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CLEAR THE STAGE FOR TIMBER CONSTRUCTIONS

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ABSTRACT: The Globe Theater is currently under construction in Coburg, an ensemble of four buildings connected by intermediate structures. The center of the building complex is formed by a striking round building in timber hybrid construction. The three adjoining buildings are designed as two-story timber buildings in skeleton construction. Initially, the Globe Theater will serve as an interim venue for the Landestheater, which is undergoing fundamental renovation. In the long term, the new building will be used for various purposes. The circular theater structure, which is predominantly made of wood as a building material, involves many engineering challenges. In structural design, these included the "subtensioned system" of the ceiling over the open area, the "compression-tension ring system" that mutually supports the roof structure, the cantilevered wood-concrete composite ceiling, and the trusses that span the stage. In the fire protection planning, the challenge lay in the detailed design as well as the integration of the technical systems into the building structure. In the process, details were developed that are outside the rules and regulations. This article explains these special features. However, the Globe Theater is not only special in its construction. Among other things, the design also has the special feature that it was created by two students from Coburg University of Applied Sciences. The implementation of a student design into reality is something very special.

KEYWORDS: Structural timber engineering, hybrid structures, structural fire protection, vibrations

1 INTRODUCTION

The idea for the circular shape of the theater building came from Coburg architecture students Isabel Stengel and Anders Macht. The design is based on the Elizabethan Globe Theatre in London. This picked up on Coburg's connection to the British royal family, which came originated from the marriage of Prince Albert to Queen Victoria in 1840.

The main building has a diameter of 36 m and a height of 18 m. The basement is designed as a water-impermeable reinforced concrete structure. The high-value building component is assigned to service class A and additionally protected against groundwater by means of fresh concrete composite foil.

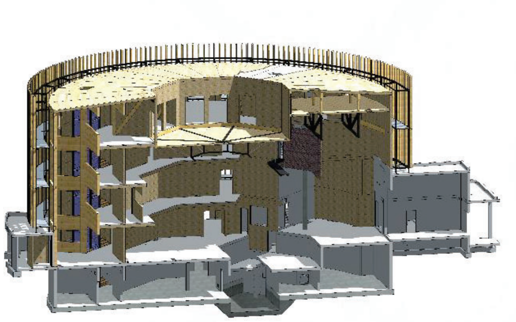

Figure 1: *Cross section through the main building*

The 18 m high wooden building consists of four floors and has a gross floor area of about 5,100 m^2. The first floor houses the revolving stage and the auditorium as well as the height-adjustable orchestra pit. In the entrance area is the foyer, which is open across all floors up to the roof. The foyer is flanked on both sides by representative staircases made of solid wood.

Figure 2: *Foyer area*

The first and second floors contain the galleries. The third floor contains preparation rooms and an interior open-air area (Figs. 1 and 3).

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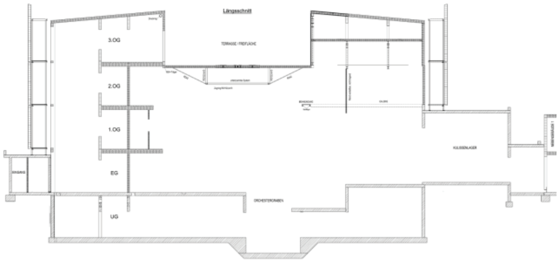

Figure 3: *Cross section through the main building*

In addition to the main building, there are three subsidiary buildings as a wooden structure (Fig. 4) with a total gross floor area of about 1,750 m^2. These buildings are connected to the main building via the stage storage area and are also connected with each other via an open arcade.

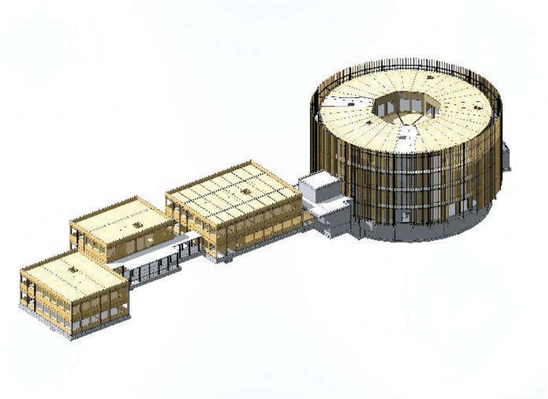

Figure 4:: *Main building with outbuildings and connecting corridor*

Figure 5:: *Aerial photo with main building in foreground*

2 STRUCTURE

2.1 Overview of the structure

The basement and two stairwells as well as the scenery storage are made of reinforced concrete. The four-story main building is largely made of wood from the first floor to the attic. The exterior and interior walls as well as the roof are made of cross-laminated timber and the slabs are a wood-concrete composite construction. Above the auditorium, there is an accessible open space on the 3rd floor (Figs. 3 and 7). This is designed as a subtensioned system. The polygonal structure of the top floor is mutually supported on the inner side by a steel compression-tension ring system. Above the stage are three steel trusses that support the floor above and the lacing floor. The structure is braced by the two reinforced concrete stairwells and the cross-laminated timber walls.

Figure 6: *State of construction of the main building*

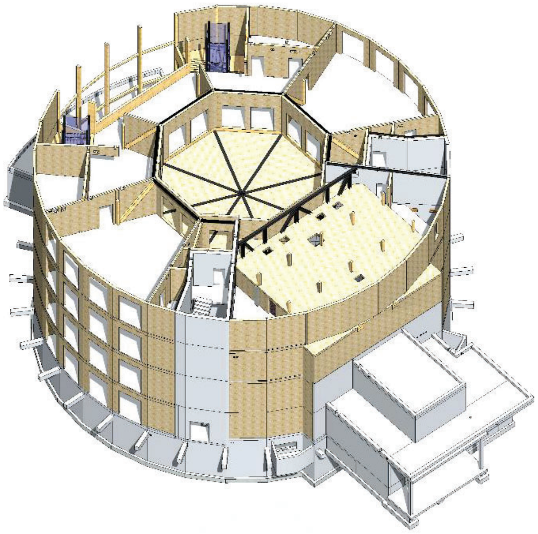

Figure 7: *Illustration upper floor*

2.2 Subtensioned system

The roof structure above the auditorium is designed as an subtensioned system (Fig. 9). For this purpose, eight steel girders are arranged in a star shape and infilled with triangular cross-laminated timber elements. The steel girders are supported by eight air columns, which are connected by a tension ring (octagon) and attached to the steel girders by inclined tension rods. Thus the tensile forces are short-circuited in the steel girder (compression element). In order to dispense with shoring, the star-shaped roof structure was pre-assembled on the construction side and lifted into place. To reduce the weight, not all the cross-laminated timber elements were installed, only the amount necessary for holding the steel girders with respect to bending torsional buckling. The

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remaining cross laminated timber (CLT) elements were subsequently lifted into place.

***Figure 8:**: Lifting of the subtensioned system*

Since the subtensioned ceiling is fixed below the compression ring structure of the roof, a mounting joint of the steel girders close to the support had to be provided for reasons of space. The subtensioned system is supported by the large truss spanning the gap between the stairwells and, in the remaining area, by vertical steel tension elements attached to the compression ring.

***Figure 9:**: Suspended System above the spectators*

2.3 Compression-tension ring system

The vertical load is mainly carried by the outer walls (outer ring) and the parallel inner walls (inner ring) (Fig. 3). The inwardly cantilevered ceilings serve as spectator galleries on the first and second floors and as usable space for preparation rooms on the third floor. Further, on the third floor, the subtensioned ceiling above the auditorium is suspended from the compression ring and further derived into the wooden compression struts.

Since the polygonal three-story wooden structure on the 3rd floor cantilevers inward and receives additional loads from the suspended, subtensioned ceiling, the structure requires horizontal support from the compression ring. The steel compression ring runs underneath the roof and supports the roof structure. The compressive forces are transmitted via the compression struts from the roof level to the ceiling level and there to the tension ring (Fig. 10). The tension ring consists of a steel plate that is milled into the CLT slab and installed below the concrete slab of the wood-concrete composite floor. The vertical component of the compression strut is transferred into the interior wall below. A steel detail was developed for the footing (Fig. 17) to transfer the loads through the slab. When the tension or compression ring is closed, the horizontal forces in the ring cancel each other out. In the Globe, however, these are interrupted in the area of the platforms, so that the forces are transferred into the reinforced concrete stairwells.

***Figure 10:**: compression ring and compression strut at the 3rd floor*

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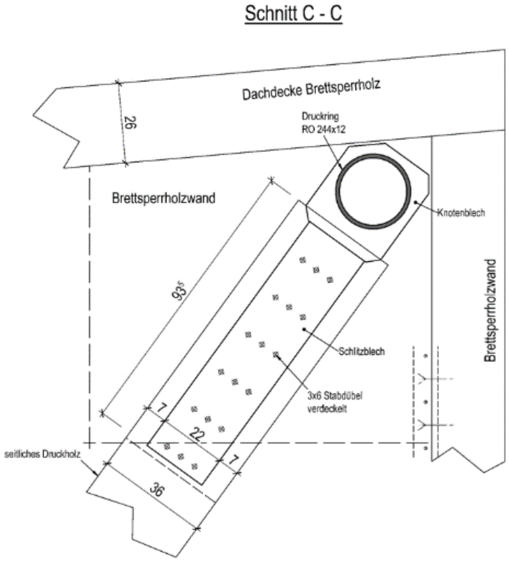

Figure 11:: Detail tension-compression ring: compression strut*

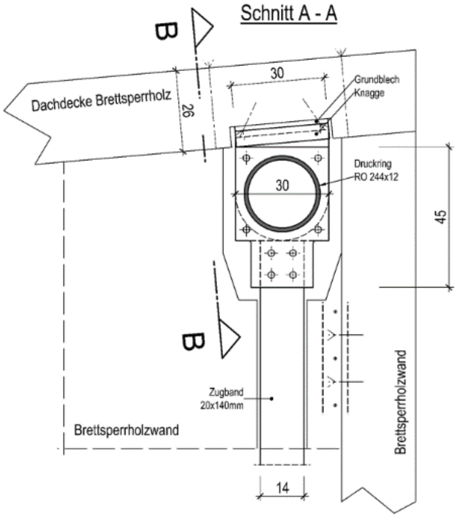

***Figure 12:** Detail tension-compression ring: tension rod that hangs up the open-air area to the compression ring*

2.4 Wood-concrete composite deck

Another special feature is the wood-concrete composite floor. Since this has cantilevered areas, the simplified assumption that the tensile forces are absorbed in the wood and the compressive forces in the concrete is deviated from. In the area of the supporting moment, it is the other way round. The tensile forces occur in the concrete, which must be reinforced accordingly. The wood-concrete composite floor was modeled as a framework model according to Kneidl/Hartmann. The cross laminated timber element was considered as the lower chord, the concrete slab as the upper chord and the connecting elements for coupling the two chords. The connecting elements was modeled with compliant bond to obtain the internal forces and deformations as close to reality as possible. For economic design, the slab was divided into sections to adjust the spacing of the connecting elements to the shear force line. In particular, the length of the upper tension zone had to be taken into account depending on the load combinations. The cracked concrete in the support area was taken into account by modifying the stiffnesses. The concrete slabs are precast elements and were bolted to the cross-laminated timber slabs on site.

***Figure 13:** Cantilevered ceiling elements in the as-built condition*

Thus, the penetration of moisture into the wood was reduced, the ceiling was immediately loadable and the construction process could be continued steadily.

***Figure 14:** Screwing the concrete slab at the construction site*

2.5 Truss girder

Above the stage, steel lattice girders were used to span the stage area without supports. In addition to the technical equipment above the stage, the lattice girders also support part of the open-air area on the 3rd floor.

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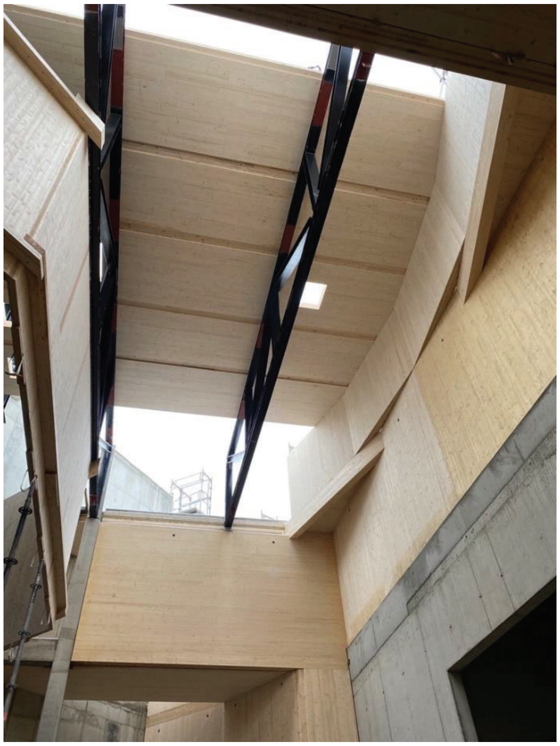

Figure 15: *Truss girder above the stage*

Figure 16: *Trusses in the area of the lacing floor*

3 CONSTRUCTION AND DETAILS

3.1 Connection of compression strut to tension ring

The compression strut, which transmits the compressive forces from the compression ring, meets the tension ring and the wall below in the area of the ceiling above the 2nd floor. The horizontal component of the compressive force must be transferred to the tension ring. There is a steel part developed for this purpose, which is the base of the compression strut and at the same time connected to the tension ring (Fig. 18). The connection must allow horizontal slip parallel to the compression strut so that the tension ring is activated and the horizontal force is not transferred into the ceiling. At the same time, however, the joint must transfer horizontal differential forces into the ceiling. These arise in the tension ring due to asymmetrical loading of the sub-tensioned ceiling structure.

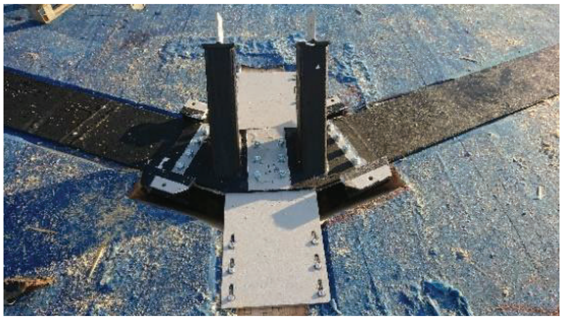

Figure 17: *Detail of the base of the compression strut on the tension ring – tension ring and steel connector*

Figure 18: *Detail of the base of the compression strut on the tension ring – including wooden column*

3.2 Connection of foyer column to concrete ceiling

The foyer column must absorb tensile and compressive forces. To be able to absorb the tensile forces, threaded rods were glued into the wooden column. The threaded rods were attached to a steel profile that was designed and dimensioned for this joint. The anchoring in the reinforced concrete slab was done by welded reinforcement.

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Figure 19: *Detail of the base of the foyer column with special steel part and glued-in threaded rods*

3.3 Joint of beam to foyer support

The beam that spans along the foyer serves as a support for the ceilings. Since the ceilings in the auditorium cantilever, lifting forces also occur here. To be more effective in terms of assembly, the beam was connected to the foyer support using fully threaded bolts. For this purpose, protection against the effects of fire had to be provided by covering. In order to avoid increasing the cross-sections as much as possible, gypsum fiberboards were milled into the joint area and these in turn were joined with wood materials.

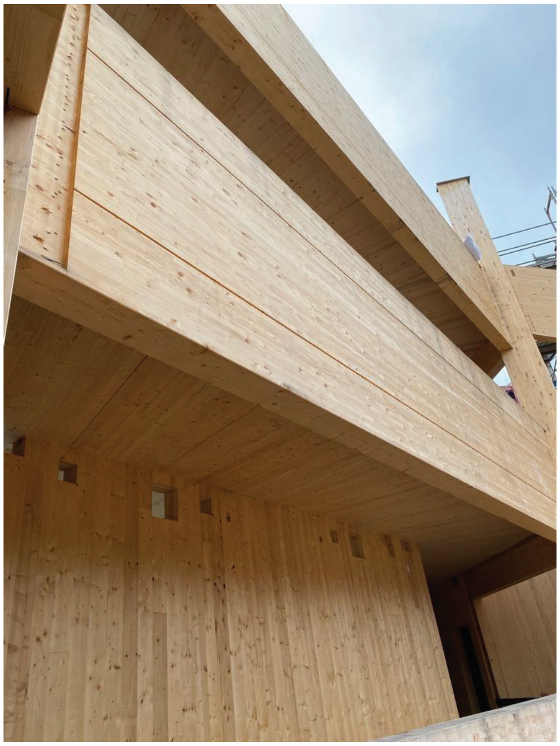

Figure 20: *Interceptor beam with cut-out for capping on the left side*

4 CONSTRUCTIVE FIRE PROTECTION

Fire protection was a particular challenge for this special wooden building. While the model timber construction guideline was used for the ancillary buildings, most of the details had to be developed individually for the round main building with regard to the fire resistance criteria. Most of the structural components are rated for a fire resistance duration of 90 minutes. The wooden components are dimensioned by taking into account the fire. The steel components as well as connecting elements of the joint are also largely manufactured with sufficient timber covering or capping.

In order to keep the component cross-sections as slim as possible, some connections are provided with cut-outs, installed in the gypsum boards and then covered again with three-layer wooden-boards. Exposed steel parts are provided with a fire protection coating.

5 VIBRATIONS

Since visitors to theater performances also sit quietly in the stands and thus on the cantilever, low-intensity vibrations can also be felt. People react differently to the vibration behavior of structures. When used as a theater, special attention was paid to this. Human-induced vibrations caused by foot traffic were reduced to a minimum by the wood-concrete composite ceiling, so that during quiet performances there is no risk of visitors feeling uncomfortable due to building vibrations. Furthermore, the vibration behavior due to the excitation "bouncing" was also investigated. This load situation can also be absorbed by the selected slab system. For evaluation, the natural frequency and the deformation under static load were considered on both the two-dimensional system and the three-dimensional system. The natural frequency of the ceiling is about 9.4 Hertz, which is above the human excitable range and above the Eurocode 1 limit of 8 Hertz. In addition, the limit deformations under a load of 2 kN on the cantilever were also considered, and the limit values are complied with.

6 FACADE

The circular theater building received a closed formwork of vertical boards as a facade cladding. To "hide" the maintenance aisles in front of it, the building is enclosed by a second facade in the form of glulam slats with varying spacing. Where there are foyer areas and thus large window areas, the distances are larger, in the area of closed walls they are smaller. Sheet metal covers on the slat heads and air-flushed connections ensure that water cannot penetrate anywhere or dry out again properly. The wood was given a pre-greying coating. The wooden slats have been designed in a way that damaged wood can be replaced.

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Figure 21: *Facade*

7 CONCLUSIONS

The round Globe Theater, built predominantly in wood, consists of a sophisticated timber construction. The building material wood was focused on from the beginning for reasons of sustainability. The approach to only use wood from the region was not implemented in the value chain due to the logistical effort. Nevertheless, the implementation in wood is a success for timber construction.

For the ceilings, a wood-concrete composite ceiling was used, particularly because of the vibration requirements. Prefabricated reinforced concrete elements were used, which were screwed onto the cross-laminated timber panels at the construction site. Although the precast reinforced concrete elements consisted of a tapered geometry, the assembly on the construction site worked very well. This is also a very good variant for the future in the prefabrication of hybrid structures.

Fire protection is always a major challenge in timber structures. The planners of the fire protection, the structural design, the technical building equipment as well as the inspectors have to work together very well.

In fire protection planning, the challenge lay in the detailed design of the demanding supporting structure and the integration of the technical systems into the building structure. In the process, details were developed that are outside of the rules and regulations.

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Text and images are by the author.

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