Abstract. This paper shows a design and building application of a novel structure concept which is presented and developed by the author. The form-found pavilion demonstrates the validity of the design methodology and the related technical details of the design and fabrication process in an arbitrary design domain. The large pavilion (7m*6m*2.5m) with only 1mm paperboard also shows the great potentials of the thin sheet materials to be used in shell structure designs. The structural concept is based on the spatial tessellation of shell spaces into groups of cellular cavities. The cellular cavity is mainly composed of two curved membranes and the circumferential ribs. Both global and local membrane actions can be activated by the use of materials as thin as 1mm. Based on the structural analysis of the foregoing pavilion, the structural behavior is discussed in detail with a physical compressive test of the different group of cellular cavities. The assembly process of the pavilion is discussed with a prototype in full scale. As a successful efficient paper-shell structure, this pavilion demonstrates the structural concept and could inspire the potentials of thin materials for future shell designs.

Keywords. Cellular Cavity Structure; Shell Structure; Thin Paperboard; Large Pavilion Design; Parametric Design Method.

1. Introduction

Shell structures have taken and will take an important role in architecture and engineering due to its ability to create eye-catching forms and to resist loads in an efficient way (Adriaenssens et al., 2014). As the thin cross-section and the curved geometry itself will enable the transfer of external loads to its supports predominantly through the in-plane stress in the shell surface (which is so-called membrane actions), it enables architects to use very little material to create the long-span structure with elegant geometry.

Although the curved geometry and the inherited form-finding technique have always been in the central position of shell structure designs, it is mostly in the building process that the distinctive material characteristics inspire the final design, the details and the form itself. From the ancient masonry domes to the popular spatial framework structure with steel and glass, it can be observed that a transition of structure morphology has always been emerging...
with a material-driven inspiration in structural design (Ramm, 2011). With the development of computational fabrication techniques and the explosion of materials in architectural design, this research focuses mostly on the new efficient possibilities of building new shell structures with new materials. The thin sheet materials, with their high qualities and advantages such as low cost, lightweight and the environment-friendly recyclability, are chosen as one typical type of the materials.

Specific to the thin panel forms of industrial thin sheet products, researches have been carried out to develop shell structure concepts aimed at different corresponding materials such as metal sheets (Hachul 2006), timber panels (La Magna, Waimer et al. 2012, Krieg, Schwinn et al. 2015, Schwinn and Menges 2015) and glass sheets (Aanhaanen 2008, Bagger 2010). Since 2012, a novel structural concept has been proposed and researched by the author to develop an innovative structure concept which enables the application of thinner industrial sheets in the shell structure by introducing a “cellular cavity structure” to activate both the global and local membrane-actions of the structural system (Wang 2017). In this paper, more researches of such concept and an experimental application of such structural concept (Figure 1) are presented.

Figure 1. A Form-found pavilion built with the concept of Cellular Cavity structure.

2. Concept of Cellular Cavity Structure and its design process

In the preliminary empirical experiments with super thin sheet materials and traditional ribbed shells and grid shells, it is found that an innovative structural concept was required due to the insufficient structural stiffness from the cross-section of materials. Based on the researches on the natural
cellular structures and their basic geometrical principles (Brinkmann and Flächenträgerwerke 1990, Pottmann, Jiang et al. 2015), a cavity alternative is designed for the targeted super thin sheets to provide sufficient strength and stiffness for the structure.

![Figure 2. Diagram of the cellular cavity structural concept.](image)

2.1. GEOMETRY AND DEVELOPABLE SURFACES

A cellular cavity is mainly composed of two single-curved membranes and the circumferential ribs which define the basic tessellation of the shell space (Figure 2). With a suitable tessellation such as a Voronoi method in this paper, the discretization of a shell space based on an arbitrary surface or a mesh system can be achieved. Geometrically, the developable surfaces are investigated in the generation of the structural system to guarantee an efficient building process of the cellular cavity structure. Based on a 3-valency mesh, advantages can be derived from the design of the shell. On one hand, as the 3-valency mesh is derived from a triangulation system, planar surfaces of the circumferential ribs can be guaranteed by defining the corner point of the 3-valency mesh on the center point of the circumferential circle of the triangles (Wang, 2017). At the same time, because a G3 continuous spatial curve can be gotten by interpolating the corner vertices of the mesh, it is possible to define the two membranes as the developable surface by extruding the curve to the center seed point of the mesh polygon. On the other hand, as the transfer of forces between the cells can be assumed as the edges of the triangulation system, an equilibrium of the shell can be found through a form-finding technique and the membranes can work in this system to provide enough local stiffness for the flexible circumferential ribs.
2.2. STRUCTURAL CONSIDERATION AND UNDERSTANDING OF THE SYSTEM

As the structure is divided into cells and the cells are also defined with circumferential ribs and covering membranes, the structural behavior of the cellular cavity structure should also be understood in a discrete way with a hierarchical method. Globally, the system should be considered as an anisotropic shell where the anisotropy is defined similarly to the property of the double-layered shell with inner and outer membranes and in-between ribs (Flügge 2013). Because only limited in-between bonding connection can be provided for the structure, the design of the structure system should first be the design of the equilibrium state of the discrete cells in the system. In this case, a first assumption is made that every cell could provide enough compressive capacity so that the global design can be achieved by the form-finding techniques with methods such as the Force Density Methods and the Dynamic Relaxation Method. Locally, the covering membranes are defined as two conical-like developable surfaces facing each other. In this way, the distance of both the membranes varies, with the closest distance at the apex point of the membranes surfaces (the seed point of the mesh polygon) and the largest distance at the corners of the outer circumferential ribs. So that both the membranes will work as the local stiffeners in the structural system and transfer the stresses in-between the cells with in-plane stresses on the membrane surfaces. Hence, the local membrane actions will be activated to enable the application of super thin materials. At the same time, as the curvature will cause a stress concentration in the center of the cell, a tube element is designed to provide enough stiffness for every cell.

As an integrated and interacting system, the shell should bear the external load mainly through the membrane forces on the surface of the covering membranes to simulate the theoretical behavior of the double-layered shell (Flügge 2013). The separation of the whole shell through ribs, membranes and the tube helps to establish a coupling structure which leads to a higher stiffness of the superstructure. In this way, the ribs will obtain extra stiffness against its lateral buckling which can be caused by its thin cross-section and will also be saved to minimize the possibility against the lateral torsional buckling behavior.

The combination of the global membrane behavior such as in the masonry shells and the local membrane behavior in the double-layered shells offers a certain amount of redundancy of the structure’s strength. This can be achieved in the first design process by considering only the global transferring of forces without the extra stiffening effect of the covering membranes. In the next design step, when the local membranes are added onto the structure to activate their membrane actions, the stresses in every element in the structure will be reduced as expected in the double-layered shell theory. In this case, if any element fails, e.g. due to the buckling of membranes or damage by external forces, the whole structure will be guaranteed that it will not collapse or be further damaged.
2.3. CONSTRUCTION DETAILS AND PROTOTYPE

Especially for the application of thin sheet materials in an efficient and feasible building process, a prototype is made firstly to discuss a possible fabrication method with folding and gluing as the main connecting technique. In this way, the complicated and coupled geometry can be divided into different classes and can be fabricated with the CNC laser cutter and manually gluing of the finger strips as well as an assistant curved frame. A prototype was then built as a group with 4 cells in different sizes (Figure 3).

The fabrication process can be divided into several steps: 1, fold the rib frame to create the basic form of the cells, connect the ribs with bolts, nuts and washers; 2, paste the assist curved frame to find the correct form of the cell through the cut geometry and also to offer more adherent surface for the membranes, at the same time prefabricating the curved membranes; 3, paste the membranes and inserting the center tube, which will make the cellular cavity structure very stable.

Figure 3. Prototype and construction details of the cell group.

2.4. DESIGN PROCEDURE OF CELLULAR CAVITY STRUCTURES

Based on the assumption and the analysis of the expected structural behavior, a final summary of the whole design procedure of the structure system is made as the guideline of the design process for the structure concept. Starting from an arbitrary geometry or a simple planar region as design domain, a basic tessellation should be generated as the primary discretization of the structural system. Form-finding techniques can be applied in the next step to gain the spatial mesh in pure compressive equilibrium. By changing the triangulation into the reciprocal 3-valency mesh or by optimizing the quadrilateral mesh into a circular mesh, the circumferential ribs can be obtained as planar surfaces. By adding both the top and bottom covering membranes into the structure, an initial design can be achieved in a feasible and rational method. However, a full structural FEM analysis or a physical test is still required as there are some assumptions in the design. In conclusion, a workflow should be required to establish such a design methodology of the negotiation between form and forces and the iteration loops of the design procedure are introduced from both the architectural and structural realms.
3. Material Analysis and the Structural Behavior

3.1. PROPERTIES OF PAPERBOARD AND THE PARAMETRIZED MODEL

In the research presented in this paper, the paperboard is chosen as the representative building material. As the applied press paperboard has been specifically treated with a chemical process, the mechanical properties and behavior need a suitable model for analysis and dimensioning the structure. Based on the similar researches on the same kind of materials (Schönwälder and Rots, 2008), it is possible to connect the design parameters with proportionality factors from material testing, reducing the amount of key parameters that are needed for analysis. So the parametric model was extended and scaled for the use in the design of the pavilion. The simplified TSAI-WU-criterion for paper products (Niskanen, 2012) was used for dimensioning and the safety model from the Eurocode 5 design standard integrated to incorporate creep and relaxation via kmod-factors, which was necessary since creep and relaxation of wood and paper products are still subject of research and a suitable generalized model is up to date not available. A simple linear model used for the design with a trilinear approximation of the actual tensile stress diagram was used as the parameters of the materials (Table 1).
3.2. STRUCTURAL ANALYSIS WITH A SIMPLE HALF-DOME PAVILION

A full structural analysis with the FEM software is carried out and finished in the foregoing research pavilion with a relatively simple pavilion (Figure 5a) and is also used as the foundation of the design of the shell in this paper, because the shape of a half dome is classic and symmetric so that multiple simplification of the structure and multiple load cases can be analyzed and also compared with the theoretical structural analysis of the dome shells. As shown in Figure 5b, shell surfaces were simplified with a constant substitute thickness and the model is simplified to treat the local membrane action on both covering membranes as a simple membrane action on a fictitious shell surface. In this case, multiple load cases such as the self-weight and its combination with the assumed wind load and the snow load are considered and analyzed (Figure 5c). While effective (von Mises-) stresses were used to visualize stress concentrations, the stress checks were done externally with the maximum-stress- and Tsai-Wu-criterion. To examine stability, eigenmodes of the structure were used as imperfection and the second and third order theories were applied, the latter because of higher deformations were expected.

Figure 5. Finite Element Analysis of the foregoing research pavilion of the Cellular Cavity Structure.

The result of the basic structural analysis shows a similar structural behavior as the classic half sphere dome structure. Finally, a hemisphere section model solely with shell elements was used to reproduce the structure as close to reality as possible and to compare with the analysis of the simplified model. As shown

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Tangent modulus</td>
<td>f_{tm}</td>
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<tr>
<td>Minimum fracture tensile strength f_{t}</td>
<td>100 MPa</td>
</tr>
<tr>
<td>Fracture strain</td>
<td>f_{s}</td>
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<tr>
<td>Mean tensile yield strength (linear)</td>
<td>f_{ty}</td>
</tr>
<tr>
<td>Mean compressive strength (linear)</td>
<td>f_{cy}</td>
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<tr>
<td>Mean fracture strain</td>
<td>f_{fr}</td>
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in Figure 5d, a similar global stress distribution can be observed as the simplified model and meanwhile a prominent reduction of maximum stresses can be found in the detailed model with both covering membranes. The result follows the expected structural behavior as explained in section 2.2. The covering membranes together take most of the external load through the membrane forces and the stresses concentrate on the apex point of every curved membranes. The ribs themselves take little stresses in the stable condition and will help to stiffen the superstructure. In conclusion, the expected global and local membrane behavior are both testified with the FEM analysis and the global structural behavior is also similar to the traditional theoretical analysis of the classic dome structure.

3.3. BUCKLING ANALYSIS AND PHYSICAL EXPERIMENTS

To test the effect of the covering membranes for the local stability under axial compression, a pressing test is finished in laboratory as a basis of the building practice (Figure 6a). As it is impossible to design a compressive test under bidirectional forces, a uni-axial compressive test is carried out with extra supports on the other axis. At the same time, different shapes of the covering membranes (conical, folded and planar) are also compared to test the effectiveness of the curved membranes to activate the local membrane behavior (Figure 6b).

Figure 6. Pressing test and the DIC analysis of the buckling behavior.

The result of the physical tests of different groups (Figure 6c) and the detailed DIC analysis (Figure 6d) show the similar structural behavior as the FEM analysis. However, the critical buckling load in the physical tests has shown to be largely reduced compared with the theoretical critical load in the linear buckling analysis in the Finite Element Software. This shows the possible great effect of initial imperfections of the geometry on the buckling behavior of the structure. However, for the chosen curved membranes, it has been shown that the critical buckling load in the physical tests (about 5739N) was almost 1200 times of the self-weight of the tested specimen. Hence the assumption that the cells could be considered as stable enough under compression can be proved as correct.
4. The Design, Fabrication and Assembly of a Long-span Form-found Pavilion

The pavilion is built with 179 distinct cellular cavities whose design and fabrication process is fully under a parametric approach. The global geometry of the pavilion is defined through a form-finding technique of shell structure with a funicular system with a triangular mesh as a preliminary design. A Voronoi tessellation is then applied onto this system to find the developable surfaces of all the structural elements. The fabrication of all the cells are then finished with a laser machine and a simple manually gluing process.

The fabrication process of the complicated and large shell pavilion demonstrates the high efficiency of the structural concept. The whole fabrication and building process of the large pavilion is finished by a workshop in 3 days with 15 students. The total budget of the shell pavilion is only about 1300 US Dollar and no extra scaffolds are required due to the light weight of the structural elements. The high redundancy of the structure is proved because the structure is still left unfinished without most of the bottom covering membranes. It is found during the assembly that the structure itself already provides enough stiffness to stand only by itself.

The assembly process of the pavilion is finished by the group of student in a short time about 4 hours. Because a group strategy is applied in the prefabrication to build the structural elements into several groups, it only needs to fix the connection in-between the groups with screws. As the holes are prefabricated with CNC laser cutter, the accuracy of the arrangement of cells can also be provided during the assembly process. Hence the building techniques of the proposed in this paper is also demonstrated to be feasible to be used in complicated shell designs.

5. Conclusion and Future Researches

With the complicated form-found shell and the sufficient structural analysis and tests, the cellular cavity structure has shown its great potentials and feasibility as a more efficient structural concept for the selected materials and as suitable to be used in a complex design condition and domain. The research method of
the generation process of this structural concept will lead a further research on
the discrete cellular structure based on the structural-performative design method
as well as an automated digital fabrication process based on the application of
machines such as the robotics.

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