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Advancing Timber for the Future Built Environment

GLUED WIDE-SPAN TIMBER TRUSSES – A DESIGN AND EXPERIMENTAL APPROACH

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ABSTRACT: The aim of this research work is to develop a resource-efficient, economical, and aesthetically sophisticated timber structure for wide-span hall constructions. Based on the concept of a resolved timber truss, a novel type of load-bearing structure has been developed. This structure fundamentally relies on glued truss nodes to transfer tensile forces. To enable a largely moment-free construction, a special stepped compression contact joint has also been designed to transfer compressive forces. As a result of this design process, the system axes align at a single point of intersection. Gluing timber trusses to be used in wide-span hall constructions is an enormous challenge, often investigated but never fully successful for wide-span applications. This is now coming closer thanks to the newly developed truss geometry and accompanying glued truss nodes. A complex, parameterized structural design model is developed, and the results of the calculations are validated using specially developed setups for testing the glued truss nodes. In this context, a large-scale experimental setup is designed to validate the results at full scale (1:1). In practical applications, the novel timber truss offers several advantages. The assembly of two truss halves with a steel coupling joint at the construction site into a complete wide-span timber truss makes handling and transportation easier. Furthermore, an easy disassembly for a circular economy has also been considered.

KEYWORDS: timber truss, glued truss nodes, stepped compression contact joint, resource efficiency, circular economy

1 – INTRODUCTION

Against the background of an upcoming long-term shortage of resources and increasing prices, including for the renewable raw material wood, the Brüninghoff Group began developing a wood-based resolved load-bearing structure for wide-span hall constructions. The basic idea is to use glued joints within the truss nodes, a connection technology that has been investigated many times but has never really reached practical viability for wide-span applications. Therefore, the timber truss presented in this contribution is a genuine innovation that is about to be approved for general use in the building industry.

2 – BACKGROUND

Presently, in engineered timber construction, solid and therefore potentially resource-wasting glued laminated timber (GLT) beams are predominantly used for medium and wide-span wooden roof constructions. In contrast, state-of-the-art timber trusses require many steel fasteners. Therefore, assembly is extremely time-consuming and thus not very economical. As a result, resolved timber trusses are used to a much lesser extent. Glued timber trusses have often been the subject of scientific studies, e.g. [1][2], or even historical applications [3]. Nevertheless, they are not widely used in today's timber engineering practice, especially for wide-span constructions. The timber truss presented here is being developed with the aim of achieving an excellent mechanical behavior while saving material. In addition, the ability to dismantle and recycle is an important criterion in the development process. This led to the creation of a completely novel truss design (Fig. 1).

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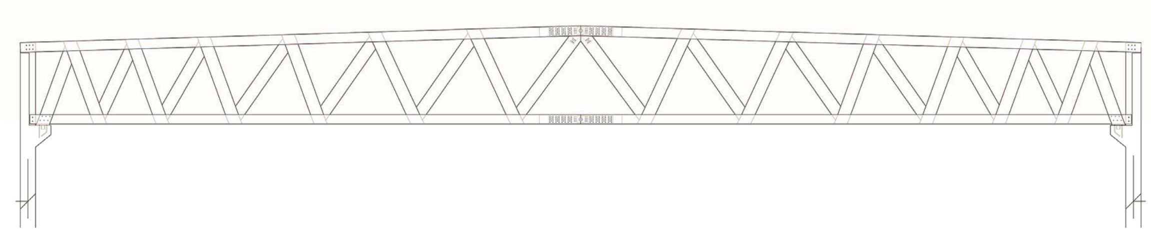

Figure 1. Glued timber truss – geometry of chords and diagonals, steel coupling joint, concrete columns as supporting structure

3 – DESCRIPTION OF THE PROJECT

The presented work addresses the WCTE 2025 theme “innovation & challenges”, as it is a genuinely new approach for designing a timber truss based on glued interfaces within the truss nodes. The basic idea is a double chord construction of the truss. The truss nodes combine a glued interface between the chords and a modified stepped compression contact joint between the diagonals. Both are highly innovative, as the glued interface is a completely novel design, and the stepped compression contact joint with unequal step sizes is a substantial further development of existing solutions. The chords are made of standard-GLT and the diagonals consist of GLT or glued laminated veneer lumber (GLVL), depending on the material properties required according to structural design. The newly developed timber truss is supported on reinforced concrete columns with a bracket to ideally transfer the loads from the horizontal truss to the vertical columns.

3.1 GENERAL DESIGN OF THE TIMBER TRUSS

The design and construction of the newly developed timber truss described below are based on intensive research carried out in recent years within the Brüninghoff Group, in cooperation with the Materials Testing Institute (MPA) at the University of Stuttgart. Based on the European timber design standard EN 1995-1-1 [4], the particular mechanical behavior of the novel truss nodes had to be taken into account by means of numerical modelling and experimental verification.

3.1.1 Resolved structure with glued truss nodes

The concept with a double chord and glued-in diagonals ensures a more rigid and cost-effective connection than conventional mechanical steel fasteners (Fig. 2).

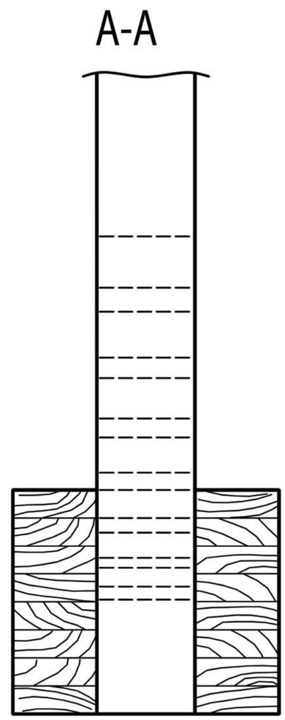

Figure 2. Concept of the double chord with glued-in diagonals

However, gluing of the diagonals between the double chords initially appears to contradict the ideal truss concept. But thanks to the novel design of the truss nodes – with glued interfaces between the tension diagonal and double chords, and an additional direct compressive connection between the diagonals themselves – the system axes align at one intersection point, minimizing the occurring moments (Fig. 3).

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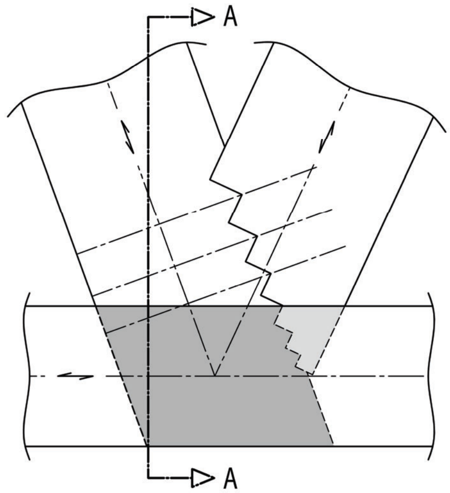

Figure 3. Detail of the glued truss node, glued interface dark grey

Each truss node is designed according to structural requirements, which means that the angle of the diagonals is variable with the applied load – according to the principle of "form follows function" (Fig 1). This enables simultaneous optimization of the truss for the lowest possible amount of timber used and the lowest possible construction height – efficiency in both ways. The ratio of span to height achieves a value of 12.50 to 1, which is advantageously higher than that of conventional timber trusses (10 to 1). The double chord allows the outmost diagonal to transfer the axial load directly into a bracket on the supporting concrete column. In the first step, the structural design and dimensioning of the components are based on a span of up to 36 m. Compared to usual solid GLT beams, a significant volume of timber can be saved.

As the diagonals show different angles within the timber truss, they have been limited to a range between 40° and 70°. This is based on preliminary tests on the non-fiber-parallel gluing of wood and the calculation of the load transfer via the glued interfaces. The angle of the diagonals can be constructively chosen within this range. This means that all requirements from the truss length to be produced can be met by the geometric design of the diagonals. However, the angle of the diagonals should be chosen so that the total number of diagonals is as low as possible – without disregarding the optimum load transfer. This process is currently carried out experimentally, but the aim is to determine the geometry automatically in the future. The parameterized models required for this are currently implemented using the frame and truss analysis software RSTAB (Dlubal Software GmbH, Tiefenbach, Germany).

3.1.2 Steel coupling joint for connecting two truss-halves

In order to produce and transport the timber truss economically, a special steel coupling joint has been developed (Fig. 4). This makes it possible to produce the truss in two halves and transport it to the construction site. At the construction site, the two halves of the truss are connected using just two pins. They are guided through pin-ended members that were preassembled in the factory. Finally, the connected timber truss is lifted into its final position.

The structural verification in the ultimate limit state (ULS) follows the requirements of EN 1995-1-1 [4] and is thus regulated by European standards. The reduced tensile capacity caused by the internally positioned slotted plates, which are used for fire protection purposes, is compensated through the application of self-tapping fully threaded screws. As a result, the timber cannot deform due to the eccentric tensile forces, allowing its full strength to be considered. The combination of dowel-type fasteners and fully threaded screws ensures that no dowel needs to be replaced by a bolt to achieve a permanent clamping effect. The connection of the two steel coupling joints using the pin-connected members (Fig. 5) is in accordance with EN 1995-1-1 [4] as well as EN 1995-1-8 [5]. This connection type has the advantage that the load-bearing cross-sections of the double chords do not need to be weakened in order to achieve a rigid connection in the coupling joint.

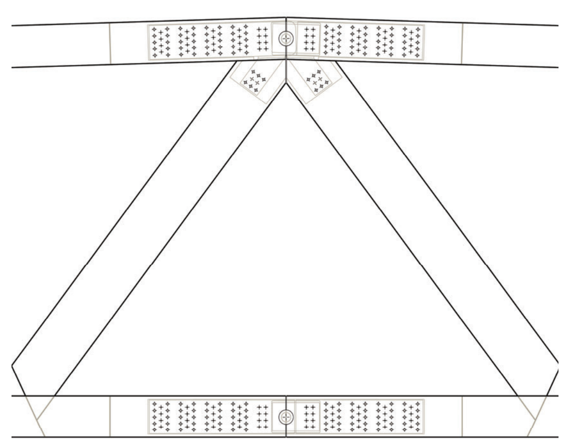

Figure 4. Steel coupling joint for connecting the two truss-halves

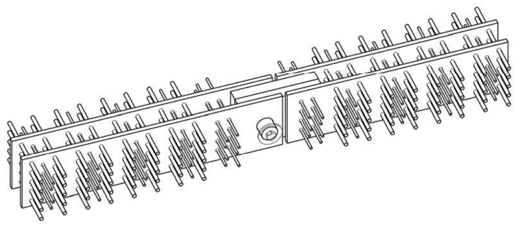

Figure 5. Detail of the coupling joint, steel plates, rod dowels and screws

While assembling the pin-ended members in the factory, a larger pin diameter with a correspondingly smaller clearance is used compared to the pins used for assembling the truss-halves at the construction site. This ensures that the connection can be easily assembled during on-site installation. Furthermore, the internal collaboration between engineers and the steel and timber departments within the Brüninghoff Group contributes to the precise and practical fabrication of the coupling joint. The pin-based steel connection is standardized for many truss configurations, making it efficient and economical to manufacture.

The internally positioned steel coupling joint is protected from fire exposure by the GLT chords. The special fire behavior of timber compared to steel in this case enhances the fire resistance of the coupling joint. Fire resistance follows EN 1995-1-2 [6]. Covering the steel with a sufficiently thick timber layer ensures the robustness of the coupling joint in case of fire, as it significantly delays excessive heating of the steel.

3.1.3 Advantages of the novel truss design

The newly developed truss node to connect the chords and diagonals is the greatest advantage of the innovative timber truss. This enables a significantly reduced manufacturing effort by utilizing glued interfaces instead of mechanical fasteners. The challenge of non-ideally aligning system axes due to rectangular diagonal cross-sections was solved by a special stepped compression contact joint. As a result, the intersection of all three system axes aligns at a single point. The variable angle of the diagonals along the truss length ensures ideal force transmission. Therefore, this development enhances both the individual truss node and the overall truss design.

Cable and pipe routing is possible without prior planning in a resolved structural system, such as the novel timber truss. The open spaces between the diagonals are sufficient for standard pipe diameters. This presents a significant additional advantage compared to solid GLT beams. Typically, routing cables or pipes through GLT beams requires openings whose shape and position are strictly limited. Depending on the size of these openings, the cross-section of the whole beam must be enlarged which may lead to reduced resource efficiency. Additionally, the positioning of these openings next to the vertical support is prohibited for structural safety reasons. With the resolved timber truss structure, however, routing near vertical supports is possible, providing pronouncedly greater design flexibility.

The double chords with glued-in diagonals show a high truss-width – in this case, 38 cm – which allows for a greater fastener spacing of the roof covering (e.g., trapezoidal metal sheets). This increased spacing ensures that the bottom chord of the truss does not require additional stabilization in the wind uplift load case. The torsional rigidity of roof fastening provides sufficient stability. In this regard, the double-chord timber truss offers significant advantages compared to a solid GLT beam. In contrast, a GLT beam requires additional knee braces for stabilization, which are not necessary for the novel timber truss.

The developed steel coupling joint for connecting two truss-halves shows several advantages. It enables, on the one hand, simplified in-house logistics during the production of the timber truss and, on the other hand, significantly easier transportation to the construction site, as no oversized components have to be transported by road or rail.

3.2 DESIGN OF THE TRUSS NODE

The design of the truss node realizes tensile connection via the gluing of diagonals between the double chord and compressive connection via a form-fit compression contact joint.

3.2.1 Tensile forces - glued truss node

The tension diagonals are glued to the double chord with glued interfaces on both sides, meaning they are positioned between the two parts of the double chord (Fig. 2). The transfer of coupled forces from the compression diagonals and tension diagonals into the chords – via the truss node – occurs exclusively through the two glued interfaces between the tension diagonal and the double chord. The connection between tension diagonal and compression diagonal is achieved purely mechanically through the special stepped compression contact joint described below.

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In addition to the axial force, the glued interface also absorbs a bending moment. The rigid connection through gluing enables the transmission of both internal forces. No additional metallic fasteners – such as screws or dowel-type fasteners – are used to connect the tension diagonal to the chords. A combined load transfer using both glued interfaces and metallic fasteners would be mechanically impractical due to the differing stiffness of these two connection types. Furthermore, additional fasteners in the glued interfaces would reduce the effective glued area and create stress concentrations. For this reason, the tension diagonals to be glued are positioned during production without any fasteners penetrating the glued interface.

3.2.2 Compressive forces - contact joint

The transmission of compressive forces in the developed truss node is achieved using a modified form-fit stepped compression contact joint. In doing so, the compressive force is transferred to the tension diagonal via a contact joint and then into the chords via a glued joint. The applied compression contact joint geometry represents an advanced design with unequal step sizes (Fig. 2) and is dimensioned according to the Enders-Comberg approach [7]. This further development pushes the load-bearing capacity of the contact joint to its limits and is particularly recommended for GLVL diagonals with vertically oriented veneer layers. The varying step sizes and their gradation ensure that multiple veneer layers are activated for the load transfer. Through the interaction of shear and transverse compression, a sufficiently high resistance is generated. The enhanced stepped compression contact joint is generally suitable for both GLVL and GLT diagonals. However, the compression diagonal transmits only compressive forces through the compression contact to the tension diagonal, and subsequently to the chords. In the wind uplift load case (load reversal), the contact joint is subjected to tensile forces. Therefore, self-tapping fully threaded screws are additionally used to transfer this tensile force from the compression diagonal under wind uplift conditions.

3.2.3 Manufacturing of the truss nodes

In the context of European timber design standards for block-gluing of GLT or GLVL members, type I adhesives according to EN 301 [8] may be used, such as, e.g., phenol-resorcinol-formaldehyde adhesives. According to EN 1995-1-1 [4], type I adhesives as specified in EN 301 are approved for all service classes concerning moisture exposure. Type I adhesives are thermosetting resins, which offer additional advantages under fire exposure conditions. For gluing the developed truss nodes, an adhesive from Dynea AS (Lilleström, Norway) is used. The phenol-resorcinol adhesive Prefere 4040 is a liquid adhesive, primarily applied in the manufacturing of load-bearing timber components. This adhesive is classified as EN 301-I-90-GP-0.6-M. Being a "GP - general purpose" adhesive, Prefere 4040 is suitable for bond line thicknesses up to 0.6 mm. This property is crucial for its application in the developed truss nodes, as it allows for certain tolerances in the flatness of the glued interfaces. Before application, the resin must be prepared as an adhesive mixture using a hardener in the pre-mixing process ("M"). In this case, the Prefere 5839 hardener is used.

Embedding of the compression diagonal into the tension diagonal via the stepped contact joint possibly leads to an unfavorable contact of the compression diagonal with the double chord. If the compression diagonal is slightly thicker than the tension diagonal to be glued between the double chord – because of tolerances in the material – the compression diagonal would prevent the clamping pressure to be applied to the glued interface. To avoid this contact and the resulting constraint, the compression diagonal is tapered in the area where it lies between the double chord (Fig. 6). The diagonals are pre-assembled using the fully threaded screws which are in any case necessary to secure against wind uplift conditions. After preparing the glued interfaces by sanding, the adhesive is applied at a rate of 550 g/m² using a notched trowel. Once the components are positioned, the clamping pressure is applied using a press specifically designed for manufacturing the novel timber truss. The pressure is introduced via spindles (Fig. 7). A pressure of approximately 0.8 N/mm² is set, corresponding to a defined torque on the spindle. The press is 18 meters long, consisting of three 6 m modules, and features 50 freely adjustable press frames, each equipped with a spindle. This allows flexible positioning of the nodes within the timber truss. The gluing of a truss node using three press frames is shown in Fig. 7.

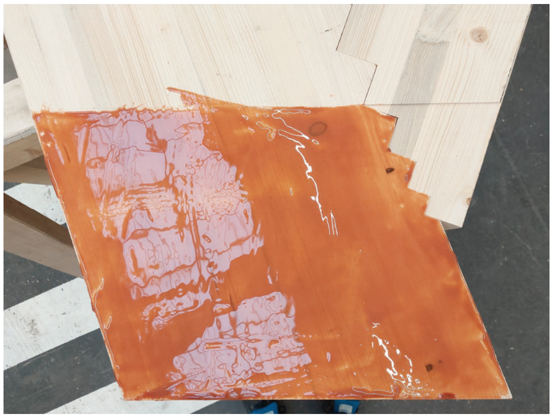

Figure 6. Detail of the glued truss node, glued interface using Dynea Prefere 4040 adhesive

Figure 7. Manufacturing of glued truss node test specimens

3.3 CIRCULAR ECONOMY – RE-USE AND RE-CYCLING

The novel timber truss with glued truss nodes can be fully reused. The support at the columns is designed according to the principles of a circular economy, allowing for easy disassembly. When the building is dismantled and prepared for reuse, the timber truss can simply be lifted off the support and separated into two halves – easily by removing those two pins which originally allowed the quick assembly.

At the new location, the steel coupling joint is reassembled, enabling the timber truss to be reused with a second service life.

If the timber truss is not reused as a whole, the diagonals and chords can be separated and recycled independently. The small number of screws used to secure the diagonals against wind uplift at the stepped compression contact joint can be removed. The glued truss nodes can be easily separated, simply by sawing the diagonals from the chords with the cut made in the diagonals. A major advantage of the glued joint is that it can be mechanically separated by cutting, as it is completely metal-free. The chords can be slightly planed on one side, making them fully available for other applications. The diagonals can be processed into smaller cross-sections, e.g., for use in timber frame constructions. Otherwise, they can be used for the production of engineered wood products, such as particleboard.

4 – LARGE-SCALE EXPERIMENTAL SETUP

Up to now, single truss nodes have been tested. Thus, a new type of test setup was developed in cooperation with the Materials Testing Institute (MPA) at the University of Stuttgart, in order to test the performance of the developed glued truss nodes. This allows a direct validation of loads calculated from the design model in practice. The test is designed as a tensile test and requires an elaborate steel construction to ensure ideal, constraint-free support of the test specimen. More details are provided in the submitted paper by Stimpfle et al. [9].

As a next step, a large-scale test 18 m in length is planned. This test will load half of a truss to failure. From these results, it will be possible to deduce how the individual nodes behave when interacting and thus validate the structural design of the novel timber truss.

4.1 AIM OF THE LARGE-SCALE TEST

The large-scale test is intended to assess the performance of the glued truss nodes, as determined in the single-node tests [9], when multiple nodes interact within the entire timber truss. This allows for the validation of the developed design concept. The primary objective of the large-scale test is to load the timber truss to failure. A destructive test is carried out to determine the fracture load of the novel timber truss.

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To avoid the need for scaling down the truss for testing – which would result in inaccurate results due to size effects of the glued interfaces – and given the obvious dimensional limitations of the test stand, only one half of the timber truss is tested. Consequently, the test specimen has a length of 18 meters.

4.2 CONSTRUCTION OF THE TEST SETUP

The timber truss is supported with its outermost diagonal on a concrete block that serves as a bracket, as the concrete columns do in the actual building. Due to the test setup using only one truss-half, a substantial steel structure is required. It serves as a reaction frame on the opposite side, where the second half of the truss would be connected to the coupling joint in the actual building (Fig. 8). This steel structure simulates the symmetry boundary conditions of the construction. Therefore, the test configuration accurately replicates the load-bearing behavior of the timber truss in reality. In addition to the test setup itself, the load application must also correspond to real conditions. In the actual building, the timber truss is subjected to a line load from the roof covering. Thus, in the test setup several hydraulic cylinders are positioned between the truss nodes. The point loads are approximately converted into a line load by placing steel beams on top serving as a load distribution structure. As in the actual building, the largest deformation occurs at midspan of the entire timber truss, which in the test setup corresponds to the location of the reaction frame.

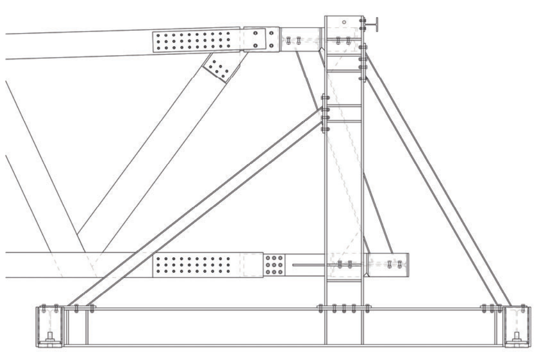

Figure 8. Steel supporting structure for the large-scale test with truss-half, side view

The steel structure must be sufficiently stiff for the test. However, a vertical deformation must be allowed through a virtually frictionless design. In contrast, the reaction frame must allow only minimal deformations in the horizontal direction. The total horizontal deformation must be limited to less than 2 mm to ensure that the conditions at the reaction frame correspond to those in the actual building. The maximum deformation thus is in line with the standard tolerances applied in building construction, effectively representing a rigid support. These strict requirements on deformation are therefore met in the test setup just as they would be under real-life conditions.

The loads acting in the large-scale test significantly exceed the design load of the timber truss in reality, as this is a destructive test. As a result, internal forces are expected within the timber truss that would not occur in the actual building, even under permanent and temporary design situations (wind load, snow load). However, the large-scale test requires a basis for determining the loads to be applied. The load magnitude is therefore defined based on the axial force in the outermost tension diagonal. It is assumed that this axial force corresponds to the mean value obtained from the load-bearing capacity of single truss nodes, determined by Stimpfle et al. [9]. This tensile force is then increased by a factor of 2.64, representing all safety and modification factors defined by the design in the applied semi-probabilistic safety concept. Thus, it is expected to lead to the failure of the timber truss.

Due to the significantly increased loads in the timber truss for the destructive test, the steel coupling joint does not provide sufficient resistance. Since the objective is to test the glued nodes of the timber truss, failure must not occur in the timber chords at the connection to the steel structure. Consequently, the steel components of the coupling joint must also be adapted. For this reason, two additional slotted plates are used, and all dowel-type fasteners are replaced with bolts (Fig. 9). This ensures that the connection between the timber truss and the reaction frame no longer represents an unintended weak spot. The increase in the axial force in the tension diagonal also leads to a proportional increase in the field moment. Ultimately, the connection of the chords to the steel structure of the reaction frame is designed for an axial force of ± 2000 kN. Due to the high forces acting, the reaction frame consists of approximately 10 tons of steel.

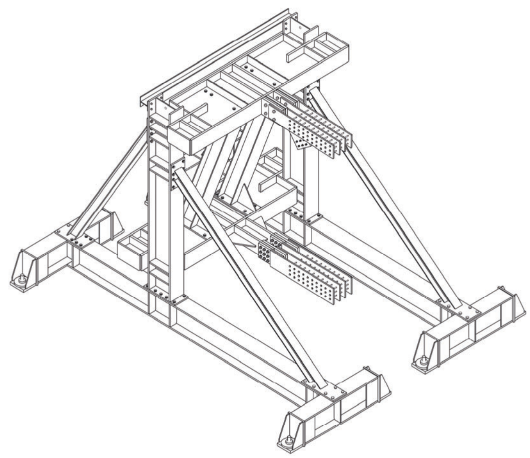

Figure 9. Steel supporting structure for the large-scale test, perspective view

In addition to the aspects regarding displacement, theoretical considerations also include rotation in the truss nodes. However, in practice, the glued joint prevents the node from rotating almost completely, which was proven experimentally in the single-node tests by means of deformation measurements [9]. As a result, the glued joint is subjected to an internal moment load because the bending stiffness of the node is activated. The large-scale test will determine which type of stress ultimately causes failure of the truss nodes – longitudinal shear stress in the compression contact joint between tension diagonal and compression diagonal or moment-influenced rolling shear stress in the glued joint between tension diagonal and the chords. This large-scale test will not only determine the maximum load-bearing capacity of the novel timber truss but also indicate which component of the truss represents a potential weak spot.

The development, design, and fabrication of the large-scale test are made possible through the close collaboration between the planning and production units of the Brüninghoff Group and the MPA Stuttgart. In addition to the novel timber truss itself, the steel structure serving as the reaction frame is entirely manufactured at Brüninghoff.

5 – CONCLUSIONS AND RECOMMENDATIONS

The double chord design of the novel timber truss, along with the glued joints and in combination with the modified stepped compression contact joint, makes it possible to realize a meaningful alignment of the system axes. The use of glued truss nodes offers great potential for constructing wide-span timber trusses that are resource-efficient, economical, and reusable as well as recyclable. In the case of dismantling, the developed truss node can be easily disassembled using simple cutting tools. The chords can be reused as whole GLT beams and the diagonals can also be repurposed for other applications, such as timber frame constructions – ideal conditions for the circular economy.

Based on single-node tests, a complete parameterized design model following EN 1995-1-1 [4] is developed for the novel type of timber truss. This allows for simple scaling of the span and determination of the associated loads. The large-scale experimental setup will verify the findings by Stimpfle et al. [9] with testing a truss-half to investigate the load-bearing behaviour of a complete truss. The load-bearing system consisting of the novel timber truss supported by reinforced concrete columns has proven to be potentially very efficient. Especially the glued truss nodes show a great potential for further improvements of the developed resolved timber structure. Further studies and pilot-applications are now needed to prove the concept in practice.

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