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DESIGN AND FABRICATION OF ORIGAMI DOME

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Introduction

Origami is representative of a traditional Japanese craft, and is a promising technique for frontier fields (e.g., spatial structures [1], medical stents [2]). The improvement in portability achieved by folding is a great advantage for these applications. In addition, in the architectural field, the folded plate structure has been applied to many long-span roofs, although they are not deployable in common. Graduate school students in the architectural design class at Mukogawa Women's University designed and fabricated a portable and deployable dome with a folded plate structure, shown in Fig. 1, as an assignment in the first semester of 2015. Students considered the aspects of aesthetics, structure, thermal environment, and construction method. In this paper, the following three factors are summarized: design and fabrication process, thermal performance, and structural performance of the dome.

(a) Exterior view (b) Interior view (b) Night view in winter

Fig. 1: Final product of the origami dome

Design process

First, the students set the architectural usage type as a temporary facility used for a private space, or a resting place at events. Next, students studied the form and the type of folding method by creating various forms with paper and cardboard, as shown in Fig. 2. Moreover, they understood that the diamond pattern known as the "Yoshimura Pattern [3]" was appropriate to fold a plate of that thickness. Following this, a mock-up model with a simple vault form was constructed using polypropylene cardboard, as shown in Fig 3. This structure required rigid frames around the open edges for stability. Finally, the form of a dome, which does not have any open edges, was adopted. The size of dome was determined taking the wind load, floor area, and workability into consideration. Polypropylene cardboard was selected as the main material of the dome structure for the following reasons: it is lightweight for its strength; it has high heat insulation properties (thermal conductivity of 0.061 W/mK); its capability of being made hinges by ruled line fabrication using a hot wire method, without the requirement for additional metal parts.

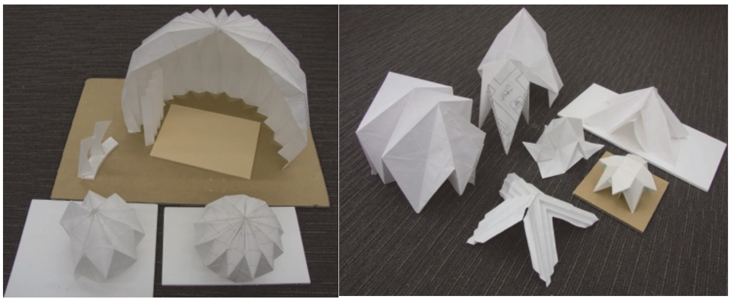
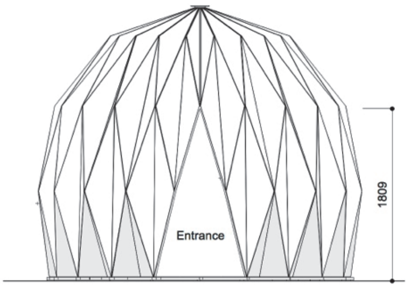


Fig. 2: Intermediate paper design models

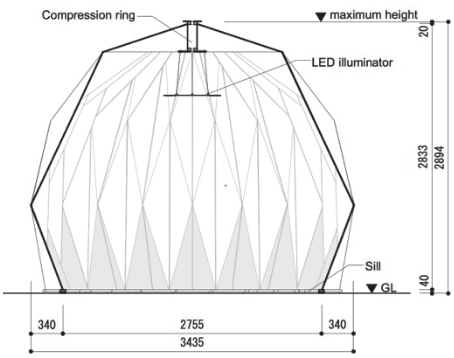
Fig. 3: Initial mock-up model

The final product

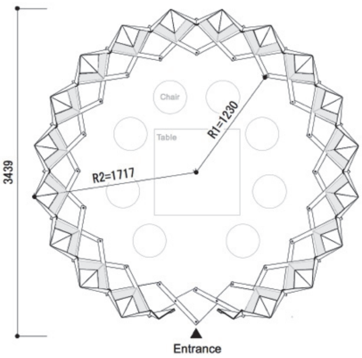
The drawings and other basic information of the final product of the origami dome designed and fabricated by the students are shown in Fig. 4. The details of the joints used in this structure are shown in Figs. 5, 6, 7 and 8.



(a) Elevation



(b) Section



(c) Plan

Floor area: 6.8 m^2, Weight: 25.7 kg
Material: Main part of dome: Polypropylene cardboard (4mm in thickness and 0.6 kg/m^2 in density)
Bottom of dome: Polycarbonate cardboard (4mm in thickness and 1.0 kg/m^2 in density)
Sill: Cedar

Fig. 4: Drawings and basic information of the origami dome

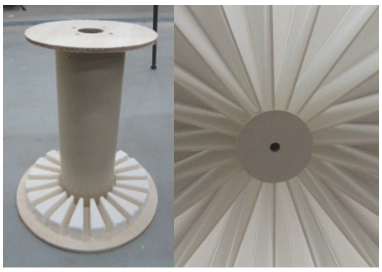


Fig. 5: Compression ring

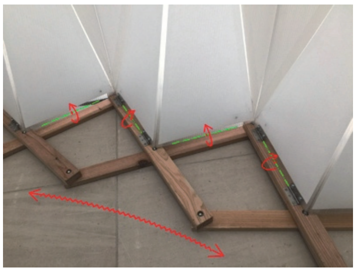


Fig. 6: Joint of folded plate and sill

Fig. 7: Reinforcement at vertex

Fig. 8: Joint by zippers

The ridges and valleys of the upper end of the folded plate are concentrated at the compression ring, which is comprised of a paper tube and inserted into the radial slits (Fig. 5). The bottom edge of the dome is connected by metal hinges to the sill, which has a structure with scissor-like-element (Fig. 6). This mechanism enables the dome to deploy and fold uniformly in linkage with the movement of scissors. The dome is fixed to the ground by weights on the sill or pegs. Four ridge lines and two valley lines concentrate at each vertex. This point contains a hole, which was sealed and reinforced with adhesive tape and four sets of bolts and nuts (Fig. 7). The dome is divided into two units, connected by zippers (Fig. 8).

Deployment process

When not in use, the dome is divided into three parts: a compression ring and two units of folded plate. The deployment process of the dome is shown in Fig. 9. The dome is manually deployed and folded in approximately four minutes by seven female students.

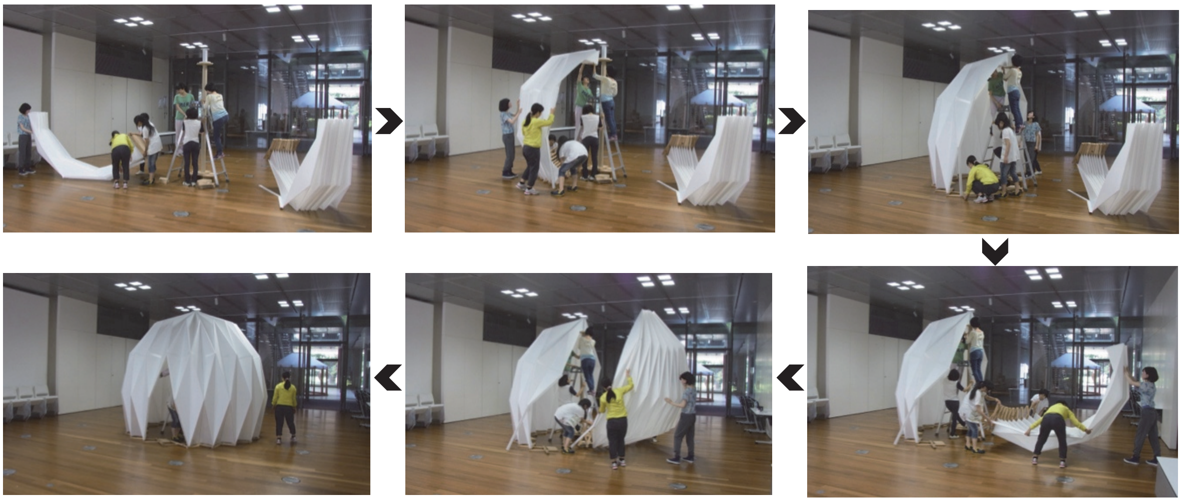


Fig. 9: Deployment process of the origami dome

Thermal performance

A simple experiment with internal heat generation (1200W) was conducted at the entrance hall in the architectural studio, in order to understand the thermal performance of the dome in winter. The heat losses through the walls and floor, and by air exchange, were estimated at the steady state of the measured internal air temperature. When the openings were not closed, the internal temperature of the lower part closely approximated that of the outside air (Fig.10 left), and 45% of the heat loss was caused by the air exchange (Fig.10 right). In the case of the closed opening, the internal temperature could be higher, and the heat loss by the air exchange was reduced to 2%.

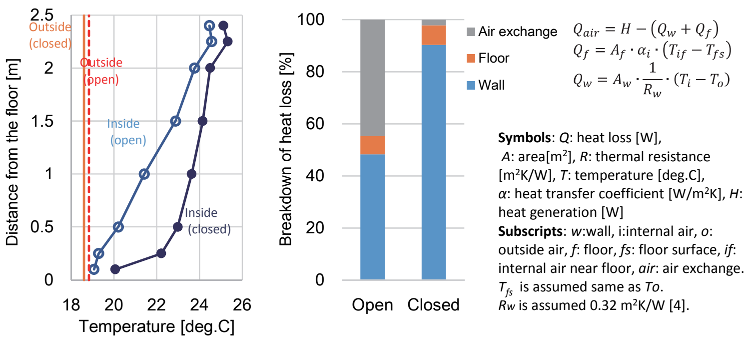
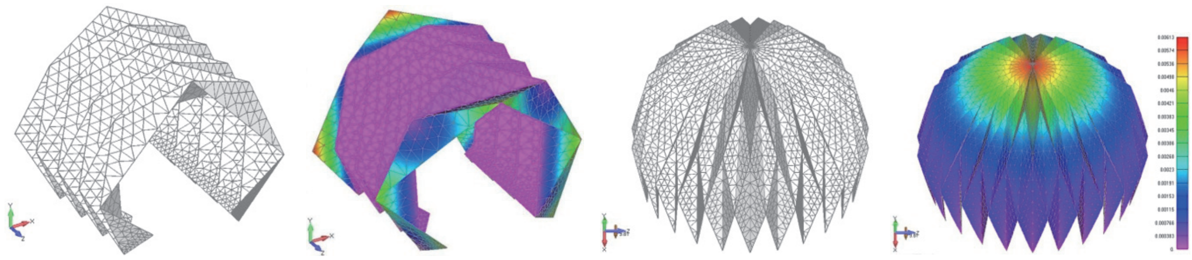


Fig. 10: Internal vertical temperature distribution (left) and breakdown of heat loss (right)

The majority of the heat loss was through the polypropylene cardboard. However, there is a possibility that the thermal resistance of the cardboard was underestimated because it seems that the heat loss of the air exchange is slightly low. An improvement in the thermal performance of the cardboard is required for better thermal conditions.

Structural analysis

Structural analyses are conducted for two types of origami structures, as shown in Fig. 11. The first one is a vault form structure, as shown in Fig. 11(a), which is representative of the initial mock-up model in Fig. 3. The second is a dome form structure, as shown in Fig. 11(c), which is representative of the final product shown in Fig. 4. As shown in Fig. 11(b), large displacements occur in the regions around the open edges when subjected to gravitational loading. This result suggests that rigid frames in the span direction are necessary to stabilize the vault form structure. In contrast, as shown in Fig. 11(d), the dome model has a maximum displacement of approximately 6 mm, which is small, when subjected to gravitational loading. These analysis results correspond well to the observation during the fabrication of the origami dome.



(a) Vault model (b) Analysis result (c) Dome model (d) Analysis result

Fig. 11: Analysis models and analysis for gravitational loading

Conclusions

A portable and deployable dome with a folded plate structure, such as in origami, was designed and fabricated in architectural design class. This dome has excellent portability and workability in construction. By measuring the heat loss, the thermal performances were estimated. It was further confirmed by structural analyses that the origami dome is more stable than the vault form structure.

References

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