Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

A Paradigm in Digital Detail Design for a Complex Timber Framework

Timo CLAUS*, Kaspar EHRHARDT, Alexander MICHALSKI, Julian LIENHARD,
Philipp STUTE[a], Stephan BURGER[a]

* str.ucture GmbH,
Lindenspürstraße 32, 70176 Stuttgart
claus@str-ucture.com

[a] wulf architekten,
Breitscheidstraße 8, 70174 Stuttgart

Abstract

Detail design is still a challenge in structural timber constructions. On the one hand, there is a large variety of different fasteners that must be described neutrally and on the other hand, the solutions are depending on the manufacturing possibilities of the timber construction company, which is not known while planning the constructional details. Due to the uncommon spatial timber construction of the new museum in Reutlingen, a solution had to be found for both requirements, which also reduces the cost risk for the contractor and the client. Thus, the detail concept and the information behind are node-based. The use of attribution-based design in a Building Information Modelling (BIM) environment played a key role in this project to ensure a centralized model. The use of Rhino 7 in combination with Grasshopper and other plugins enabled a central management of all fasteners and the assignment of details with a single source of truth. The result was an open interface model that formed the basis for the final factory planning.

Keywords: architectural engineering, timber constructions, timber-to-timber joints, form-fitting connections, interlocking connections, parametric 3D planning, BIM, data-based modelling, digital fabrication, building in existing structures,

1. Introduction

The former stone house at Oberamteistrasse in Reutlingen (Germany) from the 14th century supported the historic row of houses. The demolition of the building in 1972 led to a gap between the buildings and destabilization of the adjacent buildings. In an open architectural competition in 2017 the previously unused site was addressed without given a certain use of the building. The controversial design of a new museum by wulf architekten from Stuttgart won the competition. The design exactly reproduced the cubature of the historic stone house (Fig. 1).

The semi-transparent façade made of glass plain tiles creates a hologram of the former stone house without windows and doors. A place of remembrance of the destroyed building, but also a conscious new interpretation of the surrounding constructions. The building envelope is supported by a multi-level wooden structure. Inside the building, the historic cellar has been uncovered and is visible and tangible from all viewpoints. The trapezoidal floor plan measures approx. b = 13.3 m x l = 13.3 m. The ridge height of the gabled roof is approx. h = 17.3 m. The eaves height is h = 8.8 m.

The façade is only clad on two sides due to the adjacent buildings. The exterior walls of the adjacent buildings remain visible from the inside due to the open construction.

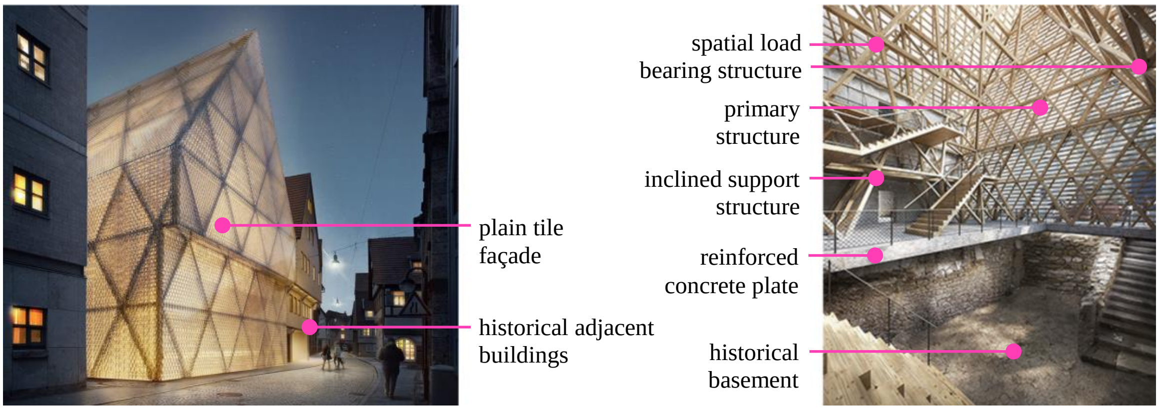

Figure 1: Architectural design of the new museum in Reutlingen from the outside (left) and from the inside (right) by wulf architekten Stuttgart, Germany.

The building was planned as one part of the local history museum in Reutlingen and is used for the exhibition space in the basement and ground floor and to provide access to the historic half-timbered building in Oberamteistraße via stairs and an elevator.

In addition, the spatial load-bearing structure supports the row of half-timbered houses in the historical Oberamteistraße due to the skewed buildings and the horizontal earthquake effects. The building envelope also protects the historic cellar which one is accessible via a large seating stair.

The façade is open and ventilated and thus the building is uninsulated and unheated. The façade provides visual and weather protection. There are no requirements for sound insulation or thermal insulation for the new building (Fig. 1).

As no active ventilation is planned, the building technology can be reduced to the dewatering and electrical installations. In order not to distract from the low-fi character of the open supporting structure, the electrical installations were laid as much invisibly as possible. However, a complex design was required, particularly for the walkways of the supporting structure and the reinforced concrete floor slab.

2. Load Bearing Structure

The primary load-bearing structure of the spatial framework consists exclusively of timber from silver fir (Abies alba) with a square cross-section of a width of b = 0,2 m. The supporting structure is divided into six stories with a height of approx. h = 2.5 meters each. In addition to the spatial supporting structure, there is a lift tower in the corner between the existing buildings, which extends up to the eaves over the first three stories. In the area of the inclined supporting structure, access to the neighbouring buildings is supplemented by horizontal walkways, which are arranged over a wide area and form the platforms for the flights of stairs.

In addition to the outer flat truss structure and the inclined supporting structure, a spatial load-bearing structure extends from the second level inwards, which transfers the loads from the roof to the foundation plate. All struts form triangles with each other and thus they enable efficient load transfer. The foundation plate is built on the historical masonry walls and new vertical and inclined piles.

The trapezoidal ground plan creates a slightly irregular load-bearing structure, resulting in a ruled hp-surfaces so that the nodes - apart from those of the flat outer surfaces - always vary in detail.

2.1 Loads

For the calculations, permanent loads, live loads snow- and wind loads as well as earthquake impact was analysed. Apart from the self-weight of the structure, permanent loads only from the building envelope were considered. Snow loads were considered on the roof, especially between both pitched roofs of the new and the old house. The roofs and façades are exposed to horizontal and vertical wind loads. Live loads occur on the two platforms and on the construction of the overhanging stairs. Reutlingen is located in a seismic area with a ground acceleration of about $S_{aP,R}$ = 2,25 m/s². Assessing the simplified response spectrum method this results to a total earthquake effect of F = 185 kN. Furthermore, a collision of a vehicle in the exposed corner of the building was simulated taking into account the loss of a main column on the ground floor.

As already introduced, the inclined construction of the new museum supports the adjacent buildings. In detail, the loads due to the misalignment of the old houses are transferred in the first, second and third level of the new construction. Apart from the permanent loads of the construction and the variable snow and live loads, also the loads from the seismic action of these buildings are transferred to the spatial structure of the new construction. The sum of the horizontal loads from earthquakes results to F = 470 kN in the transverse direction of the new construction.

Due to the irregular structure of the inclined area a spatial load transfer is required because of missing struts for the necessary walkways. However, massive timber construction made of cross laminated timber (CLT) used for the elevator is supporting the spatial structure and allows to carry a relevant share of the acting loads.

Due to the definition of the building as a canopy, the fire resistance of the primary structure only needs to be guaranteed for thirty minutes.

2.2 Structural Model

The timber structure was calculated in the RFEM 5 software environment from Dlubal. All components and connections were checked using the RF-/TimberPro add-on. The stiffness of the connections was modelled in a simplified manner identically for all member ends in the spatial framework model. In accordance with ETA-14/0354, the stiffness of the screw connection group was calculated as

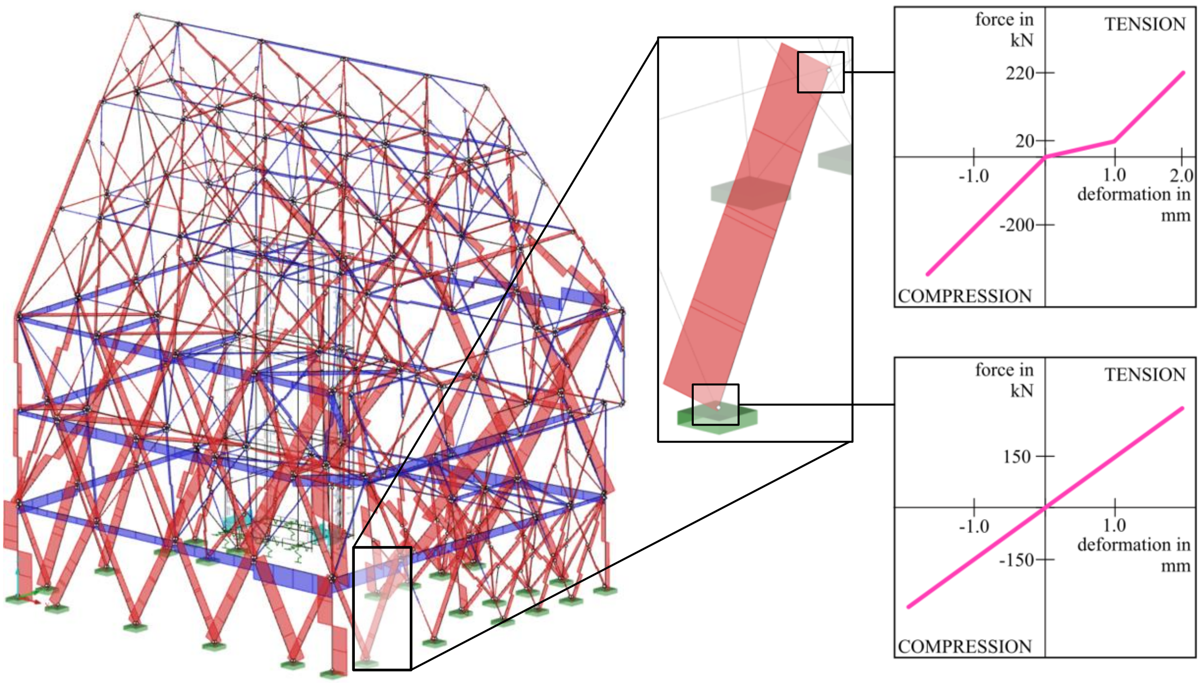

Figure 2: Structural system with axial forces (red: compression, blue: tension) in the beam members and the definition of the major hinges for a strut connected to a continuous beam (top) and to the foundation plate (bottom).

$$k_{ax,c} = n \cdot d \cdot l_{ef} = 8 \cdot 30 \cdot 8 \cdot 100 \ \approx 200.000 \ \mathrm{N/mm}. \tag{1}$$

This spring stiffness was selected linearly for the compressive load due to the form-fit interlocking under compressive loads (Fig. 2). Under tensile loads, a slip within the connection is assumed. This leads to an idealized reduction in stiffness in the first 1.0 mm of deformation to one tenth of the calculated spring stiffness:

$$k_{ax,t,ini} = \frac{1}{10} \cdot k_{ax} = 20.000 \ \mathrm{N/mm} \tag{2}$$

2.3 Structural Analysis

The internal member forces were determined according to the second-order theory. The diagonal struts mainly carry compression loads and the continuous beams carry tension loads under permanent action (Fig. 2). In addition, some horizontal timber truss girders allow to distribute the horizontal forces from the roof structure into the outer supporting walls. In simple terms it can be said that the axial member forces are lower in the roof structure and increases to the bottom members.

Due to the excavating gable façade from the third level upwards, some irregular axial forces and bending moments in the primary structure occur.

While seismic load cases acting in all horizontal directions, most of the struts carry axial compressive and tensile forces. The minimum axial compressive force is about N = -150 kN and the maximum tensile force is about N = 80 kN.

The comparatively high stiffness of the interlocking connections and those with fully threaded screws leads to only small deformations in horizontal and vertical direction of the entire construction.

3. Detail Design

3.1 Detail Concept

The struts of the primary supporting structure are connected in the nodes. In terms of the architectural design, the intention was to base the joint concept on historical construction methods. The focus was therefore on form-fit solutions with contact between the timber members. As a spatial load transfer is necessary and all struts are subjected to tensile and compressive loads due to the alternating effects of wind and earthquake, the form-fit solution had to be supplemented with a force-fit solution. Summarized, there are three different joining principles in this project:

- joints with form-fit interlocking and fully threaded screws
- joints with fully threaded screws
- joints with slotted plates and dowel pin connections

The different joining principles were used in different ways depending on the height and direction of the applied force and the geometrical situation. The special features of the form-fit joining concept will be discussed below.

A major advantage of the architectural design is that all lines of action of the struts are brought together exactly in the nodes and thus no eccentricities occur. In the standard detail, four struts are joined to one continuous beam. A special feature is given in the level below the ridge, where a total of ten struts are joined to one continuous beam (Fig. 3).

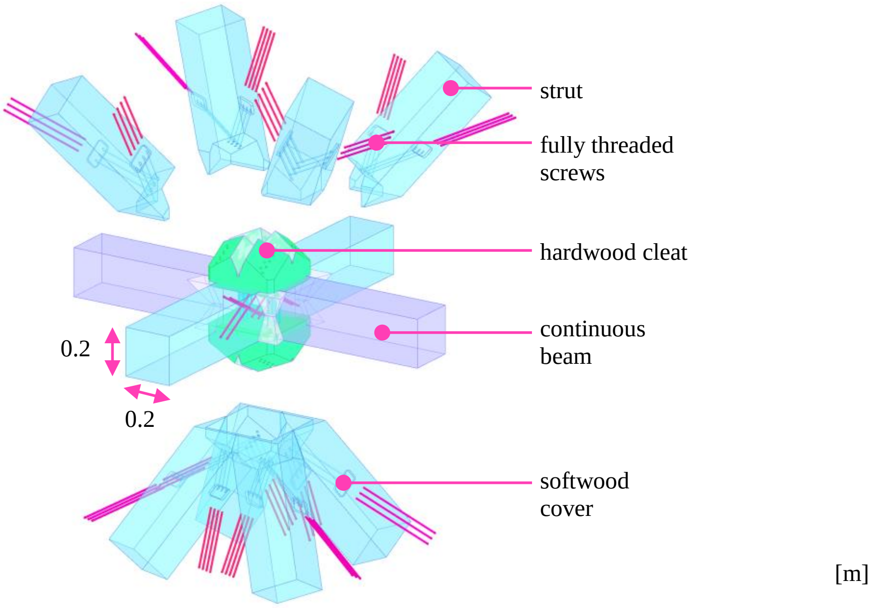

Figure 3: Example of a complex timber joint with twelve beams connected in one node with hardwood cleats on the top and the bottom of the continuous beam.

3.2 Transfer of Compressive Forces

The axial compressive forces are transferred via the end grain of the struts to a hardwood cleat made of beech laminated veneer lumber (beech LVL) of the material BauBuche GL75 in accordance with ETA-14/0354. The upright veneer layers have a higher compressive strength compared to the glulam of strength class GL24h in the fibre direction.

In the cleat, the inclined forces are divided into the parallel and vertical force components of the continuous beam. The parallel forces are transferred into the continuous beams parallel to the fibres via a comparatively small contact surface at the front of the cleat. For this purpose, the cleat is embedded in the continuous beam.

The vertical force is distributed over the large base area of the cleat and can therefore be transferred into the continuous beam without additional reinforcements - only via contact. The value of the pressure perpendicular to the fibre is consequently reduced by the load distribution in the cleat. Any shear forces that occur are safely transferred by the high-performance material of the cleat.

The cleats for connecting two struts to a continuous beam therefore require a width of 160 mm, a length of approx. 300 mm and a height of approx. 120 mm. The contact surfaces to the struts are always arranged perpendicular to the axis of the strut. This arrangement makes it possible to transfer compressive forces of up to N_{ax} = -120 kN between each other.

3.3 Transferring Tensile Forces

The axial tensile forces are transferred from the strut to the cleat via inclined fully threaded screws at an angle of 30°. Due to the higher load-bearing capacity of the fully threaded screws in hardwood, the ratio of the bond length of the strut to the cleat is two to one. The higher density of the laminated veneer lumber therefore also has a positive effect here and the volume of the cleat could be reduced.

Within the cleat, the tensile forces are then transferred via groups of fully threaded screws between the cleat and the continuous beam. Axial tensile forces of up to approx. N_{ax} = 75kN per strut can be transmitted via the screw groups. The tensile forces are short-circuited by the overlapping screw connections in the area of the continuous beams and transferred directly to the neighbouring cleat.

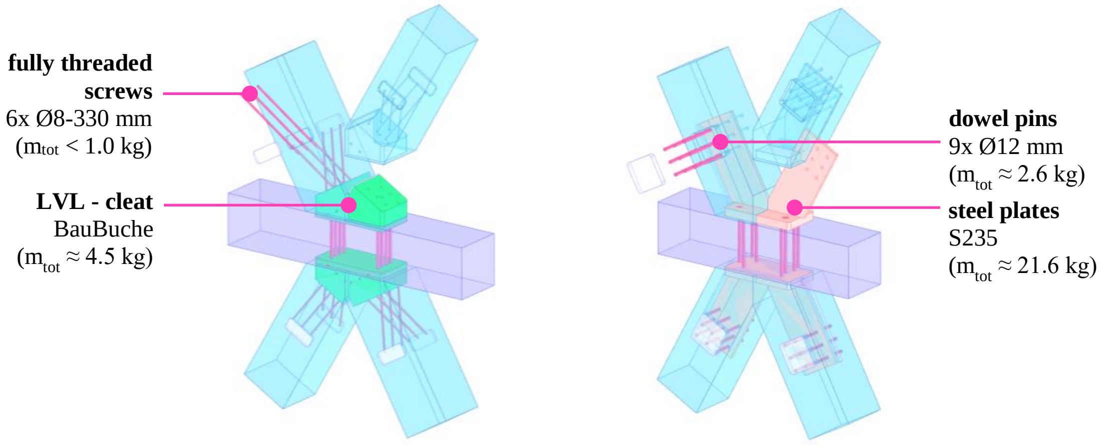

Figure 4: Comparison of a standard joint with a hardwood cleat connected with fully threaded screws (left) and a steel plate to wood connection with dowel pins (right).

3.4 Interim Conclusion

Similar connections with centring cleats made of hardwood have already been used in the office building "The Cradle" (Düsseldorf, Germany, 2023) [1] and the church of St. Josef (Holzkirchen, Germany, 2017) [2]. The advantages of the form-fit joint with additional fully threaded screws are the material-specific design of the connection, which considers the advantages of homogenized material technologies as well as efficient fasteners. The forces are ideally distributed thanks to the well-shaped geometry of the cleat. No risk of cracking inside the timber members occurs due to shear forces and corresponding tension forces perpendicular to the grain. Even more the fully threaded screws reinforce the timber parts in terms of compressive and tensile forces perpendicular to the grain.

As a result, the neighbouring cross-sections of the struts and continuous beams are reduced as little as possible and the load-bearing capacity of the components remains largely unaffected. In addition, the small space requirement of the cleat results in an almost invisible solution. Only with larger forces and an additional out-of-plane loads leads to the limit of the form-fit detail, making other solutions necessary. The cleats also offer the advantage that the production can be carried out by the timber constructor. Less additional material needs to be purchased. This increases the contractor's added value. When connecting two struts, steel with a mass of approx. 25 kg is replaced by a cleat weighing 4.5 kg. The details are also smaller in terms of cubature. This simplifies the handling and transport of the partially prefabricated continuous beams (comp. Fig. 4).

The assembly concept of the cleats is designed so that the struts can always be joined vertically. A second insertion direction is also possible. Common tools and degrees of freedom of the joining machines were considered (comp. to Mork et al. [3]). Screw joining to the cleats and closing the screw heads with prefabricated covers only takes place after joining.

For this complex strut and tie framework, it was useful to choose a node based detailing concept which reacts to the different number, hierarchy, inclination and loading of the connected struts. The decision also had impact on the modelling of the structure.

4. Data-based Modelling

A "parametric sub-script oriented step-by-step" (Stehling et al. [5]) approach was employed to tackle geometrical complexities in the primary wooden structure, especially in the roof area with ruled hp-surfaces. Strut intersections and load-bearing details were meticulously planned and modelled separately. This approach prioritized enhancing architecturally significant components. Through parametric planning, all timber connections were formulated during an extended detail planning phase. Communication between subprocesses in Grasshopper was facilitated by attributing components in the central model. Manual attribution for special components remained practical for information exchange within the global information modelling workflow and local Grasshopper subprocesses, enabling a smooth transition between direct manipulation, associative modelling, and scripting as shown in Aish [7].

In total more than 96% of the statically relevant details and strut intersections were automatically resolved via rule-based scripts using Grasshopper, corresponding to an overall effort of approximately 80%. Only less than 4% of the struts and details were manually modelled through direct manipulation, corresponding to an effort of 20%.

4.1 Central model and submodels

The entire scope of planning was structured into the statically relevant central model and individual submodels. The central model comprises the statically relevant construction geometries and the spatial primary framework of struts, including solid timber construction. Subsequent submodels, such as the facade comprising secondary and tertiary support structures and timber frame walls, as well as the MEP planning, roof assembly, and drainage system, are contingent upon the primary framework. Synchronization of these models with the central file is facilitated through Rhino *Worksessions*. To ensure structural integration and cost certainty, planning within an existing structure's point cloud is essential. Parametric details for connecting the primary framework to existing structures are aligned with the point cloud data linked as partial model.

Initial organization involved numbering all nodes of the primary structure and centrally managing data for all details and fasteners through Excel, synchronized with structural calculation models in RFEM. Rhino and Revit models drew from the same data source, ensuring consistency. Grasshopper scripts communicated with Excel to place details at designated nodes, while a library of 3D blocks provided fasteners, adjusting spatially across construction planes for optimal synchronization between scripted geometries and block types.

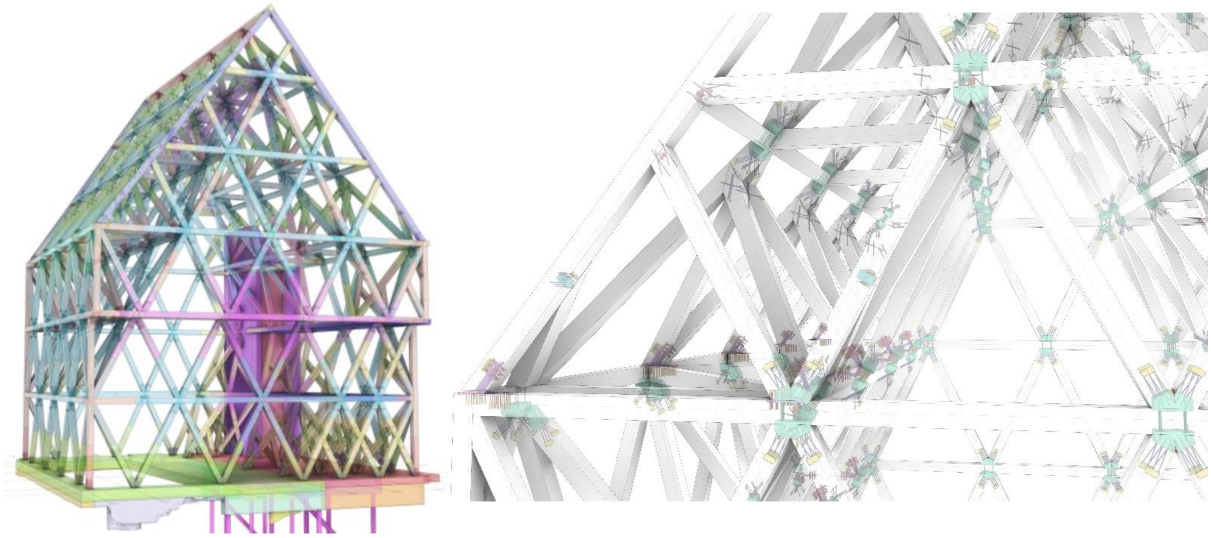

Figure 6: Overview of the central information model (left) and the level of detail (right).

For tendering, estimation, and coordination with structural proof engineers, plans detailing the timber framework and concrete formwork were generated. Utilizing streamed geometries and component data extracted from the central model via Rhino.Inside integration, these plans were created within Revit. Specialized sections like *SQ.xx* served dual purposes: facilitating geometric operations within the central model and providing textual information in the Revit plans. Changes made to the 3D representation in the Rhino model were seamlessly reflected in the Revit plans, ensuring consistency. Revit plans not only conveyed the quantification and cross-sectional assignment of all struts but also detailed placements of components. Knot references for these details were extracted from the centrally managed Excel file.

4.2 Attribute-based centralized Design

- Design for Manufacturing and Assembly

Drawing from resources like Mork et al. [3] and Stehling et al. [6] connection geometries such as hardwood shear locks and MEP subtraction solids are crafted as BTL-compliant components in the central model. These serve as foundational elements for generating machine data (CAM) during workshop planning. Manufacturing-related tolerances of 0.0001mm were meticulously accounted for during the planning phase, starting from the early collaboration between architecture and structural engineering to avoid re-modelling during workshop planning.

- Data structure and global IDs

The central information interfaces for parametric modelling are formed by a coherent data structure, akin to the information structure developed in Lienhard et al. [4]. With-in this data tree, each node is assigned a custom ID. The system lines of the struts between the nodes are segmented and combined with the ID of the subsequent node. The system lines of the strut components are the combinations of their respective segments and IDs. Therefore, each strut segment is exclusively attributed to one node, while the strut components, composed of segments, connect to at least two nodes. Due to the data tree, in parametric detailed planning, the geometries of segments and completed components of all struts can be maintained parallel to the node ID and utilized as geometric boundaries for the detail. This approach avoids complex sorting routines with high computational capacity or intricate data trees. The scheme of data transfer is shown in Fig. 7.

- Hierarchy of intersections in the node via colour coding of the system lines

In order to achieve an appealing design solution in the primary structure together with the architecture, a decision was made in favour of model-related communication via strut hierarchies in colour coding. This initial visual decision of the dominant and recessive connections in the nodes is then transferred to an attribute *str_order* and informs the line model. In the line model, a strut component as a volume consists of segments of different hierarchies in the respective connection points (Fig.7 (1)).

- Strut orientation via construction plane sub-model

Based on the line model, a plane model of the enveloping surfaces and the spaces in the spatial strut structure was created. These planes serve as *str_cPlane1* for the orientation of the cross-sections. Special orientations of individual cross-sections could thus also be efficiently integrated into this process and fed into the further workflow (Fig.7 (2)).

- Knot Types

The strut cross-sections, defined by the construction plane *str_cPlane1* and stored in the attribute *str_crossSection*, vary based on standard or special requirements. Standard cross-sections maintain a profile of w/h=200/200cm, while special cross-sections, utilized in support-block, eaves, ridge, and verge areas, are managed via position numbers cq = xx. Manually drawn special cross-sections are stored as point coordinates, utilizing the same attribute *str_crossSection*, and can be spatially oriented to construction planes for conversion into *Crvs* and *Solids* (Fig.7 (3)).

In organizing the primary framework, distinct families and types of strut intersections within the knots are determined by the attribute *str_order*. Control over these intersections is facilitated through Grasshopper subscripts, allowing for modifications to accommodate different intersection types. Unique intersections, not efficiently scripted due to their infrequency, are manually modelled and seamlessly integrated into the BIM workflow with their respective attributes.

Identification of individual strut segments originating from knots enables their merging into components. During this process, the attribute *str_data* is merged into a globally unique position number, *str_POS*. Struts typically consist of two or three segments; however, if connections exceed three, segments are merged into continuous beams like horizontal purlins or verge beams. The central model comprises 1,101 strut-segments, forming 454 strut-components.

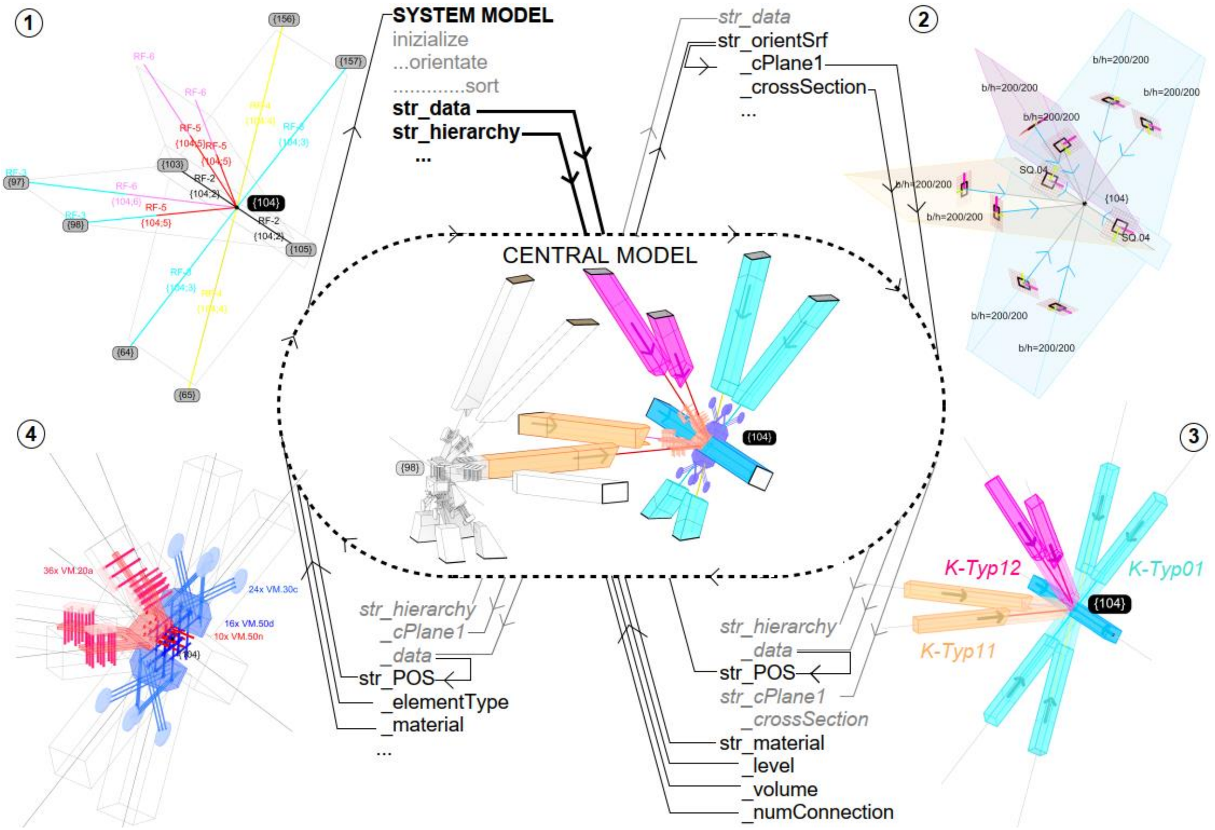

Figure 7: Centralized information workflow within the parametric sub-scripts.

- Detail Types

The detail scripts are organized into rule-based families and types, which combine geometric similarities to automatically adjust the elements precisely to the respective spatial configuration. This allows multiple details to be aligned at a node and connect to the respective struts. The typification of strut intersections is independent of the detail types. This means that two identical strut intersection types can result in two different detail families according to the structural requirements. For the creation of the shear locks the attributes str_cPlane1, str_order and str_data are decisive in retrieving the spatial construction planes of each node and its associated struts (Fig.7 (4)).

To ensure efficient workshop planning by the timber construction company, all fasteners and tenons are created as individual blocks for processing in compliance with the Building Information Modelling (BIM) Transfer Language (BTL) as explained in [3] and [6]. The fasteners are aligned to 3D construction planes relative to the struts by streaming the respective fastener block from the library onto the relative construction plane in space (Fig. 7). Once all relevant attributes have been assigned to the geometries and blocks, they are transferred into Rhino geometries in the central model. Collisions between fasteners and with other trades were avoided through precise positioning. In total all details of the primary framework include more than 9,300 blocks of screws, fasteners, tenons and covers and 2,200 Solids.

- Special Details via Direct Modelling

As the transitions to the existing building were non-rule-based special items, the manual creation of detail geometries and attributes or information enabled the global BIM workflow. By differentiating between automated, rule-based elements and the individual special items, the planning process could be accelerated and optimized globally.

- Revisions and model-based communication

Changes are also communicated model-based after the central model is transferred to the timber constructor. Each component is given a revision index in the *str_index* attribute when changes are made and, if necessary, a comment is added under *str_am*. This metadata can be called up at any time via a script and superimposed on the central model as additional information. This process can also be used to make minor adjustments such as screw spacing, screw lengths or joint widths.

Detailed information of the modelling process and the data driven concept are published by Ehrhardt et al. [8].

5. Conclusion

With the museum at Oberamteistrasse Reutlingen, a planning process was developed making possible to develop spatial load-bearing structures made of timber applying an innovative form- and force-fit node concept increasing value creation of the timber construction company and decreasing steel parts and accompanying emissions.

On the one hand the node-based joining concept was essential to simplify the load distribution for complex node situations and on the other hand the detailed modelling was necessary to guarantee a cost-efficient solution for the client and low risks for the contracting timber construction company. Therefore, a detailed 3D model was set up checking and visualising all member clashes already in the detail design planning stage not knowing the executing company and their capabilities regarding digital data processing and workshop possibilities.

The result was an open informed data and building model used for the description of the buildings specifications, the communication to the checking engineers and moreover to the final workshop planning of the timber construction company.

References

[1] M. Steppler, F. Tschümperlin: «The Cradle» Holzhybridbau in Düsseldorf nach cradle-to-cradle-Prinzipien (“The Cradle" timber hybrid building in Düsseldorf based on cradle-to-cradle principles). *Proceedings of 26. International Holzbau-Forum IHF, Innsbruck*, 2022.

[2] J. Wiesler: Holzkirche in Holzkirchen (Wooden church in Holzkirchen), *Proceedings of 22. International Holzbau-Forum IHF, Innsbruck,* 2016.

[3] J. H. Mork, M. Luczkowski, B. Manum, A. Rønnquis: Parametric Timber Toolkit: A Timber Tailored Approach, *WCTE 2018, Seoul, Republic of Korea,* 2018.

[4] J. Lienhard, C. Bergmann, R. La Magna, J. Runeberger: A Collaborative Model for the Design and Engineering of a Textile Hybrid Structure*, Proceedings of the International Association for Shell and Spatial Structures (IASS),* 2017.

[5] H. Stehling, F. Scheurer, S. Usai: Large-scale free-form timber grid shell: Digital planning of the new swatch headquarter in Biel, Switzerland, 2020. https://doi.org/10.2307/j.ctv13xpsvw.32

[6] H. Stehling, F. Scheurer, J. Roulier: Bridging the Gap from CAD to CAM: Concepts, Caveats and a new Grasshopper Plug-In, in Gramazio F., Kohler M., Lengenberg S. (eds.), *Fabricate 2017: Negotiating Design and Making: UCL Press,* pp. 52-59, 2017.

[7] R. Aish: DesignScript: origins, explanation, illustration. Proceeding of the Design Modelling Symposium (DMS), Springer, Berlin, 2011.

[8] K. Ehrhardt, T. Claus, A. Michalski, J. Lienhard, Ph. Stute, S. Burger: A Case of Integrated Architectural and Structural Innovation in Timber Construction, Digital Modelling, *Proceedings of Design Modelling Symposium (DMS)*, Kassel, Germany, 2024.