B. Dave, A. I. Li, N. Gu, H.-J. Park (eds.), *New Frontiers: Proceedings of the 15th International Conference on Computer-Aided Architectural Design Research in Asia CAADRIA 2010*, 565–574. ©2010, Association for Research in Computer-Aided Architectural Research in Asia (CAADRIA), Hong Kong

BIO-SHELL (BIODEGRADABLE VACUUM-FORMED MODULARISED SHELTER)

S. OKUDA and Z. OU
National University of Singapore, Singapore 117566
akiso@nus.edu.sg, g0800214@nus.edu.sg

Abstract. This paper demonstrates how digitally fabricated vacuum-formed components can provide a new type of efficient construction applicable to architecture. Vacuum forming has the advantage of rapid mass-production capability of 3D curved forms. Recent digital fabrication technologies, such as 3D CAD and CNC machining, have dramatically reduced the cost and time for making the mould. In combination with biodegradable plastic, such as PLA (poly lactic acid) made of biopolymer, it could open up new type of sustainable construction system, which is applicable for temporal disaster housings or exhibition booths.

Keywords. Digital fabrication; biodegradable; vacuum forming; finite element; lightweight structure.

1. Introduction

The importance of material-efficient construction is significantly increasing due to recent growing concern for a worldwide shortage of natural resources and rising material costs (*The Economist*, 2007). Most of temporal structures are material-efficient and lightweight as they often require quicker construction. The material-efficiency ensures not only savings in material consumption but also reduces transportation energy.

There are mainly three types of temporal construction systems. Firstly, tensile structure, such as tent, has proven as one of the most material-efficient structures in human history. However, it often sacrifices efficiency of usable space and adaptability due to required continuous membrane forces (figure1a). Secondly, frame and panel structure which is almost ubiquitous in contemporary environment, and provides highly efficient space and adaptability although it is less lightweight than the tensile structure (figure1b). Thirdly, surface structure such as thin-shell dome is both space and material-efficient, however, few have been constructed recently due to difficulty in its fabrication process and costly 3D formwork (figure1c).

Recent rise of digital fabrication technologies, such as computer-aided design and manufacturing (CAD-CAM) have dramatically reduced the cost and time for making complex 3D mould. Finite element (FE) method can simulate structures prior to construction. The advanced digital technologies suggest that we reconsider use of surface structure as reasonable material-efficient construction method. Such temporal constructions are also often required to be collapsible and efficiently stacked while not in use. Because of shorter building life cycles, issue of construction waste becomes more significant than in permanent constructions.

Figure 1. Lightweight structural type:. (a) tensile, (b) frame and panel, (c) surface.

This paper aims to demonstrate how advanced digitally assisted design and fabrication processes can create temporal lightweight surface structures which provide efficient usable space and adaptability with various configurations yet reduce amount of construction waste after its use. First an overview of the bio-shell will be presented, followed by its structural geometry, FE analysis, digital fabrication and assembly testing. The paper concludes with comparative analysis with precedents.

2. Biodegradable vacuum-formed modularised shell (bio-shell)

The bio-shell is a lightweight shelter for sustainable construction made of biodegradable plastics. Each component is rapidly vacuum-formed with digitally fabricated 3D curved moulds in order to increase its structural stiffness instantly. It is ideal for temporal constructions which need to be cleared swiftly after its use without burdening the environment.

In 2007, the first author conceptualized the bio-shell in Hong Kong through a series of field researches on fabrication processes and materials in Pearl River Delta in China, named the world factory. The concept was awarded at the international architecture competition, Self-Sufficient Housing, in Barcelona. Since then several prototypes under the same concept are developed.

This paper introduces the latest and the most material-efficient structural prototype among the past and current explorations.

We take a multidisciplinary approach which includes the following four steps: 1) Structural geometry, 2) FE analysis, 3) Digital fabrication and vacuum forming, and 4) Assembly and joinery testing. These steps are repeated until we reach an optimized design. Constant feedbacks are made to the master 3D modeling data generated by Rhinoceros, NURBS modeling software that are then reflected to the all steps simultaneously.

2.1. SURFACE STRUCTURE GEOMETRY

2.1.1. Structural design concept

Four major principles of modular shell structural geometry are employed. Firstly, the overall configuration should be almost cubic like geometry in order to maximise usable space and adaptability. Secondly, the wall and roof panel geometry may consist of hyperbolic paraboloid (HP) shell in order to achieve material-efficient structure. The balance between usable space and structural efficiency should define the aspect ratio, namely the proportion of length and height of HP shell. The higher the aspect ratio, the thicker the wall panel, which means stronger structure but fewer usable space. Thirdly, those HP shell wall / roof panels should be smoothly connected with each other to transfer forces efficiently from roof to wall, or vice versa. Finally, the HP shell wall / roof panels should be articulated into repetitive smaller scale components due to producible size of vacuum-forming process.

Combining all those principles, we develop the HP shell-cube structure (figure2). The whole structure resembles the shape of a cube while its surfaces are of HP shell (figure2a). The ribs, which are inevitable residual parts of vacuum forming process, are corrugated and innovatively configured so that they serve both as the joint between the modular components and the bracing system for the overall HP shell-cube structure (figure2c). It can be self-supported without the need of additional bracing system. The Surface-frame, which is a corrugated single curvature shell surface, achieves the force transfer between the roof and walls (figure 2b).

2.1.2. Hyperbolic paraboloid shell theory

The HP is a double curvature thin shell structure that is capable of having a large span with a great bearing capacity, mathematically expressed as:

$$2y = (x^2/c^2) - (z^2/d^2) \qquad (1)$$

where c and d are constants. Under a constant projected load p over the surface,

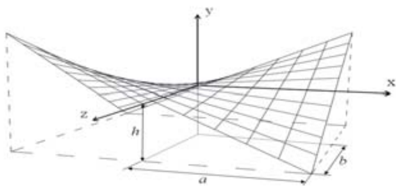

Figure 2 (left). A sample HP shell-cube structure, which is a hybrid of (a) HP shell; (b) Surface-frame; (c) Rib structure. Figure 3 (right). Hyperbolic paraboloid.

$$N_{xz} = -(ab/2h)p = -kp \tag{2}$$

it is customary to assume the axial forces are zero in HP, and the shear forces are:

In the case where $a = b$, the aspect ratio a/h plays a pivotal role in the load-carrying capacity of HP (figure 3).

2.2. FINITE ELEMENT SIMULATION

The FE modelling utilises the geometric models built in Rhinoceros by importing them into Patran which generates FE models which adopt eight-node shell. Uniform pressure loads are applied onto the weaker wall. Figure 4a shows the FE meshes and loads for a typical model in the current study. The FE analyses are performed in the general-purpose FE software Abaqus, which include both geometric and material nonlinearity.

The interactions between the surfaces of ribs and between the ribs and the bolts / washers are very difficult to model numerically. The simplified FE models assume that the whole structure is fully continuous as if it is fabricated as one piece in a fabrication mould. To offset the overestimation of the structural performance as a result of the above simplification, the thickness of the ribs is reduced by half which would lead to reduced bending stiffness of the ribs and hence conservatism for the overall structure.

The identification of the appropriate thickness and aspect ratio for the HP-Shell-Cube structure is aided by FE analyses. Table 1 compares the effect of thickness. All the models are of the same aspect ratio $a/h = 2.8$. The strengths of the models with 2 mm thickness are not satisfactory. The analysis for the model with 3 sidewalls does not proceed as the capacity of the model with corner top panel removed is under 200 Pa which is already unacceptable. When the thickness is increased from 2 mm to 3 mm, the capacities of the respective models all increase by a significant amount. All of them can resist a wind pressure of at least 1000 Pa.

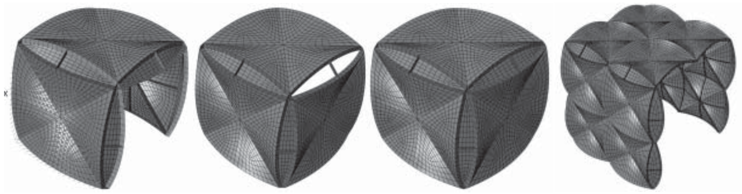

Figure 4. Sample mesh for a HP-Shell-Cube. (a) single module, 3 sidewall + roof (with entrance); (b) single module with corner top panel removed (ventilated); (c) single module, full model; (d) multiple modules, 3 sidewall + roof (with entrance).

The choice between single module and multiple module models is influenced by two competing factors: performance (load-carrying capacity) and cost. With the same overall dimensions and aspect ratio, multiple modules models give lower wind load resistance but they are cheaper than single module models because the size of moulds required for multiple modules is about one quarter. Given the same overall model size and modular component size, the model with lower aspect ratio a/h can resist a larger wind load. Table 2 summarises the load-carrying capacity for different configurations. The goal is to choose a cost-effective structure. While the load-carrying capacity of single module model with aspect ratio 1:4 and multiple modules model with aspect ratio of 1:2.8 are about the same, the multiple module option is cheaper.

The stress contours of two different configurations are presented in figure 5. The regions under almost zero stress are indicated in blue, while the regions under higher stresses are indicated in red and gray. For illustration purpose, any region having a stress above 5 MPa is indicated in gray. All the highly

Table 1. Wind load resistance for different thickness (aspect ratio a/h = 2.8)

Thickness PLA(mm)		Full model	Corner top panel removed (ventilated)	3 sidewall + roof (with Entrance)
2	Load (%)	32	14	-
	Load (Pa)	410	174	-
3	Load (%)	100	89	81
	Load (Pa)	1280	1135	1040

Table 2. Wind load resistance of different configurations (model size: 3m × 3m × 3m).

Configuration (aspect ratio *a/h*)	**Load resistance (Pa)**
Single Module (4)	470
Single Module (2.8)	1040
Multiple Module (2.8)	480

stressed regions are along the lines that connect modular components and surface frames. This common stress pattern suggests that the structural design details for the connections/joints are very important.

2.3. DIGITAL FABRICATION TESTING

The master 3D data generated by Rhinoceros is saved as STL format, and then pre-processed for CNC routing in Cut 3D (Vectric) CAM software for the route pass generation. Frogmill (Streamline Automation) CNC router is used for the subtractive rapid prototyping process (figure 6a).

Due to relatively low temperatures and pressures employed in vacuum forming, medium-density fibreboard (MDF) is selected for the mould prototype. It is economical and has fine homogeneous grains suitable for detailed shape. For mass production, more durable aluminium powder-filled epoxy or polyurethane mould is necessary (Gruenwald, 1998). It takes about 8 hours to complete the CNC routing process for 400 × 400 mm 1:5 scale moulds (Fig. 6b). As the mould making takes time, it is critical to reduce the types of mould. By mass-customisation, only 2 types of mould with minor variations of each, with and without corner pieces are fabricated.

2.4. VACUUM-FORMING TESTING

Vacuum forming has advantage in rapid mass-production of complex 3-D forms. It can deform a thin sheet of plastic to increase its stiffness instantly (figure 7). Vacuum forming is mainly used for making industrial products such as bathtubs, disposable cups and other packaging components. The shape of

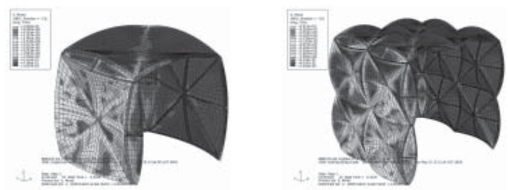

Figure 5. Stress contour (a) single module, a/h = 4 at wind load 470 Pa; (b) multiple modules, a/h = 2.8 at wind load 480 Pa.

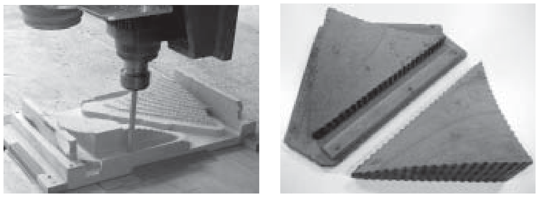

Figure 6. (a) CNC milling of the moulds; (b) Moulds for Vacuum-forming.

mould is restricted by technical constraints associated with vacuum forming process; for instance, at least 3 to 6 % outward taper all around the periphery is recommended for successful mass production (Gruenwald, 1998). Higher and deeper moulds also require thicker plastic sheets, which then result in an increased difficulty of removing the mould and trimming the periphery after moulding. Other thermo-forming methods, such as drape forming could also make 3-D form relatively easily, but it is not suitable for detailed mould, such as with corrugated periphery. Splay moulding could fabricate with much stronger materials, such as fibre-reinforced plastics, but it takes far longer period than vacuum forming.

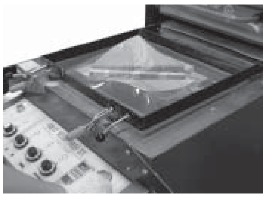

Figure 7. Vacuum forming process with MDF mould fabricated by CNC routing.

2.4.1. Selection of thermoplastics

Four types of plastics are tested for comparison: PC (polycarbonate), PS (polystyrene), PVC (polyvinyl chloride) and PLA (poly lactic acid, biodegradable plastic).

PC is stiff and seems ideal for architectural use. But it has difficulty in stretching to trace detailed moulds and also to trim the periphery after moulding. Of the four, PS is the most stretchable. Traceability to a complex mould is exceptional. However, it becomes too brittle after cooling down. Therefore it is not suitable when component strength is required to resist repeated bending and stretching action as is the case for a shell. PVC is the one most balanced between stiffness and flexibility. It follows shapes of mould tightly with relatively lower heating temperature. After cooling, it still maintains flexibility, thus it can be removed from moulds easily. PVC components can also resist frequent bending and stretching actions, and it is also easy to trim. PLA is a kind of biodegradable plastic made of biopolymer. It may degrade into soil above 60°C with certain humidity and microorganism. Its material property is in between PS and PVC, which has enough traceability for complex mould but becomes relatively brittle after thermoforming. For the above reasons, we select PVC as the initial material for structural testing to optimise the geometry and fabrication processes, while we target PLA for final prototypes, in prospect that the properties of PLA would be improved for external architectural use in near future.

2.4.2. Vacuum forming stretch testing

By vacuum forming process, materials are stretched and the thickness will be deflected. The higher the mould is, the thinner the sheet thickness becomes. We estimate the deflected thickness by using square grid lined sheets. After vacuum forming, the deformation of the square grid lines indicates how the sheet is stretched, both in direction and dimensions (figures 8a, b). The vertical surfaces stretch most up to 200%, which implies that the thickness become about a half. We identify the most critical stress concentration regions (those in red to grey colours) in the FE analysis stress contour (figures 5a, b), then to make sure that those points maintain the required thickness of 3mm.

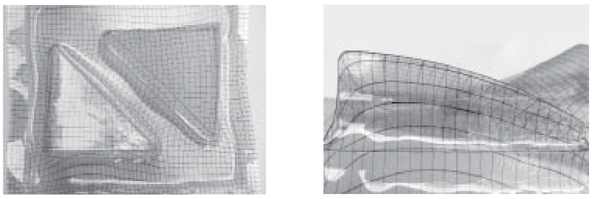

Figure 8. (a) Vacuum form stretch testing with 10 mm square grid sheet; (b) Vertical surfaces stretch up to 200 %, while its thickness becomes a half inversely.

2.5. ASSEMBLY TESTING

The bio-shell assembly process requires both structural continuity of HP shell components and quick assembly / disassembly. Clipping joints seem to be too weak to ensure the structural continuity, while gluing and welding connections are not suitable for dismantling purpose. Mechanical joints, such as bolting, would be the most appropriate to ensure the both. The drawback is relatively longer time required for jointing. The corrugated surface joints are applied all along component peripheries, which increase the structural continuity by frictions while minimizing bolting to where critically necessary. The central circular joints, which tighten up 8 triangular HP-Shell components also play critical role to enhance structural continuity with just 1 bolt (figure 9b). Those vacuum formed components are identical thus easily stacked compactly for transportation (figure 9a).

3. Conclusion

Table 3 summarises comparisons between the bio-shell and 3 other lightweight shelter types. The tent has the lightest weight / volume (kg/m^3) ratio, which

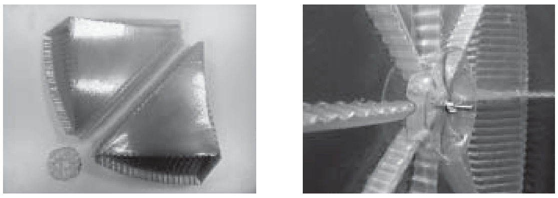

Figure 9. (a) Stacked components for one wall panel. (b) Corrugated surface-joint and Centre joint.

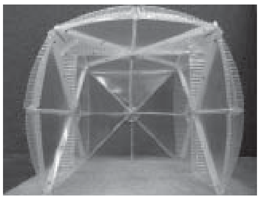

Figure 10 (left). Completed 1:5 structural model.
Figure 11 (right). Multiple module application as refugee shelter. Organic heat insulation (straw, etc.) is to be sandwiched between double layers of vacuum-formed components. Sand-bags on site will weigh down foundation thus no anchoring required.

is approximately 1/100 of the container, while its space efficiency and adaptability are low. On the other hand, the container has merit on space efficiency and quick assembly by prefabrication. The dome has second lowest weight / volume ratio; however it takes 160–200 man-hours for on-site assembly.

The bio-shell prototype provides not only lower weight / volume ratio close to the dome but also adaptability by modular design and efficient space usage by cube like shape. Its cost / area ratio is not particularly further effective compared to the container and the dome, which are already low-cost shelters. However, it can provide higher transportation efficiency by stacking identical components compactly. In addition, it can be biodegraded after its use without burdening the environment.

While our current investigation mainly focuses on structural aspect, it needs to be also weatherproofed to be fully functional shelter. The J-shape joinery as a part of vacuum-formed components may integrate gutter into structural bracing without additional parts. For thermal insulation, double-layered roof/ wall with infill may reduce heat gains (figure 11) or to control translucency of PLA with colour pigment. Further research is needed to optimise PLA for structural / external use, to control conditions and durations of biodegrading process and to minimise potential structural creeping of the plastic. But this requires further collaboration with material scientists.

(US provisional patent application under serial no. 61/299,502.)

TABLE 3. Lightweight shelters comparison.

Shelter Type	Weight/ Volume (kg/m^3)	Cost/ Area (US$/ m^2)	Man-hours (on-site)	Trans-portef-fici-ency	Adapta-bility	Space effici-ency	Others
Bio-Shell [(a)] (PLA, 3mm)	**6.29** [(e)]	**641**	16	High	High	High	Bio-degra-dable
Tent [(b)] (Fig. 1a)	1.15 [(e)]	51.3	2-4	High	Low	Low	Short term use
Con-tainer [(c)] (Fig. 1b)	102.4	627	Nil	Middle	Middle	High	Prefab-ricated
Dome [(d)] (Fig. 1c)	6.92 [(e)]	750	160-200	Low	High	Middle	Insulated

(a) Estimated from 1:5 scaled model. Subject to be verified with 1:1 prototype; (b) Northstar X4, The Coleman Company Inc.; (c) 8ft Long Container, S. Jones Container Services Ltd.; (d) Dome House Type 7700, International Dome house Co. Ltd.; (e) Weight does not include floor systems.

Acknowledgements

Our sincere gratitude to Professor Somsak Swaddiwudhipong for advising his expertise on HP-Shell theory, and Assistant Professor QIAN Xudong for advising the FE simulations, both from Department of Civil Engineering, National University of Singapore. GreenGood Eco-Tech Company Limited in Hong Kong, provided PLA samples. Research Assistant Jonathan Li for dedicated commitment to CAD-CAM and vacuum forming processes, and Vishalini Rajanran for development of the bio-shell project as refugee shelter for her thesis.

References

Gruenwald, P. E.: 1998, *Thermoforming: a plastics processing guide*, Technomic Publishing.
The Economist: 2007, Material World, 18.10.2007.