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Performance Assessment of Double-Layered Timber Plate Shells using Alternative Structural Systems

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Abstract

With recent advances in digital fabrication, innovative wood-wood connections inspired by ancient timber joining techniques have recently been applied to various free-form timber plate structures. This paper focuses on the recently developed double-layered and double-curved timber plate shells. Design, fabrication and numerical automated tools have been successfully developed for these structures. However, three-point bending tests on prototypes composed of fifteen boxes with no curvature have pointed out challenges in the initial assembly system. Namely, failure paths which can be attributed to the herringbone pattern used to segment the target surface were appearing at the stretched bottom layer. This research presents the performance assessment of double-layered timber plate shells using an alternative structural system to the initial one. Numerical investigations were performed to compare both systems in terms of displacements and forces in the joints. The proposed design, involving additional abutment areas of the boxes, was shown to enhance the interlocking connection of the plates and, therefore, the stiffness of the structural system. Tensile forces in the joints were also significantly reduced.

Keywords: timber plate structures, wood-wood connections, finite element model, semi-rigidity, structural analysis

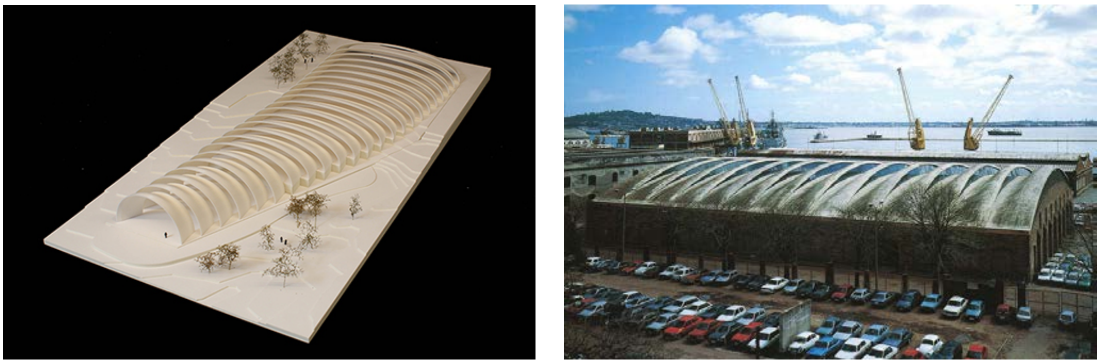
1 Introduction

In the last decades, researchers have shown a growing interest in ancient timber joining techniques initially developed for furniture and cabinetmaking. These connections were improved thanks to digital fabrication and algorithmic-parametric-geometry processing, allowing their fast and precise assembly. Initially used for timber frame structures, they have been applied to plate elements similarly to traditional cabinetmaking joints. These new wood-wood connections have been utilized in various free-form timber plate structures [1]. Recently, an assembly system for double-layered and double-curved timber plate shells using multiple tab-and-slot through-tenon joints (MTSJ-TT) has been developed [2]. It has been applied to the Annen head office in Manternach, Luxembourg. Design, fabrication and numerical automated tools have been successfully been developed for these structures having unique shaped panels and a large number of connections [3]. However, experimental tests performed on double-layered prototypes composed of 15 boxes with no curvature have highlighted weaknesses of the initial design [4]. Namely, continuous failure paths were appearing at the stretched bottom layer.

This research presents the performance assessment of double-layered and double-curved timber plate shells using two different structural systems. An alternative assembly system is presented and compared to the initial one in terms of stiffness and forces in the tenons using a numerical model in which the semi-rigidity of wood-wood connections is considered using springs.

2 Structural Systems

Two different structural systems were investigated taking the example of the Annen head office in Manternach, Luxembourg. The project is a 5800 m^2 facility which will accommodate offices as well as factory space. Its roof structure, illustrated in Figure 1a, consists of 23 singular double-layered and double-curved timber plate shells, 9-meter high and 6-meter wide, covering spans from 23 to 54 m. Their design was inspired by Eladio Dieste's Gaussian masonry vaults, such as built for the Port Warehouse illustrated in Figure 1b [6].



(a) (b)

Figure 1: (a) Model of the Annen head office project (credits: IBOIS, EPFL) (b) Eladio Dieste's Port Warehouse (1977-1975) [6]

2.1 Initial Structural System

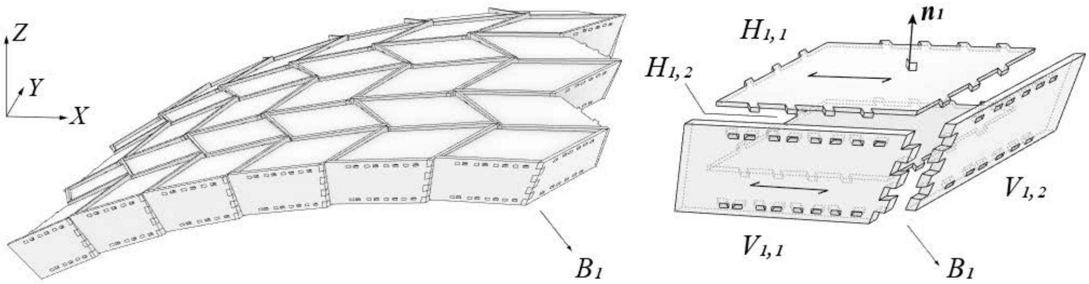
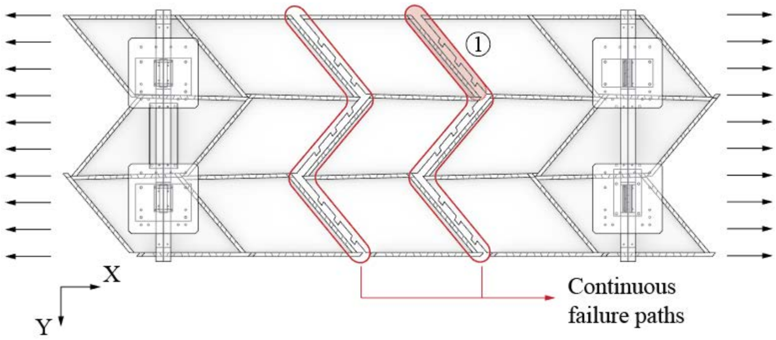


Figure 2: Initial structural system of double-layered and double-curved timber plate shells developed by Robeller et al. [2]

The reference structural system, illustrated in Figure 2, is the initial system developed by Robeller et al. [2] and applied to the Annen head office project. In this one, each shell is composed of an assembly of hexahedra-shaped boxes B_i, each made of two vertical panels $V_{i,1}$ and $V_{i,2}$ and two horizontal panels $H_{i,1}$ and $H_{i,2}$. The latter form the two layers of the structure.

Neighbouring horizontal plates are connected with single-degree-of-freedom (1 DOF) MTSJ-TT through vertical panels, which are themselves assembled with dovetail joints. Each box B_i share its vertical panels with neighbouring boxes. Boxes are individually formed and are then inserted along the vector of insertion, defined by the direction of the remaining DOF of the connections.



(a)

(b)

Figure 3: (a) Continuous failure paths highlighted by three-point bending tests (b) MTSJ-TT failure at the stretched bottom layer of the structure

Three-point bending tests performed on a 5×3 boxes double-layered prototype with no curvature have shown that continuous failure paths were appearing due to the herringbone pattern used (see Figure 3a). Wood-wood connections of the bottom stretched layer failed, presumably due to a combination of shear and traction (see Figure 3b) [4].

2.2 Alternative Structural System

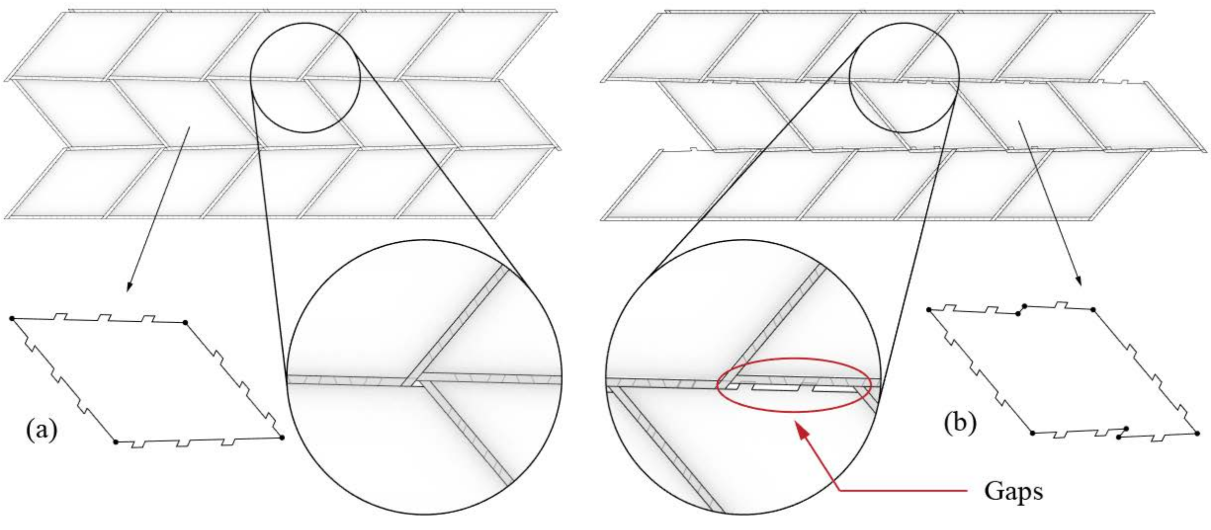
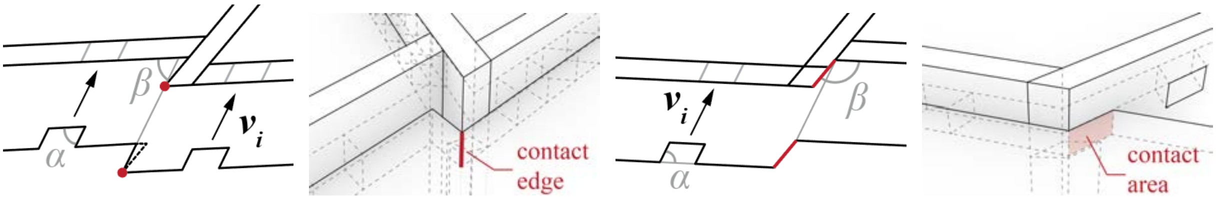


Figure 4: Shift of the boxes introducing gaps in the structure

An alternative structural system was investigated in order to tackle the problems encountered in the initial system, without changing the target surface, constraint of the project, and the

height of the boxes of 600 mm. In order to interrupt the continuous failure paths, boxes were shifted in every second row to obtain staggered rows. However, as seen in Figure 4, this shift introduced large gaps in the structure. The shape of horizontal plates was therefore modified: the quadrilaterals (without considering the tenons) used in the herringbone pattern (see Figure 4a), were replaced by non-convex octagons (see Figure 4b).
The non-convex octagonal shapes have the advantage to provide zones of abutment (see Figure 5). However, as illustrated in Figure 5a, this shape had to be modified (dashed to solid lines) to ensure the insertion of the plates if the abutment angle β was inferior to the angle α, defined by the insertion vector v_i, unique for each plates' edge. In this case, the abutment zone is reduced to a contact line (Figure 5b). When the angle β is larger than α (see Figure 5c), the contact zone is the full area of the abutment (see Figure 5d).



(a) (b) (c) (d)

Figure 5: (a) When $\beta < \alpha$, (b) the abutment zone is reduced to a contact line; (c) when $\beta > \alpha$, (d) the contact zone is the full area of the abutment

3 Material and Methods

3.1 Design Framework

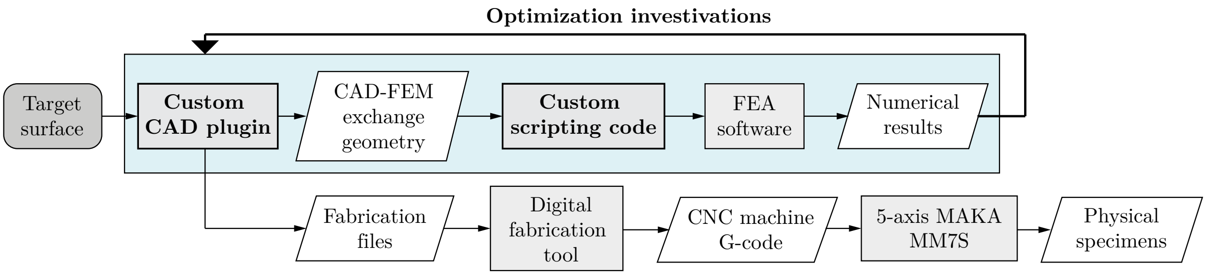


Figure 6: Optimization investigations in the design framework of double-layered and double-curved timber plate shells

The study carried out in this paper follows the design framework presented in Nguyen et al. [3] for the structural analysis of timber plate shells (see Figure 6). To obtain the geometry on large-scale structures, the custom CAD plugin initially developed by Robeller et al. [2] was modified to apply the alternative structural system to entire arches. The custom scripting code automating the generation of the finite element (FE) model was also modified to take into account non-convex octagonal plates, while the remaining code was kept unchanged.

3.2 Finite Element Model and Structural Analysis

The semi-rigid spring model used for the analysis of the 5×3 boxes prototype was used. In this model, wood-wood connections are modelled using springs with 6 components of motion (3 translations and 3 rotations) with stiffness values corresponding to the semi-rigidity of the connections [3]. The model was built in the FE software Abaqus^{TM}.
Numerical simulations were performed with and without modelling of the contact zones of the abutments to evaluate their influence. They were modelled considering nonlinear springs in series, infinitely rigid in compression and hinged in traction. When $\beta < \alpha$ (see Figure 5a), the contact line through the thickness of the plate in the 3D geometry was modelled by a contact point, since plates were modelled by their midsurface in the FEM geometry (see Figures 7a and 7b). This point, coupled to its neighbouring edges, was connected with springs to the plates in contact in the 3D geometry. When $\beta > \alpha$ (see Figure 5c), contact areas were modelled by edges (see Figures 7c and 7d) coupled to their midpoint and connected with springs to the plates in contact in the 3D geometry.

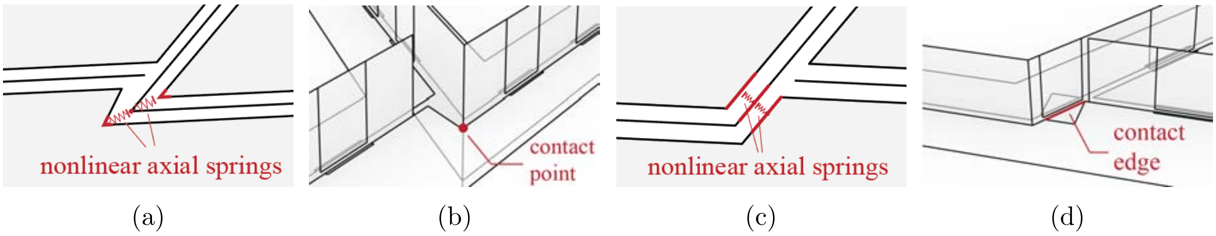


Figure 7: Contact modelling of the abutment zones

The structural systems were compared in terms of vertical displacements and forces in the tenons. Experimental tests on wood-wood connections have shown that their maximum capacity F_{max} was equal to 6.47 kN in tension and 46.83 kN in shear [7]. The distributed loads at which the first tenon reached either this tensile force or shear force for both systems were compared.
A mesh convergence study was carried out for the analysis of forces in the tenons. To achieve it, a determined force F was applied to one tenon of a timber plate and the error between the applied force F and the total force in the tenon retrieved in the numerical model was calculated for different mesh element sizes.

3.3 Material

BauBuche Q panels from Pollmeier used for the Annen head office and the prototypes tested were considered. They are 40 mm-thick beech laminated veneer lumber (LVL) panels with a characteristic density ρ_k of 730 kg/m^3. Those panels are obtained by gluing 3 mm thick beech peeled veneer layers. In the BauBuche Q panels used, two layers are placed crosswise such that the composition of the 14 beech veneer layers is III–IIIIII–III (I for longitudinal, – for crosswise veneer layer). Material properties used in the model are presented in Table 1, where E is the elastic modulus and G the shear modulus.

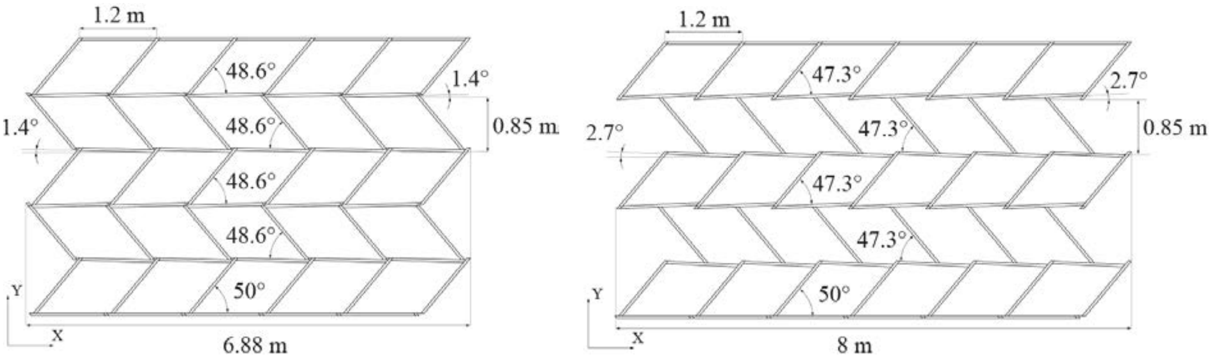
3.4 Specimens, Load and Boundary Conditions

The geometry of the specimens considered is presented in Figure 8. For the initial system, same geometric parameters as in the tested prototype of 5×3 boxes were considered (see Figure 8a).

Table 1: Material properties of BauBuche Q panels (characteristic values) [8] [3]

	Units	E_X	E_Y	E_Z	G_{XY}	G_{XZ}	G_{YZ}
BauBuche Q	[N/mm^2]	12 200	2000	2000	540	360	59

For the study of the alternative structural system, three additional boxes were added to obtain symmetry (see Figure 8b). Boundary conditions similar to those of the three-point bending tests performed were considered; namely pinned support on one side and roller support on the other [4]. A distributed load was simulated on the top layer of the structure.



(a) System n°1: initial system (b) System n°2: alternative system

Figure 8: Geometry of the specimens considered for the comparison of the two structural systems

4 Results and Discussion

4.1 Geometry Generation

The custom CAD plugin was successfully modified to generate double-layered and double-curved timber plate shells with the alternative structural system. The mesh segmentation of the target surface was first performed (Figure 9a), followed by the generation of the joints (Figure 9b), the vertical plates (Figure 9c) and the top plates (Figure 9d).

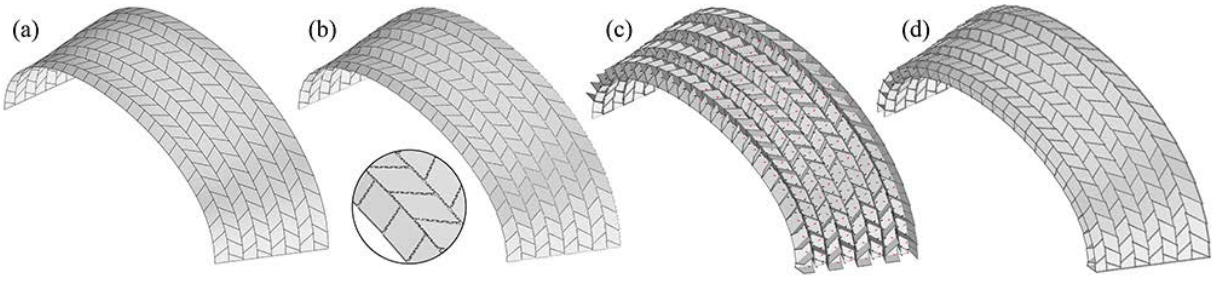
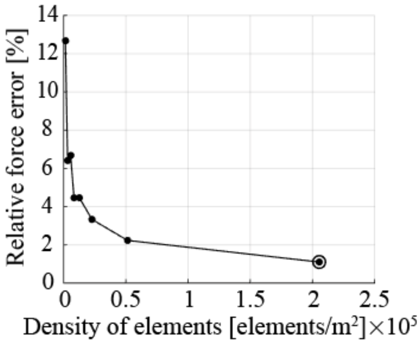


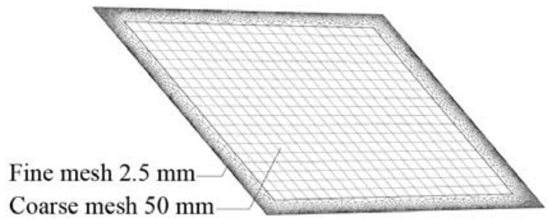
Figure 9: Generation of double-layered and double-curved timber plate shells with the alternative structural system (a) target surface segmentation and generation of (b) joints, (c) vertical plates and (d) top plates

4.2 Mesh Convergence Study

Results of the mesh convergence study for the analysis of forces in the tenons are presented in Figure 10a for mesh element sizes varying from 2.5 to 30 mm at the vicinity of the connections and 50 mm away from them. The smallest element size of 2.5 mm (see Figure 10b), leading to a relative error of 1.1 % between the force applied F and the total force in the tenon obtained, was chosen.



(a)



(b)

Figure 10: (a) Mesh convergence study for the analysis of forces in the connections. A mesh element size of 2.5 mm (circled) was chosen. (b) Coarse and fine mesh of a plate

4.3 Structural Performance

Figure 11 presents the load-displacement curves obtained for the two structural systems, modelling contact of abutment zones or not for the alternative system. As observed, the major part of the stiffness increase was due to the structural system applied and not the contact modelling. Further numerical results are presented in Table 2. With the alternative system, stiffness was increased by 76% and 91% without and with contact modelling respectively. For both systems, the maximum capacity of the joints in tension was reached before the maximum capacity in shear. Forces in the connections were reduced such that the maximum applied load at failure was increased by 85% and 229% without and with contact modelling respectively.

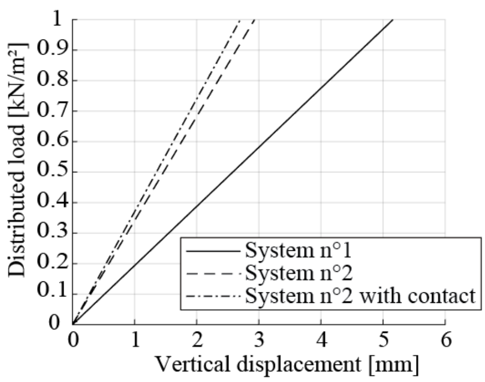


Figure 11: Load vs. displacement curves for the two structural systems with and without modelling of the contact of abutment zones

Table 2: Performance assessment of the two structural systems

	Units	System n°1	- n°2	- n°2 with contact
Load applied to reach F_{max}	[kN/m^2]	5.82	10.76	19.15
Stiffness	[kN/m^2/mm]	0.166	0.292	0.317

5 Conclusions

An alternative structural system was proposed to avoid continuous failure paths appearing with the initial system. Base on numerical investigations, it was shown to enhance the interlocking connection of the plates and, therefore, the stiffness of the structural system by 76%. Tensile forces in the joints were also significantly reduced, increasing the distributed load to reach maximum capacity of the joints in tension to 85%. Moreover, abutment areas were shown to have the potential to further enhance the structural performance of the alternative system.

6 Acknowledgements

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