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Structural Efficiency of a Hybrid Construction System for a Lightweight Timber Shell Demonstrator

ReciprocalShell case study

Hamed Karimian-Aliabadi[1], Amin Adelzadeh[2], Karl Åhlund[3], Christopher Robeller[4]
[1,2,4]Augsburg Technical University of Applied Sciences
[3]Chalmers University of Technology
[12,4]{hamed.karimian|amin.adelzadeh|christopher.robeller}@hs-augsburg.de
[3]karl.ahlund@chalmers.se

This paper evaluates the structural performance of an innovative hybrid timber system for design and construction of the robotically-fabricated shell structures. The timber system combines two configurations: hexagonal and reciprocal. While the first timber configuration generates the main skeleton of the shell based on the discretization of the input surface, the second configuration enables the cross-bracing within each hexagonal cassette. Joining the cross-bracing elements in the center of the cassettes with a reciprocal node not only resists the deformation of hexagonal cassettes and displacement of elements, but also allows for a more uniform distribution of loads that increases the structural capacity of the timber system, enabling the shell to withstand higher compression and tension forces. The joint system uses the wooden splines and screws to align and reinforce the edge connections, as well as the bolts to fasten the neighboring hexagonal cassettes. The construction system is applied to a case study of a medium-scale shell demonstrator with a maximum span of 7.5 meters that is structurally optimized by form-finding methods. The paper presents a detailed structural analysis including the Finite Element Method (FEM) results, as well as the experimental load test that is carried out to verify the validity and accuracy of the structural calculations..

Keywords: *Hybrid Timber System, Reciprocal Shell, Structural Analysis, Experimental Load Test, RFEM.*

INTRODUCTION

Recent advances in computational design and digital fabrication allowed for an in-depth study of traditional wood joints in a way that they can be optimized for structural efficiency. In particular, development of algorithm-generated joint system enabled a complete control on the geometric processing by which physical and mechanical properties of the timber systems can be dynamically optimized for reaching the highest structural performance of the timber system, paving the way for realization of the complex designs in timber construction. The presented research extend our work on the segmental timber plate shell structures. In contrast to the recent advances in timber joinery, plate-based free-form structures have some deficiencies. Plate shells which are load-bearing segmented structures are usually constructed by hexagonal plates meaning that the production process of such shell, especially when it comes to the

CLT, results in a large amount of waste, leading us to rethink the construction system and come up with a more lightweight, material-efficient and cost-effective timber joints with almost the same structural performance. As a result, a hybrid timber system was developed based on taking inspiration from the reciprocal timber frames. Formerly, architectural and structural performance of reciprocal patterns have been extensively investigated by many researchers (Song et al, 2013; Gherardini, and Leali, 2017; Mesnil et al, 2018; Apolinarska et al, 2021; Wang and Akbarzadeh. 2022). Although a variety of reciprocal timber configurations and joint details are explored, reciprocal timber system has never been directly applied as a cross bracing inside a planar polygonal frame (Adelzadeh, et al, 2023a); therefore, the hypothesis is that development of such dual timber configuration that uses the reciprocal bracing as a reinforcement agent would enable us to present and alternative timber system which has the same structural performance while is lighter, and more material-efficient. The paper aims to evaluate the structural capacity of the presented beam-based timber system and verify it by the experimental load test.

TIMBER SYSTEM

The timber system combines the polygonal frames and reciprocal bracing aligned by wooden splines in a configuration (Figure 1, 2). While the first topology creates the main skeleton of the shell structure, the reciprocal elements act as a cross bracing agent withing each cassettes, providing the counterforce to the external forces, enabling the cassettes to resist nodal displacement. Concerning the function of each timber configurations and required structural properties to increase the load-bearing capacity of the timber system, two different materials of the 21 mm building plywood and 45x145mm dimensioned spruce timber, which were easily available, were chosen for the polygonal and reciprocal beams respectively. Each timber element inside the frame was end-to-end glued and screwed to the next beam in such a way that the direction of the screw was almost perpendicular to the bisector of the corner (figure 3). The reason was to provide the most efficient engagement to the node were two different wood fiber meet each other. On the global scale, segmented were back-to-back connected to each other through two metal bolts (figure 4).

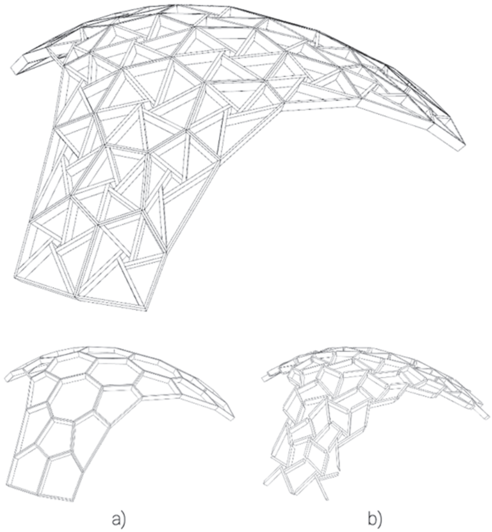


Figure 1
(a) polygonal frames
(b) reciprocal cross bracing

Figure 2
Top: Timber system including the polygonal frame and reciprocal beams.
Bottom: using wooden splines for aligning elements in a configuration

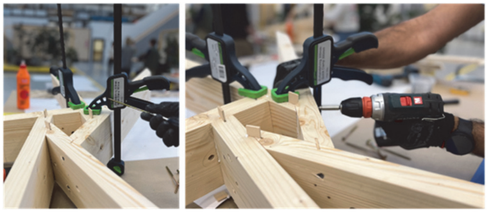


Figure 3
Left: Gluing the end-to-end connections. Right: Screwing joints

Figure 4
Joint detail of the back-to-back bolted cassettes

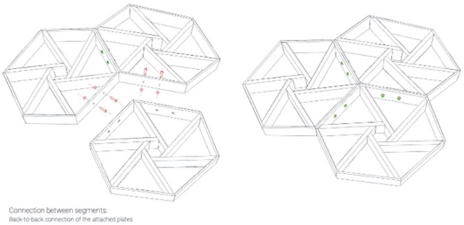


Figure 5
Assembly and displacement of cassettes with no specific deformation

These bolts enhance the quality of attachment between the segments, in such a way that during the assembly of cassettes no specific sub-structure or scaffolding were needed (Figure 5). Experimentally saying, the segments becomes strongly fastened together; so, the structure can easily keep its shape with a great level of resistance against deformation. In addition, while these bolts have a structural function, the concept of having two pre-drilled bolt holes facilitates the robotic fabrication process of solid beams as well as the assembly and disassembly of the whole structure (Adelzadeh, et al, 2023a).

STRUCTURAL ANALYSIS

To evaluate and compare the maximum deformation, material efficiently, and lightweightness of the constructed shell demonstrator, a comparative analysis, including the timber system, weight, volume, density, and cross section, was required between the beam-and plate-based demonstrator (figure 6) (table 1). To do so, the RFEM structural analysis software environment (Dlubal Software Website, n.d.) was selected due to its great tools and properties for timber structural analysis, though, the structural modeling had its own challenges and difficulties. For instance, due to the complexity of the geometry and multitude of solid elements, a rapid and efficient data interface was required to turn the geometric properties into a structural model inside the RFEM. As a continuation of our former study on the data interface modeling (Adelzadeh, et al, 2023b), a combination of custom components and the Dlubal Grasshopper Interface plugin were used to export the shell model and all the solid beams into the RFEM, where the stress and tension between the elements could be simulated and calculated. Despite the geometric complexities, the planar and hexagonal entity of facets in both models, facilitate the structural comparison between the CLT plates and beam-based cassettes.

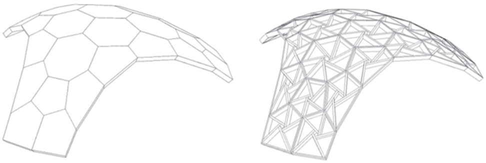


Figure 6
Plate and beam - based shell

Table 1
A general comparison between the plated and beamed timber shell systems

A comparison between the plated and beamed timber shell systems	
Plate-based system:	**Beam-based system:**
Thickness: 100mm 5*20mm	Cross section: 40*130mm
Weight: 0.45 kn/m^2	Density: 700 kg/m^3
Total volume: 1.92 m^3	Total volume: 0.75 m^3
Total mass: 865 kg	Total mass: 528 kg

RESULTS

To provide a comparative view on the structural performance of the timber system, the same shell geometry with a maximum span of 7.5 meters was modeled with two systems (Figure 7). The 10 cm thick CLT panels were used in a plate-based shell, and the reciprocal system cross-section was then calculated so that both systems have the same maximum deformation under unique load conditions. The structural analysis of both timber systems is carried out in the RFEM structural analysis software environment where deformation of both shell shape could be measured. As to the plate timber shell made of five-layered 10 cm thick CLT plates with the weight of 0.45 KN/M^2, the total CLT volume and total CLT mass were 1.92 m^3 and 865 kg respectively with the maximum deformation of 2.3 mm. On the other hand, the same evaluation was done for the timber beam system made of plywood and spruce according to the presented configuration. The analysis show that the beam timber system with cross section of 40*130 mm and density of 700 kg/m^3, had the total timber volume and total timber mass of 0.75 m^3 and 528 kg respectively, while surprisingly demonstrating almost the same maximum deformation of 2.4 mm, about 0.1 mm more than the plate shell. According to the FEM analysis, we expect an structurally efficient timber system with strong nodes that can

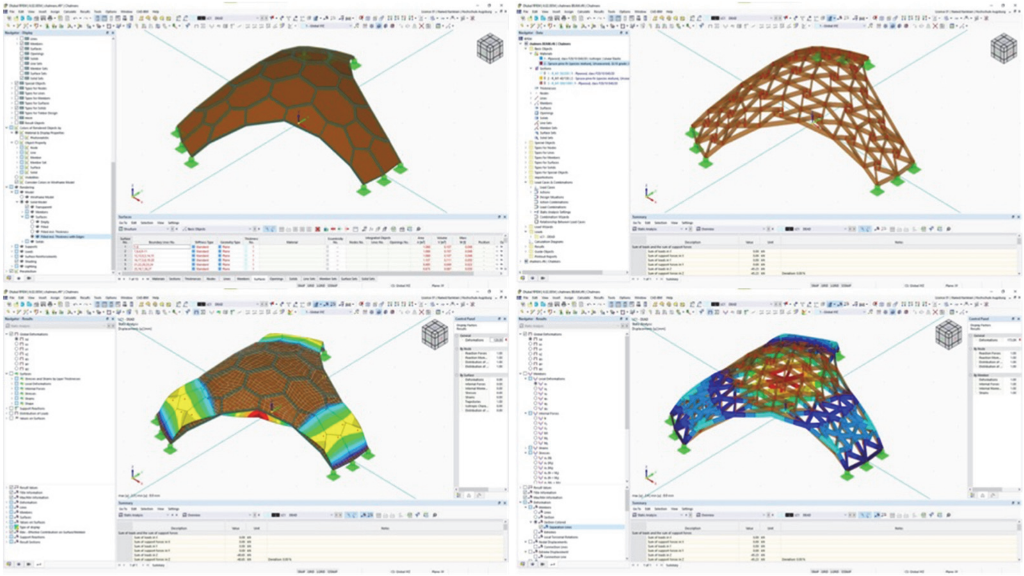


Figure 7
Comparative structural analysis and deformation between plate - based and beam-based shell structure


Figure 8
Temporary
foundation

resist local nodal displacement and global shell deformation. As a result of the structural comparison between the plate and beam-based model, the beam structure exhibits a more material-efficient design, as it requires 60% less volume and it is 40% lighter than the CLT structure. The timber system can act as an efficient solution for the load-bearing lightweight timber shell structures, especially when the material-efficiency is highly required. Regardless of the great level of structural efficiency, the shell structural has great potential application in the future timber construction.

EXPERIMENTAL LOAD TEST

After the assembly of the shell structure a temporary foundation was constructed by unused materials (Figure 8). Thereafter, the shell was placed on the top of the timber foundation which was attached to the larger sheets under it bolted to the ground. To apply the load, up to 150 kg of steel plates (which was the maximum permitted weight) were collected into a bag hanging from the three points distributed equally and symmetrically in the central area of the shell structure (Figure 9, 10). To measure the deformation of the shell under the load, the movement of each nodes was evaluated with the tolerance of 0.01 millimeter (Figure 11). As expected, no deformation or nodal displacement occurred in the shell structure. Although, we were not able to increase the load, but the shell structure proved an excellent structural stability under the hanging load of about 300 kg. The experimental load test, could verify that the deformation of structure remains in threshold where the structure could handle the maximum deformation of 0.01 mm. From the architectural point of view, it can offer a transparent timber configuration itself while providing the possibility for installation of substructure either for tiling (Karimian et al, 2022) or any other segmented roofing systems.

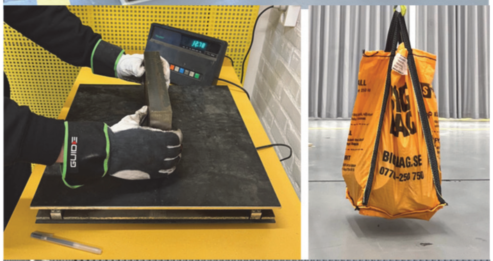
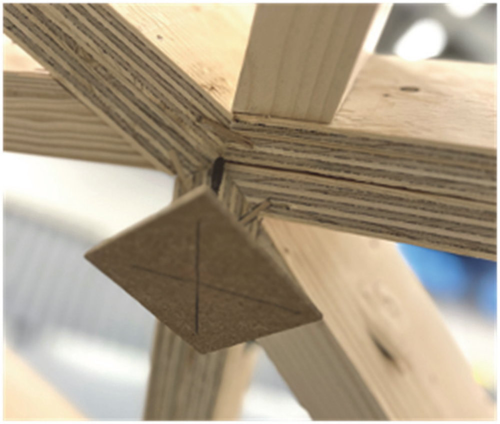


Figure 9
Experimental load
test


Figure 10
Experimental load
test



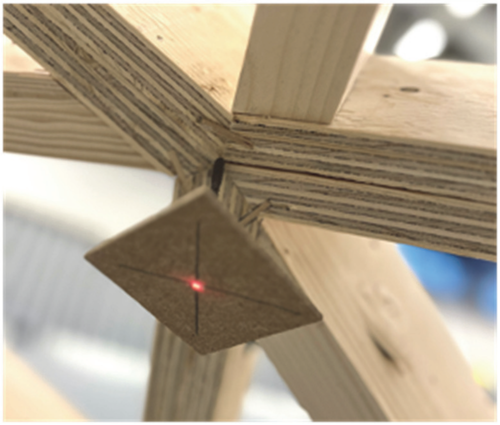


Figure 11
Measurement of deformation

CONCLUSIONS

The presented timber system shows a great structural performance under the experimental load test, verifying the FEM analysis and structural calculations. Referring to the hypothesis, the comparative analysis between plate- and beam-based timber shells shows that the beam-based timber system is able to provide similar structural efficiency while significantly reduce the material use, allowing for the construction of the more light-weight, material-efficient and cost-effective timber structures. The remarkable structural capacity of the timber joint, unlock the great architectural potential of the construction system for the future timber building applications.

Future work

The result of the article opens up a new door for further improvement of the presented timber system for the future building applications. In particular, realization of the more structural efficient timber shells with larger span of 15m is targeted . Having two separate configuration of timber element potentially allows for the material-informed timber system where hardwood and softwood with different geometric and structural properties can be integrated. The construction phase of the upcoming research demonstrator is planned for spring/summer 2023.

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