FBD) approach

The two most common linear methods of analysis, regardless of structure type, the lateral force method (LFM) and the response spectrum method (RSA), both adopted in EN 1998-1:2004 [41], are based on the design spectrum and used for the force-based design (FBD) approach. In this case, although CLT structures provide a good ability to withstand earthquakes without serious damage, behaviour factors higher than 3.0 can hardly be achieved for taller buildings [42], so they should be selected with caution. Depending on the complexity of the structure and the ability to dissipate energy, values between 1.5 and 3.0 are recommended as suitable values in previous studies [43].

Since the CLT panels have a significant effect on the vibration frequency of the structure, the anisotropic material properties of the wood and the cross-laminated layers of the panels must be considered to accurately determine the stiffness of the building. When modelled as shell elements, design-oriented FE software packages include additional modules based on laminate theory [44] that could be easily adapted to CLT panels. However, orthotropic material model methods such as the equivalent orthotropic shell model-composite theory [45] or the shear analogy method [46] provide a satisfactory estimate of stiffness compared to experimental results at the global scale [47]. In addition, dissipative vertical connections between adjacent wall panels, shear connections, and hold-downs or anchors should be simulated in the wall models by introducing linear springs or other equivalent elements with appropriate stiffness values. Connections between adjacent panels should always be hinged. The supports to RC foundation are usually also hinged and with implemented shear and uplift stiffness parameters of the corresponding connection.

In addition, underestimation of building vibration frequencies and consequently non-conservative calculation of seismic forces with longer vibration periods and/or over-design under serviceability criteria for wind loads may be caused by secondary non-structural elements, as they have a greater influence on the overall stiffness of a lightweight CLT structure, as shown in [47,48]. As shown in Figure 14, a multi-phase approach using diagonal members at location of the openings can be used to represent the influence of the non-structural elements in the exterior façade. Since the total mass has the greatest influence on the natural frequencies, the most important global mode shapes, with the highest effective modal masses can be easily excluded from the local mode shapes in the modal analysis (e.g., by implementing nodal constraints as in-plane rigid floor diaphragms and manually calculated joint masses at each floor). Following these linear FE modelling principles can save engineers time, reduce errors, and improve the final design of the CLT building.

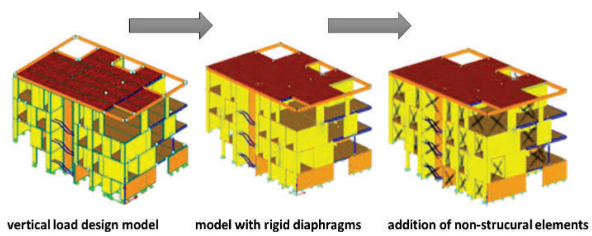

Figure 14: *FE model of a CLT building illustrating a multi-phase modelling approach and introduction of secondary elements stiffness by introducing diagonal spring members.*

Displacement-Based Design (DBD) approach

Since drift limits and target displacements are a common seismic performance objective for innovative performance-based design (PBD), the traditional FBD approach is not best suited for such a design concept. Such predefined objectives are better suited for the DBD approach, which is usually associated with the nonlinear static or pushover analysis - N2 method as described in Annex B of EN 1998-1:2004 [41]. The basis of the method uses the nonlinear response of the predefined components of the ductile structure beyond the elastic resistance and replaces the reduced response spectrum with the transformed bilinear capacity spectrum type curve of the structure under consideration. Although a minimal modification of the N2 method has been proposed in some studies on the design of multistorey CLT buildings [49], the present Eurocode 8 yields higher values for the displacement demands, so that the results are on the conservative side and thus can be safely used in the design process of CLT structures. Since the method requires a nonlinear FE model of the structure to analyse the seismic behaviour, the modelling process is consequently more complex and time-consuming.

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In addition, the nonlinear behaviour of the selected ductile connection elements should be defined with a bilinear or multilinear relationship in such a way as to reduce the problems associated with the convergence criteria. To overcome these difficulties, all the modelling principles and simplifications of the global structure as previously discussed for the FBD approach should be implemented in the nonlinear model. In order to simplify the model and reduce the number of FE elements and consequently shorten the computation time, the vertical load can be applied directly to the wall panels and the floors can be modelled as in-plane connected diaphragms only. Since different lateral loading patterns and/or positive and negative directions of load application can be crucial for undesirable structural behaviour of CLT structures at both global and local scales, all loading scenarios should be analysed, and the most undesirable result should be selected for the final design phase (Figure 15). Moreover, the effects of irregularities and their influence on the behaviour of the structure can be analysed using the extended N2 method, which provides a simple estimation of their possible unfavourable effects using the calculated correction factors [50].

An implementation of the N2 method and DBD of a case-study multi-storey CLT platform type building with a simplified nonlinear FE modelling approach, based on a validated single wall model, is presented in [51] where the adequacy of the designed building is assessed to various seismic loading. In a next step, more complex nonlinear seismic analysis methods will allow to validate and develop clear guidelines for the application of the DBD and N2 method to CLT structures.

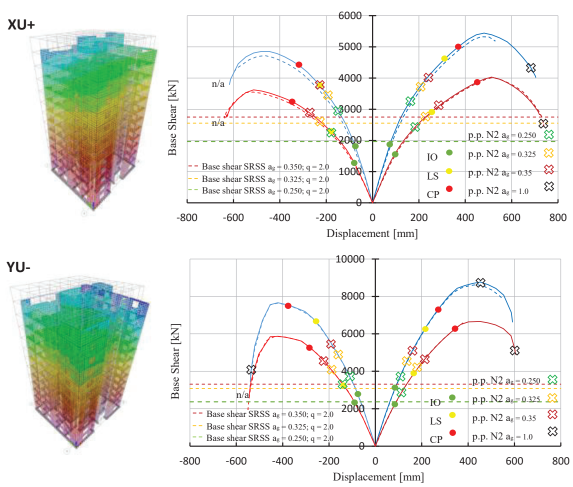

Figure 15: *Pushover analysis and capacity curves with indicated global limit states, N2 performance points and total base shear obtained based on different design spectra for a multi-storey case-study CLT building.*

3 CONCLUSIONS

The project InnoCrossLam has resulted in:

- new in-depth understanding of the mechanical behaviour of CLT components and joints,
- advanced modelling techniques,
- further development of design provisions for CLT by proposing rationally based formulae,
- recommendations for the design of CLT connections in terms of avoiding brittle CLT failure and designing connections with flexible insulation,
- properties of multifunctional CLT in terms of its mechanical and climatic performance and other.

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