A NEW COLUMN-TO-SLAB CONNECTION FOR MULTI-STOREY TIMBER BUILDINGS

EINE NEUE STÜTZEN-PLATTEN-VERBINDUNG FÜR MEHRGESCHOSSIGE HOLZBAUTEN

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SUMMARY

It is reported on first results regrading a novel column-to-slab connection suited for multi-storey timber buildings. The emphasis is on the development of a new constructive solution for a scalable, bespoken connection type, which enables to overcome today's rigid rectangular floor grid restrictions, thus enabling open-plan and flexible space architecture. The paper firstly reveals some of the recent developments of column-to-slab solutions in engineered timber construction. Then the constructive detailing, the finite element based modelling and some test results of a bonded connection, manufactured exclusively out of wood, are presented. The novel solution is based on specific orthogonally layered and stepped inserts, based on laminated veneer lumber (LVL) from beech wood, which are bonded into precisely fitting cavities in the CLT. The connection enables a multidirectional load transfer, being a prime requisite to enable biaxial plate action of the CLT elements, which span today almost exclusively uniaxially in their strong direction. The detailing and foremost the manufacture of the developed connection relies essentially on high precision CNC milling, which plays a key role in advanced timber connection solutions. This is especially true for the case of bonded connections which require very small tolerances. The novel connection was developed within the frame of the Science Cluster of Excellence IntCDC (Integrated Computational Design and Construction for Architecture), allocated at the University of Stuttgart.

ZUSAMMENFASSUNG

Es wird über erste Ergebnisse betreffend eine neuartige geklebte Stützen-Platten-Verbindung berichtet, die insbesondere auf die Erfordernisse mehrgeschossiger Holz-Hochbauten ausgerichtet ist. Im Vordergrund steht hierbei die Entwicklung eines neuen konstruktiven Lösungsansatzes für eine skalierbare, maßgeschneiderte Verbindung, die es ermöglicht, die heutigen Einschränkungen rigide rechteckiger Deckenraster zu überwinden, um frei planbare und flexible Raumarchitektur zu ermöglichen. Der Aufsatz berichtet zunächst über einige neue Entwicklungen von Stützen-Plattenanschlüssen im Holzbau. Im Anschluss wird über die konstruktive Detaillierung, die Finite Elemente Modellierung, die Herstellung sowie erste Versuchsergebnisse mit der neuen ausschließlich holzbasierten Verbindung berichtet. Die neue Anschlusslösung basiert auf speziellen, orthogonal geschichteten und abgetreppten Einlagen aus Buchen-Furnierschichtholz (LVL), die in präzis passende Ausfräsungen in der Brettsperholzplatte (CLT) eingeklebt werden. Die Verbindung erlaubt einen mehrachsigen Lastabtrag, der eine grundlegende Voraussetzung für eine zweiachsige Plattentragwirkung der CLT-Elemente ist, die heute nahezu ausschließlich einachsig in ihrer starken Richtung spannen. Die Detaillierung und sodann insbesondere die Herstellung der entwickelten Verbindung beruht essentiell auf hoch präziser CNC-Fräsung, die eine Schlüsselrolle bei fortschrittlichen Holz-Verbindungen einnimmt. Dies gilt vor allem bei geklebten Anschlüssen, die minimale Toleranzen erfordern. Die neue Verbindung wurde im Rahmen des Exzellenzclusters IntCDC (Integrated Computational Design and Construction for Architecture) an der Universität Stuttgart entwickelt.

1. INTRODUCTION

The increasing focus on high-rise timber buildings in the last years has catalyzed the research of different building systems suitable for multi-story timber structures. In this context, column-to-slab systems, consisting of cross-laminated timber (CLT) and glued laminated timber (GLT) elements, typically tied to a reinforced concrete core, are normally preferred. The high degree of prefabrication and relatively short on-site assembly times are the main reasons for this. A well-documented example of such a platform building system is the 18-story building "Brock Commons" at the University of British Columbia [5, 9]. The employed system consists of a regular rectangular grid of GLT-columns, aligned with the perimeter of the small-sized rectangular CLT plates. The corner-supported CLT elements rest on top of a steel plate attached to the surface of the columns, while the vertical load from the top floors is transmitted by means of a steel tube welded to the mentioned steel plates.

Today's realized tall wood buildings are greatly dependent on rigid, predominantly rectangular grids as ordering systems, which results in pronounced design limitations for open-plan, flexible spaces and bespoke architectural solutions. A higher degree of flexibility in the grid allows for optimizations on the distribution of inner spaces and material use, as well as for an increased design freedom. Therefore, moving in this direction represents a prerequisite towards advanced wooden, non-standard high-rise solutions. An important step for the desired flexibility has to do with the relative position of the column-to-slab connections within the CLT plate. Given that CLT plates have a rectangular geometry of typical dimensions up to 16 m in length in the strong direction and about 3 to 3.5 m in width, a flexible grid means that the position of the support for the CLT lies at an arbitrary position *within* the CLT (interior connection).

Some solutions for the sketched problem have been recently proposed. One of them—inspired by the reinforced concrete practice—consists on the use of so-called “Spider Connectors”, representing a connection with radially stretching steel profiles with self-taping screws to reinforce the CLT, as presented by Zingerle et al. [10]. Another known system relies on the so-called TS3 technology [11], where the slab region close to the column/support consists of a ”strong” material—such as LVL made of beech wood—which is then butt-glued to the narrow edge of the CLT plate. This special block, however, still has to resist large concentrated forces, then to be transferred by a technically extremely demanding end-grain bonding so far not approved/certified worldwide.

A common problem faced by the different systems further arises due to the transfer of vertical forces through a hole in the plate. Since the hole removes plate material exactly in the region of highest bending stresses, high localized tensile stress concentrations arise in the vicinity of the hole, owed to the mandatory redistribution of stresses in that area. This problem was recently studied by Muster and Frangi [8], where the problems due to elevated moment at the support position were analyzed both numerically and experimentally. In the mentioned study, local reinforcements were used to prevent the failure of the CLT plate due to the stress concentrations around the hole.

A direct implication of “loosening the grid” and optimizing the system is an increase in complexity of the system as a whole, since more individual detailing are needed. Therefore, a tight integration between the multiple aspects of the building planning phase, construction detailing design and manufacture—here termed co-design—is needed.

At the University of Stuttgart, the Cluster of Excellence “Integrative Computational Design and Construction for Architecture” (IntCDC), granted by the German Ministry of Science, is mandated to deal with these issues in a holistic manner. Within the IntCDC cluster, one of the projects (RP3) is dedicated to the specific task of developing a construction system for multi-storey wooden buildings, capable to allow a high degree of freedom in the structural grid. The work presented here is an integral part of said project.

This paper presents the state of constructive detailing and analysis of a new column-to-slab connection for multi-storey timber buildings, currently under development at the University of Stuttgart. One of the objectives of this connection is to make it highly adaptable, allowing the individual components (shapes and dimensions) to be optimized to different loading and boundary conditions. This goal is pursued within the possibilities offered by the computerized manufacture, both by traditional CNC machines and by more advanced robotic milling. The consequent adoption of these production possibilities offers unprecedented structural performances for timber structures. First Finite element (FE) simulation results are presented, then being compared to the experimental results of one prototype. The failure mechanism is discussed and the next steps are outlined, based on the experience gained from the realized experiment.

2. CONNECTION DESCRIPTION

The connection allows for a point support of CLT plates, and consists of two tailor-made beech LVL inserts glued into cavities at each side of the CLT plate, as illustrated in Fig. 1, here shown exemplary for a five-layer CLT plate. The top insert serves the purpose of reinforcing the tensile-stressed region of the continuous CLT plate, originating from the point support condition and stress concentrations in the vicinity of the hole used to transfer the vertical load (see below). The bottom insert consists of a stepped, pyramid-shaped element and has two main purposes: (i) to offer a stiffer support area for the column below, and (ii) to prevent high rolling shear stress concentrations in the region close to the support. The latter is an important aspect, as CLT, besides many superior features of this timber construction element, reveals one very poor strength property being the so-called *rolling shear strength*. This is the resistance to shear stresses acting normal to grain direction, provoking a kind of rolling separation of the tube-like wooden fibers. Rolling shear occurs at cross-layers of CLT and posses a pronounced hindrance/challenge for the transfer of highly localized loads, i.e. for *point* loaded plates (see e.g. Mestek [7] and Hochreiner et al. [6]). Since the pyramid element offers a larger support area for the CLT, it reduces the (rolling) shear stresses as well as compressive stresses perpendicular to the grain in the support area. The pyramid shaped reinforcement at the bending compression

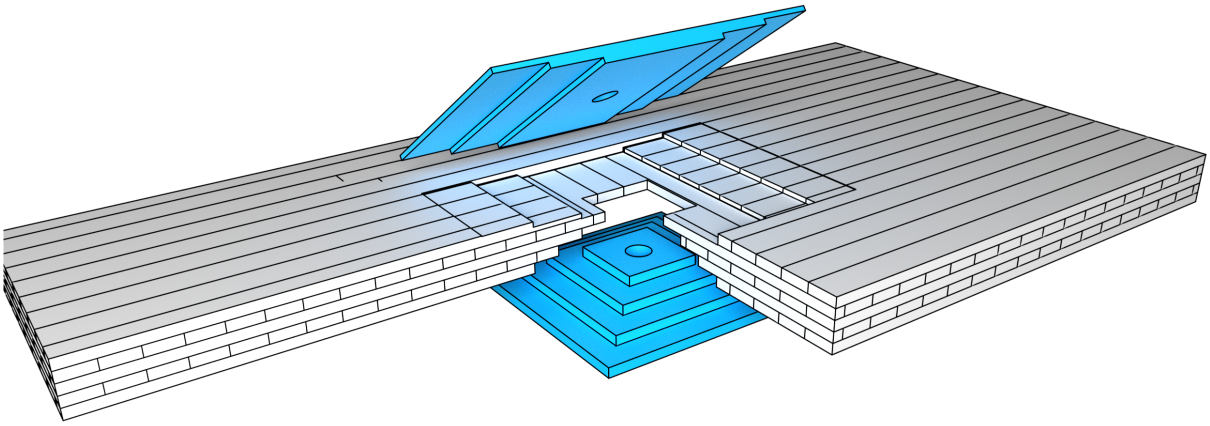


Figure 1: Illustration of the connection under development. The LVL insert on the top is designed to transfer tensile stresses, while the bottom, pyramid-shaped LVL insert is used to support the plate and better handle compressive and (rolling) shear stresses both parallel and perpendicular to the grain.

side resembles, to some degree, features in RC-column-slab connections. However, due to completely different material behavior and reinforcement options, the detailing shows significant differences.

In order to transfer the vertical load resulting from the upper floors, a hole is drilled through the center of the plate, as shown in Fig. 2. The details of the element used to transfer the vertical load are discussed in a separate paper.

Each level of the LVL-based pyramid insert composed of several LVL plates with uniaxial grain direction is oriented in a cross-wise manner as shown in Fig. 2b. This is done to align the grain direction of the LVL with the grain direction of the boards of the different CLT layers. For the layered tension insert, the two top most levels are oriented in the same direction as the principal direction of the CLT element, whilst the bottom LVL layer is oriented parallel to the CLT secondary direction (see Figs. 1 and 2a).

3. FINITE ELEMENT ANALYSIS

A 3D, parametric finite element (FE) model of the presented connection was created using the commercial software Abaqus v2020 [1]. In order to analyze the mechanical behavior in the immediate region of the connection with a high degree of detail, the submodelling technique was applied. Thus, a coarse global and a densely meshed submodel were created. In the following, a description of the relevant aspects of both models is presented.

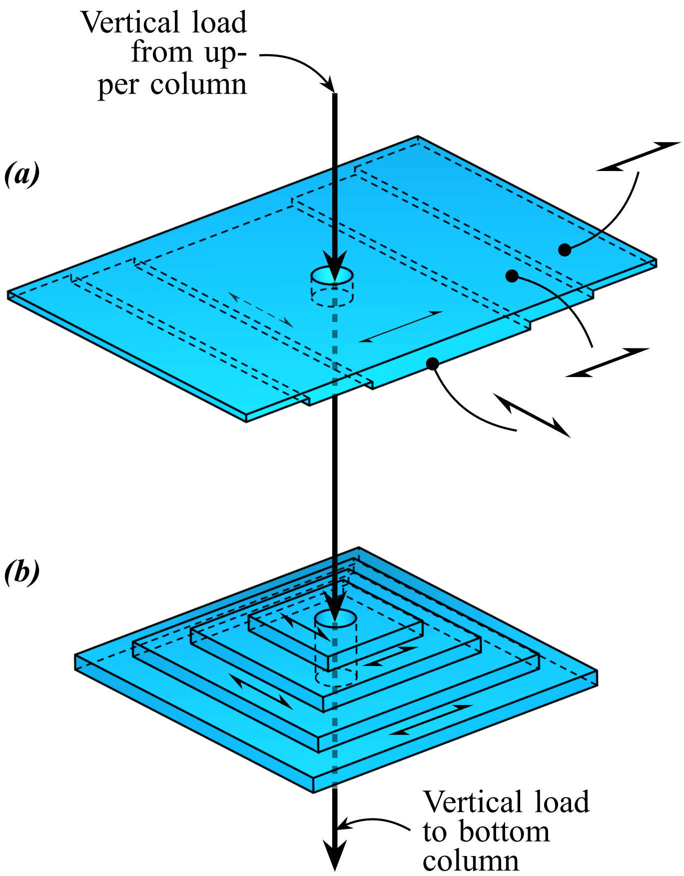


Figure 2: Transfer of vertical load through both beech LVL inserts; (a) detail of LVL tension insert plate; (b) detail of pyramid-type insert

3.1 MODEL DESCRIPTION

3.1.1 Global model

The global model simulates the loading situation corresponding to the experimental configuration (see Fig. 8), where a five-layer CLT plate of dimension $\ell \times w \times t = 3000\,\text{mm} \times 1200\,\text{mm} \times 200\,\text{mm}$ is tested in its secondary direction. The developed connection is not considered in the global model. The CLT plate is supported at the center of the CLT plate by a short GLT element with a cross-section of $200\,\text{mm} \times 200\,\text{mm}$. A total load $F = 100\,\text{kN}$ is applied on two rigid battens positioned close to the opposite narrow ends of the CLT plate, with a distance of 2800 mm in-between. The rigid battens span the entire width of the CLT plate (see Fig. 3) and simulate the support plates of the experiment.

Linear 3D elements with reduced integration (C3D8R) were used to model the CLT and GLT, whilst rigid elements of type R3D4 were defined for the loading battens. The material properties of the boards constituting the CLT element correspond to strength class C24 according to EN 338 [3] and ETA-06/0009 [4] (see Table 1).

Table 1: Stiffness values used for the materials in the finite element models

Material	E_x [MPa]	E_y [MPa]	E_z [MPa]	ν_{xy} [–]	ν_{xz} [–]	ν_{yz} [–]	G_{xy} [MPa]	G_{xz} [MPa]	G_{yz} [MPa]
Beech LVL	16 800	470	470	0.02	0.02	0.2	850	850	85
CLT	12 000[1)]	370	370	0.02	0.02	0.2	690	690	50

[1)] According to ETA-06/0009 [4]

Table 2: Characteristic strength values for the used materials

Material	$f_{m,0,k}$ [MPa]	$f_{t,0,k}$ [MPa]	$f_{c,0,k}$ [MPa]	$f_{c,90,k}$ [MPa]	$f_{v,0,k}$ [MPa]	$f_{v,R,k}$ [MPa]
Beech LVL	80.0	60.0	57.5	10.0	8.0	3.8
CLT	24.0	14.6	21.0	3.0	4.0	1.0

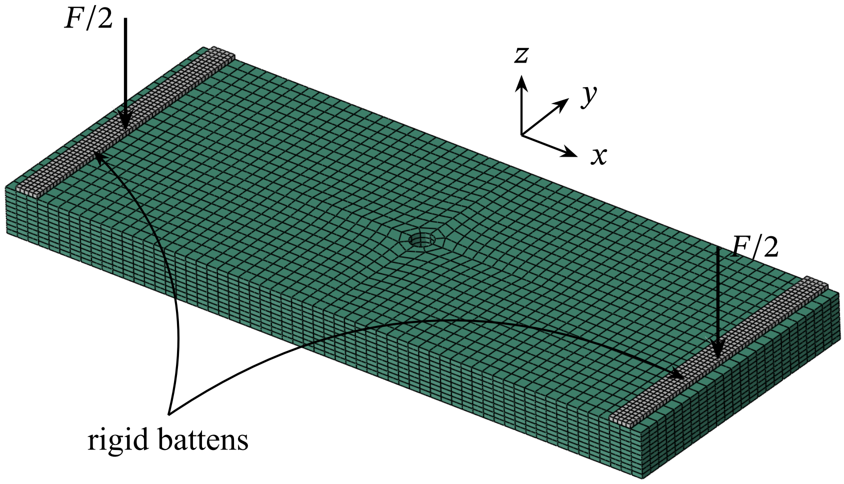


Figure 3: Geometry and mesh of the global model

3.1.2 Submodel

The submodel comprises a quarter of the section spanning $x = \pm 750$ mm from the central support. Linear elements with reduced integration (C3D8) were used to mesh most of the geometry (a few wedge elements of type C3D6 were generated by the meshing algorithm outside the connection region, too). A minimum element size of about 6 mm was used to mesh both LVL elements and the CLT region between them, and a maximum size of 30 mm was used in the outer region (see Fig. 4). The material properties used for the different parts are specified in Table 1. The interfaces between the different components (pyramid insert, tension plate insert and CLT plate) were connected by means of *Tie constraints*. The interface between the pyramid element and the (column) support was modeled with a contact interaction with rough behavior in the tangential direction.

Symmetry conditions were applied according to Fig. 4. The boundary conditions were derived from the stresses obtained for the global model, located at the sur-

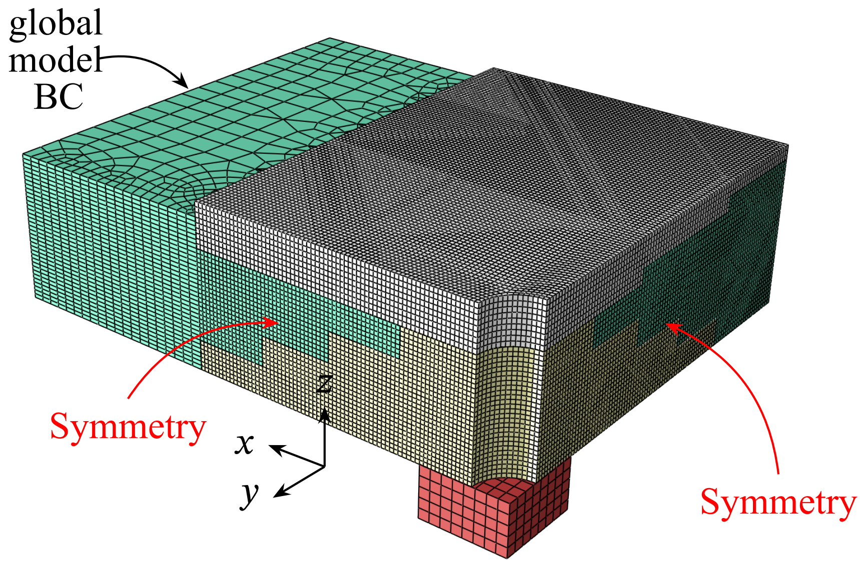


Figure 4: Mesh of the submodel and boundary conditions

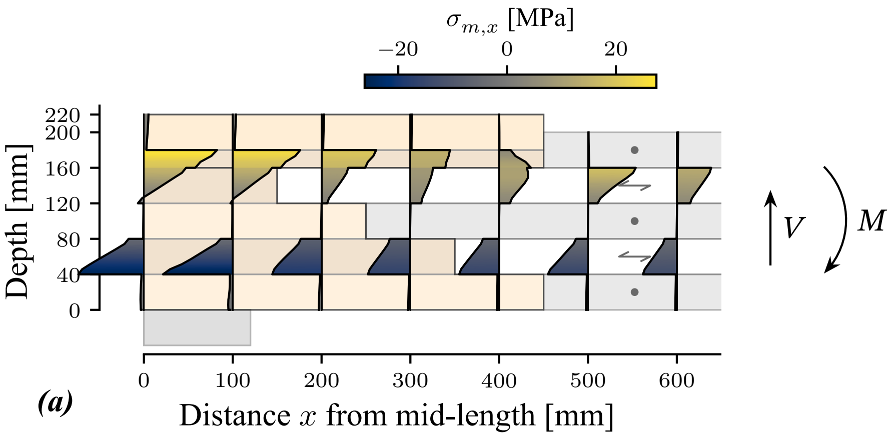
face marked as “global model BC” in Fig. 4. The interpolation of stress results from the global model into the submodel is performed internally by Abaqus.

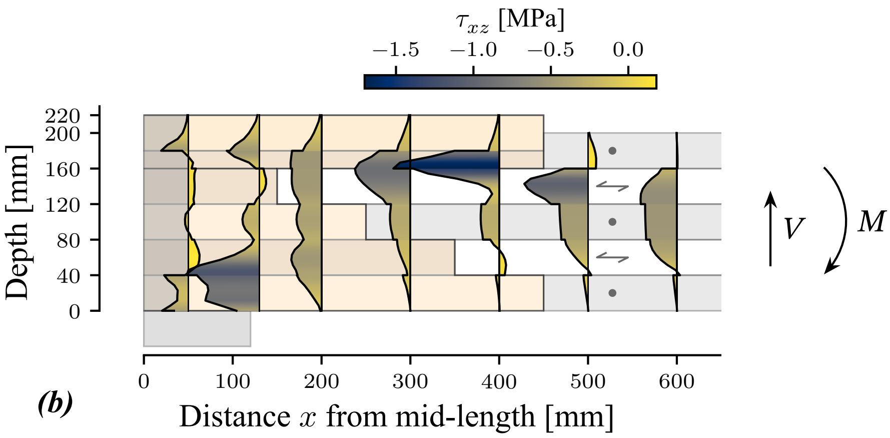
Both models were computed by means of Abaqus’ standard solver, using the static stress analysis and considering geometric nonlinearities.

3.2 STRESS DISTRIBUTION

In the following, the stresses obtained by loading the CLT plate strip in its weak direction, i.e. with both outermost board layers oriented perpendicular to the span, are discussed. Here, a rigid bonding of the narrow edges of the outermost boards is assumed. The same configuration was investigated experimentally too, reported below in Sections 4 and 5. The stresses were analyzed in the vicinity of the support in order to assess the influence of the different components of the connection. In the following, a summary of the bending and (rolling) shear stresses is presented. For this, the stresses are extracted on a series of paths that allow to visualize the evolution of the distributions as they approach and then traverse the connection region.

Figure 5a presents the bending stresses, $\sigma_{m,x}$, within a longitudinal cross-section y = const. = 100 mm, i.e. with an offset of 100 mm with respect to mid-width. This cross-section is used to avoid the hole placed at the center of the plate. It can be seen how $\sigma_{m,x}$ increases as the distance to the center diminishes, which is owed to the point loading situation, as the total force converges to the central support. It can be observed that the tension insert is gradually activated, taking a higher share of the stresses as the distance to the center is reduced. In more detail, it should be





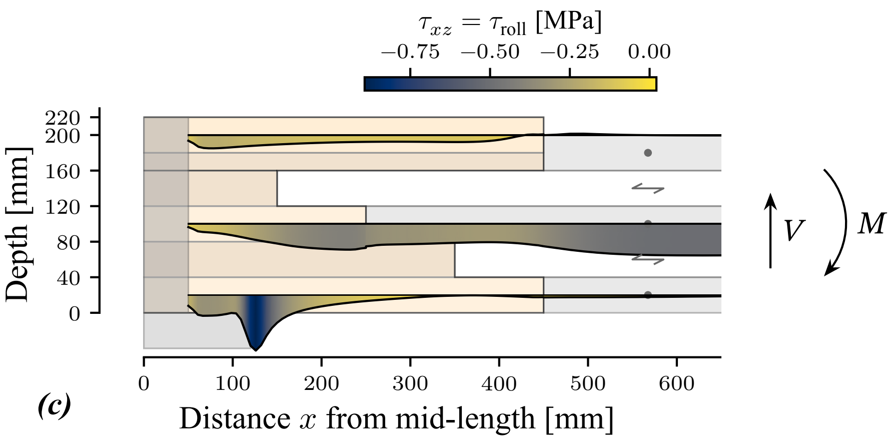


Figure 5: Stresses along paths on a cross-section of the plate connection for a centric column load $F = 100\,\text{kN}$*. (a) bending stresses* $\sigma_{m,x}$ *at* $y = -100\,\text{mm}$*, (b) shear stresses* τ_{xz} *at* $y = 0\,\text{mm}$*, and (c) rolling shear stresses* $\tau_{xz} = \tau_{roll}$ *at* $y = 0\,\text{mm}$

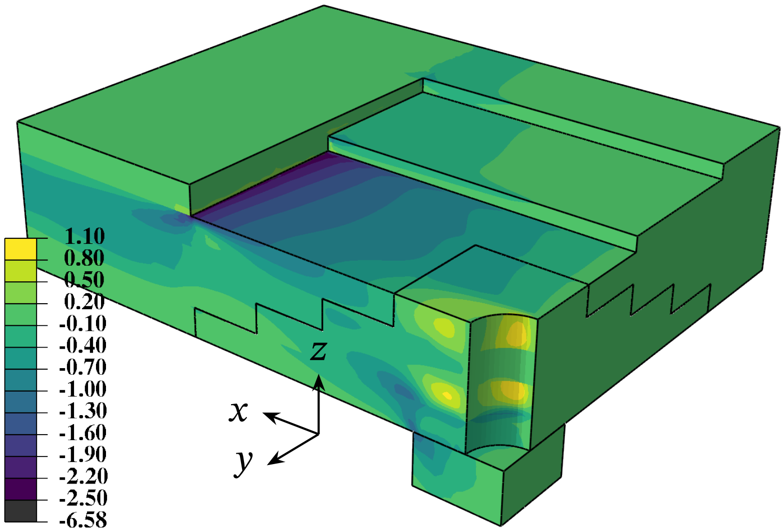


Figure 6: Shear stresses in the CLT and pyramid elements. The tension plate was removed to expose the stresses in the interface with the CLT plate

said that the lower part of the tension insert with fiber direction parallel to the CLT boards oriented in the weak x-direction are activated. Both maximum tensile and compressive stresses are located within the LVL elements. This is mechanically convenient, as the strength values of the beech LVL material are substantially higher than the strength values associated to the regarded softwood CLT (see Table 2). This aligns with the original motivation that started the development of this connection.

The shear stresses—termed rolling shear when acting in board layers with grain direction normal to the shear stress direction—are illustrated in Fig. 5b along vertical paths on a cross-section at mid-width of the plate ($y = 0$). It can be observed that, up to a certain distance from the connection, i.e. from the LVL inserts, the shear stresses present the typical rather parabolic distribution known for CLT plates. Approaching to the connection the shear stress distribution gets more skewed, associated with a high stress concentration in the interface between CLT and tension plate (see Fig. 6). These high shear stresses originate from the transfer of tensile stresses from the CLT to the LVL insert. This clearly represents a critical situation, as a strong, reliable bond between the LVL and CLT plate must be ensured, so that the stresses can be transferred successfully.

Finally, Fig. 5c presents the (rolling) shear stresses along the middle of both outer cross-layers and of the central layer of the CLT; further, the shear stresses in the LVL inserts are depicted. It can be noticed that the position of maximum rolling shear is located in the region close to the support, which can also be observed

Table 3: Computed maximum load capacities for the different failure modes of the developed connection and for a reference CLT plate without the LVL inserts

Failure mode	Max. load capacity $F_{\max}$ [kN] RF2	UF2	Δ [%]
Rolling shear	220.0	100.0	120
Shear	200.0	571.4	−65
Tension	123.0	75.7	63
Capacity	123.0	75.7	63

RF2: Reinforced CLT plate
UF2: Unreinforced CLT plate
* Note: moment vector is normal to the weak CLT direction, here denoted as x

from Figs. 5b and 6. These shear stresses would normally initiate damage to the CLT at that position, however, now the shear stresses can be safely transferred by the pyramid-shaped insert due to the better mechanical properties of the beech LVL. It can also be observed that τ_{xz} is slightly reduced in the CLT middle layer, before entering the pyramid element, which is due to the redistribution of shear stresses previously discussed.

3.3 COMPUTED FAILURE MODES

The FE model was used to identify the maximum stresses within the different components of the connection solution (CLT plate and LVL inserts), which were then used to obtain the maximum load capacity $F_{\max}$ of the studied configuration. The derivation of the ultimate theoretical capacity was done by linearly scaling the FE-stress results (obtained at 100 kN) up to the level where the stresses reach the respective component strength values. So, entirely brittle failure without any nonlinear damage evolution is assumed in a first rough approach. The capacities of the connection obtained for the different identified failure modes are presented in Table 3. For comparison purposes, Table 3 contains also the load capacities of the respective failure modes, numerically computed for a CLT plate of the same geometry (hole for vertical load transfer included) and material as the analyzed here, but without the LVL inserts. Loading and boundary conditions remain the same.

Analyzing independently by failure mode, it can be seen that the (rolling) shear capacity of the plate-to-column configuration is increased by 120 %, i.e. from 100 kN without the reinforcement to 220 kN with reinforcement. If the (interface) shear failure mode is considered, it can be noticed that the capacity is reduced by a 65 %, which is owed to the high shear stresses in the interface of CLT and tension plate (see Fig. 5b). Note: The mentioned capacity reduction in fracture mode (interface) shear is irrelevant, as the extreme high load capacity of the unreinforced CLT is of mere theoretical interest.

The dominating failure mode for the CLT plate with the reinforcing inserts according to the FE simulations is, however, the tension failure in the CLT plate ($F_{max} = 123$ kN). The failure of the non-reinforced CLT plate is also dominated by tensile failure, caused by the tensile stress concentrations in the periphery of the hole. Here, an increase of 63 % with respect to the unreinforced connection is predicted. These results will be compared below with experimental results.

4. MANUFACTURING OF PROTOTYPES

The presented connection, with its rather complex geometry, presents several challenges for the manufacture, as the bonding demands small tolerances in the interfaces of the different elements. For example, in order to ensure surface-to-surface contact on each level of the LVL-based pyramid and of the stepped tension insert with their CLT element counterpart, a high precision CNC-milling is required so that the components fit correctly. The tolerance issue is further aggravated by the fact that both, CLT and the LVL plates employed for the inserts show partly significant—however product-wise admissible—deviations from the nominal product thickness values.

4.1 INITIAL PROTOTYPE

In order to prove whether the necessary tolerances can be achieved, a first prototype of the connection region was made prior to the manufacture of the mechanically tested specimens. The dimensions for the LVL inserts of this first prototype had the same dimensions as the planned test specimen, however the CLT plate spanned only the central region containing the inserts. The prototype milling was performed and programmed by the Institute for Machine Tools (IfW), University of Stuttgart, cooperating closely in this project with the MPA, University of Stuttgart. The prototypes for the first mechanical tests (see below) were made at IfW as well.

In the initial round of prototyping, the produced connection was cut open in order to analyze the bond lines. Samples were taken and tested, delivering results that gave confidence in the feasibility of the developed concept. It was therefore decided to continue with a larger prototype for testing purposes.

4.2 PROTOTYPE FOR EXPERIMENTAL TESTING

For the larger prototype, a CLT plate of dimensions $\ell \times w \times t = 3000$ mm × 1200 mm × 200 mm was used (i.e. the same dimensions as in the FE model). The beech LVL pyramid-type insert had a squared base of 900 mm × 900 mm and vertical steps of 40 mm. It was first pre-assembled by stack-gluing LVL plates in a cross-wise manner and was then fed to the CNC machine. The three-layered tension insert with a total thickness of 60 mm had a length of 1200 mm and width of 900 mm and was assembled in a similar manner as the pyramid element. The central hole, with a diameter of 100 mm, was drilled later manually, as the milling tool was not long enough to drill through the whole thickness of the pyramid element. The final milled pyramid element and counterpart-cavity in the CLT plate are shown in Figs 7a,b, respectively.

The different components were later bonded by means of so-called screw-gluing, for which a gap-filling PRF adhesive of type EN 301 I 90 GF 1,5M [2] was used. The screws were removed prior to the testing. (Note: in the construction practice the screws would remain inserted.) The assembly process showed that the needed tolerances were met, and each element fitted perfectly in its place.

5. EXPERIMENTS

5.1 TEST SETUP AND TEST PROCEDURE

An experimental setup was designed to analyze the behavior of the reinforced connection under a loading condition that emulates a punctual support, as studied with the FE model. For this, the plate-strip was tested with regard to its capacity in the weak (secondary) CLT direction, i.e. with the outermost board layers oriented perpendicular to the span axis. In the three-point bending configuration the base of the pyramid-type insert is facing upwards, as shown in Fig. 8. A beech LVL block with a cross-section of 240 mm × 240 mm was placed on the center of the plate, simulating the supporting column. The load was applied directly on top of the LVL block in a displacement-controlled manner by a servo-hydraulic cylinder with a maximum load capacity of 1 MN fixed to a stiff portal frame. The CLT plate was simply supported both-sided on two long steel battens with lengths slightly larger than the width of the CLT plate. Steel rollers were placed under the steel plates along the full width of the plates.

The load was applied in three steps: (1) first the connection was loaded up to $F = 55$ kN and then unloaded down to $F = 10$ kN, (2) then it was loaded up

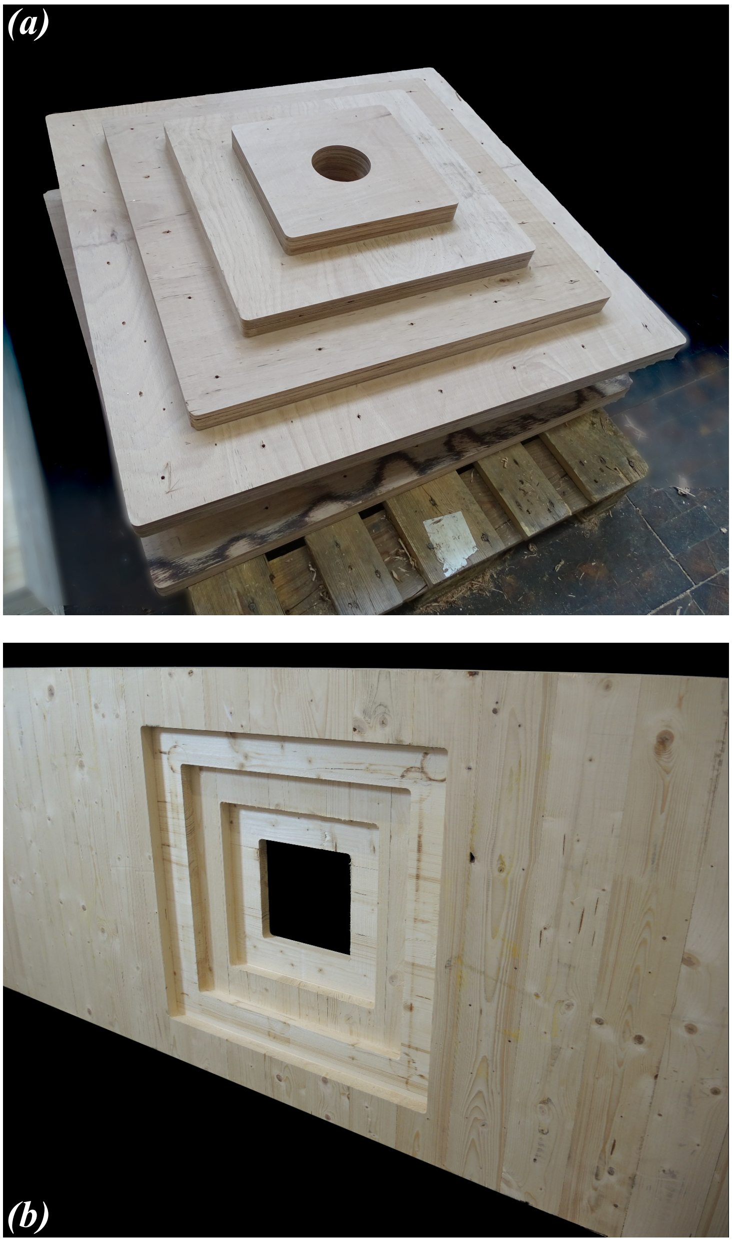


Figure 7: Milled prototypes of the elements of the connection: (a) pyramid-type insert; and (b) pyramid-shaped cavity milled in the CLT

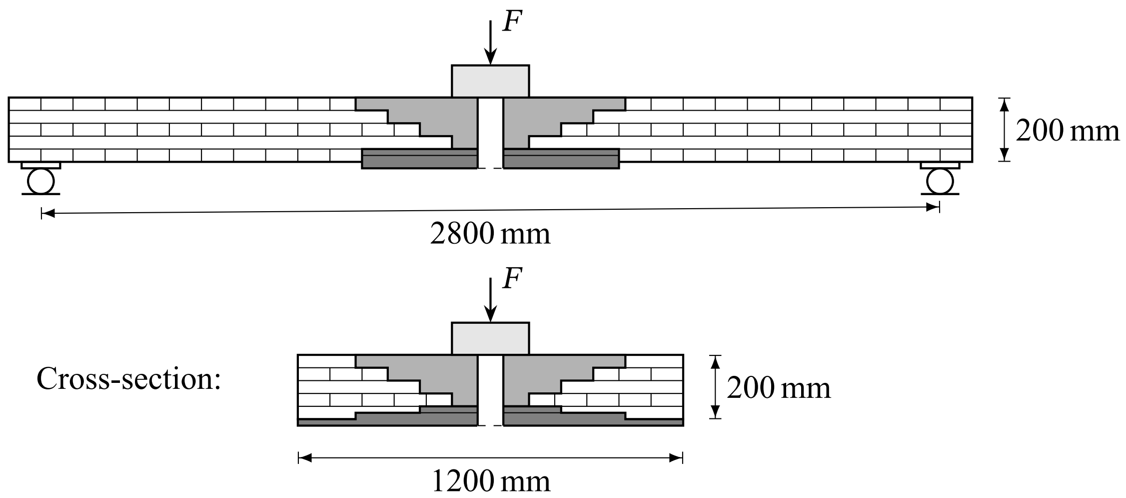


Figure 8: Experimental test setup used to study the connection in the secondary, i.e. weak direction of the CLT plate

$F = 110\,\text{kN}$ and unloaded again, and (3) finally the connection was loaded until failure.

Vertical displacements were measured by LVDTs at four points along mid-length axis on the top surface (see Fig. 9). Linear strain gauges were applied on the interfaces between CLT plate and both LVL reinforcement elements during the manufacturing process. The evaluation of the strain gauge measurements and respective comparisons with FEM results are covered in a follow-up contribution.

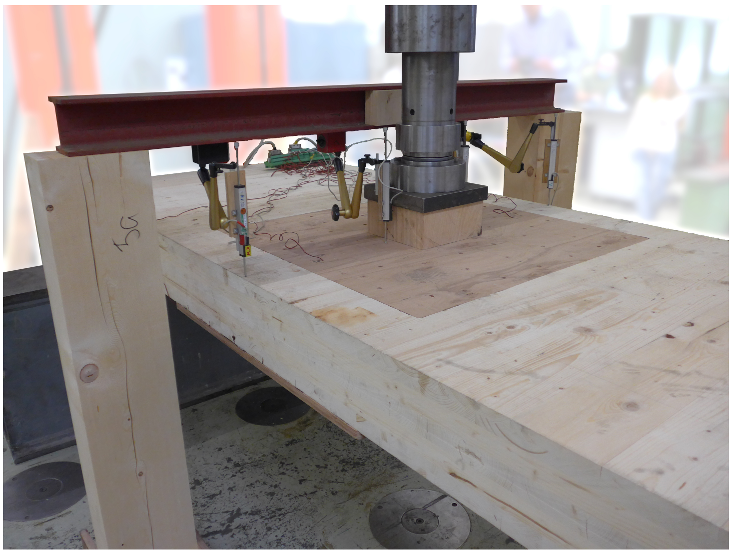


Figure 9: Realized test set-up with the developed plate-column connection

5.2 CONNECTION BEHAVIOR AND FAILURE DESCRIPTION

Figure 10 shows the load-displacement ($F - w$) curves for each of the three described loading cycles. An offset of 10 mm between the curves of the different loading phases was added for clarity. The first loading cycle exhibited throughout

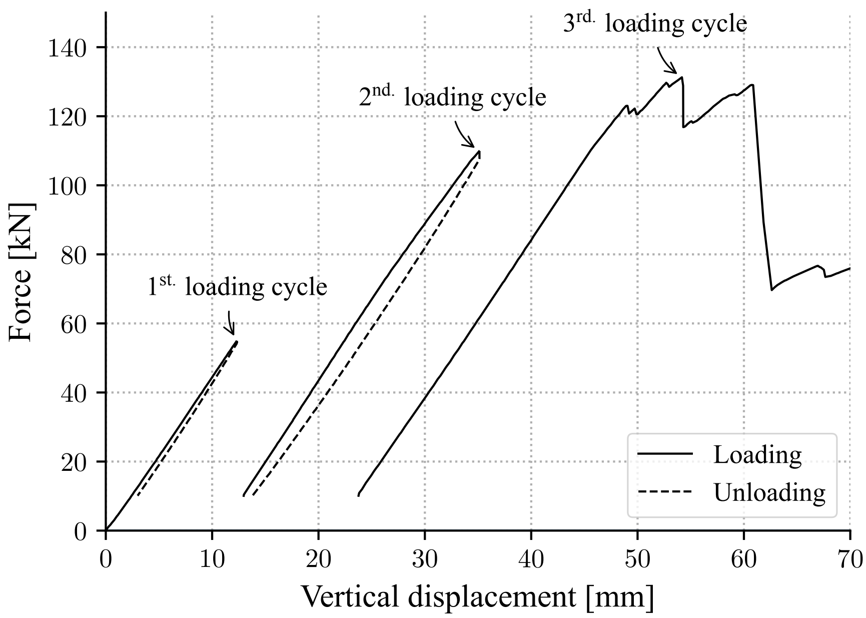


Figure 10: Load-displacement curves for the three loading cycles; the displacements represent the average of the two central LVDTs

a linear elastic behavior. At about 40 kN micro-cracking was audible, however not perturbing the linear elastic behavior of the global $F-w$ curve. It is assumed that the mentioned cracking noise stems i.a. from separation of *adhesive pearls/strips*, located in end-grain cavities between the LVL inserts and the CLT plate, yet is not related to any structurally relevant micro-crack development.

The behavior continued linear elastic with unchanged stiffness during the second loading cycle until about $F = 70$ kN, where a larger local failure occurred, accompanied by a loud sound. This localized damage produced a minor, but noticeable change in the slope of the load-displacement curve. During the testing the position of the damaged zone could not be localized.

During the final loading phase, with almost the same stiffness as in the first and second load cycle, pronounced, audible microcracking began at a load of $F = 110$ kN, however without major effects in the overall mechanical behavior of the connection. Starting from $F = 123$ kN noticeable damage became evident, expressed as load drop-downs in the $F-w$ curve, until the maximum load was finally reached at 130 kN. At this point, clear damaged zones were visible on the tension side of the connection, in the region of the reinforcement LVL insert (see below). The reached maximum load is well comparable with the maximum load capacity of 123 kN predicted above with the FE model. The FE analysis yields bending tensile stresses of 21.7 MPa at $F_{\max}$.

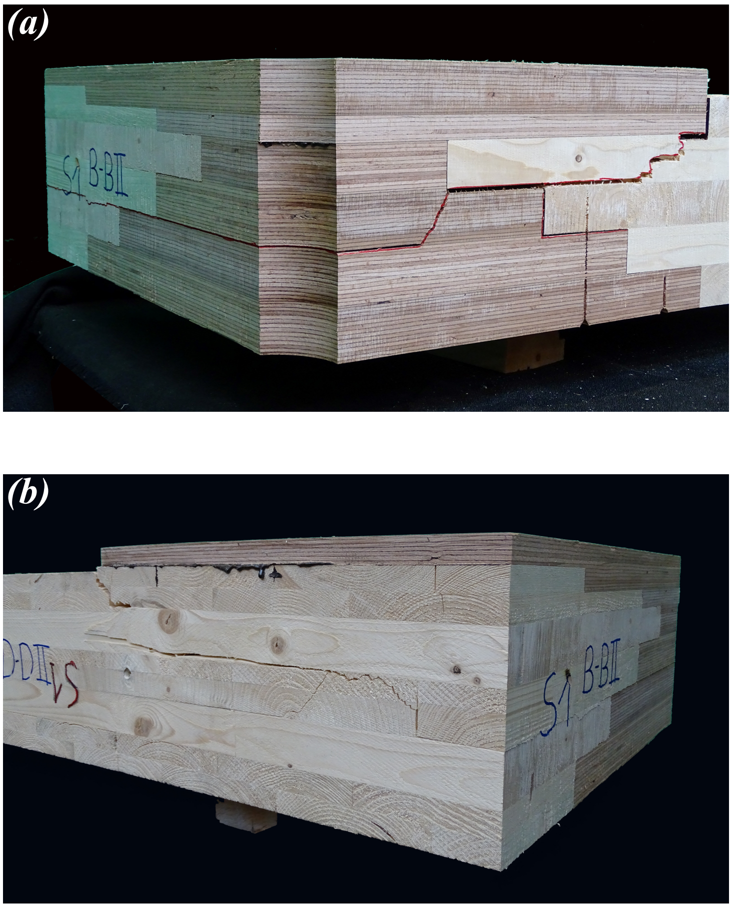


Figure 11: Details of the failure in the connection region: (a) outer face; (b) cut of the interior region of the connection

5.3 POST-FAILURE INSPECTION OF THE SPECIMEN

After the testing the specimen was cut with a chain saw along the symmetry axes of the plate in order to inspect the failure appearance in the LVL-CLT connection. Figures 11a,b show the inner and outer faces of one of the exposed quarters of the connection, respectively. In Fig. 11a a clear crack path can be observed, starting at the tip of the tension insert, then moving shortly along the interface with the CLT, where an obvious tension failure had occurred. The crack continues along the interface of the third and fourth layer (counting from bottom to top in Fig. 11a) of the CLT until it hits the LVL pyramid-type insert, here producing a shear failure with the crack propagating at the characteristic inclination of 45°. Once the crack reaches the bottom of the third layer, it continues horizontally. It can be seen that this crack traverses the whole cross-section. Figure 11b presents the discussed fracture viewed from the outer side, where a similar crack development can be observed.

This information, together with the results obtained from the FE model, allow to develop an hypothesis of the events that lead to the failure of the joint. It is most probable that the high shear stresses in the interface between tension insert and CLT element, at the overlap towards one of the supports, lead to a first local failure in that region, which was then followed by an increase in the tension stresses in the fourth layer of the CLT plate, then causing a tension failure. This probably started in the mid-width region of the CLT and then propagated outwards. The shear failure in the pyramid-type insert followed.

Although the described hypothesized failure mechanism is reasonable, it is clear that the complex geometry and mixture of materials complicates an absolute understanding of the complete failure mechanism. Further understanding of the failure behavior will be achieved on the experimental side by evaluation of the strain gauge measurements, and theoretically by incorporating some discrete cracks or other fracture mechanics concepts into the FE model. This will be pursued in the ongoing research.

6. CONCLUSIONS AND OUTLOOK

The development state of a new column-to-plate connection was presented. The rather complex geometry and mix of materials required an initial detailed numerical analysis to adjust geometrical parameters and to compute an estimation of the maximum loading capacity. A real-sized specimen was manufactured and tested in order to roughly validate the finite element model results. From this study, the following conclusions can be drawn:

- Sub-millimeter tolerances can be achieved with the used CNC machining, facilitating the use of gap-filling adhesives standardized for structural timber bonding;
- The current concept presents high shear stresses in the interface between CLT and the tension LVL insert, which very likely originated the observed failure in the prototype;
- The experiment showed that the failure mechanism presents a certain degree of redundancy, characterized by some pre-peak load drops, followed by a further load recovery;
- The predicted load capacity agreed quite well with the experimentally obtained ultimate load. However, the failure mode observed was rather complex, which requires further numerical analysis to be fully understood.

6.1 OUTLOOK

The column-slab connection presented in this paper was developed to explore the possibilities offered by industrially available computerized milling technology to solve the problem of point supported CLT slabs. The high accuracy of today's milling machines allows for advanced, complex structural topologies and joint geometries that can be optimized for a more efficient use of engineered timber products and combinations of these materials. The challenges, with regard to the manufacturing of the different components, and for the search for optimal geometries are evident. The presented connection constitutes a clear case of iterative, co-design development, where the shown example represents the first step. Further analyses and tests will be performed as part of an ongoing research within the frame of IntCDC, project RP3. Specifically, the connection will be analyzed along the principal direction of the CLT plate and in biaxial loading, too. Changes in the geometry of the different elements will be studied in search for a more efficient transmission and redistribution of stresses.

ACKNOWLEDGMENTS

The presented ongoing research is partially supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2120/1 – 390831618. Further, the authors owe many thanks to the company Pollmeier (Creuzburg, Germany) and equally to the company Binderholz (Fügen, Austria) for generously sponsoring the beech LVL plates (Baubuche) and the CLT plates, respectively, for the presented and upcoming tests.

Highest gratitude is owed to the Institute for Machine Tools (IfW), University of Stuttgart, especially to Dr. Schneider for the most remarkable engagement and performance regarding CNC milling of the CLT and the LVL-based inserts. Without this support the presented work, as well as other joint efforts reported separately, would not have been possible.

Finally, the very helpful cooperation with the Department of Building Construction and Component Testing of MPA, University of Stuttgart (Dr. Lotze, Dr. Birtel) relating to the prototype testing is gratefully acknowledged.

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