Development of a Foldable Mobile Shelter System

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Introduction

During our current research project *'Design and Analysis of Kinetic Structures in Architecture'* we have found that designing deployable structures, and more specifically, scissor structures requires a great understanding of the geometric conditions which determine wether or not the designed structure will actually be deployable. Furthermore, some structures that do comply with these geometric boundary conditions need an additional energy input to unfold from their compacted state to their completely deployed configuration. These so called 'snap-through' (or bi-stable) structures require this energy input to overcome the geometric incompatibilities that are typical of their specific morphology. That is why, in our effort to supply the designer of kinetic architecture with an easy-to-use design tool, we initially focus on kinetic structures which are characterized by stress-free deployment, otherwise called foldable structures [Langbecker 1999]. Generally speaking this means that during deployment they behave more or less like mechanisms so, once erected into their final configuration, additional bracing is needed to guarantee structural stability.

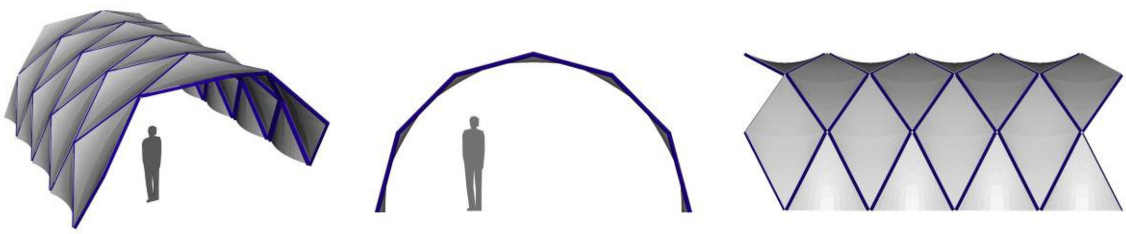
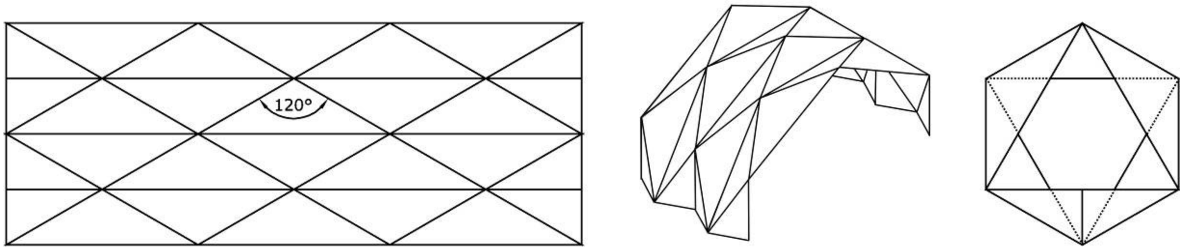


Figure 1. Foldable mobile shelter consisting of bars, connectors and cladding material

The mobile shelter system proposed in this paper serves as a case study for our research project: straight bars connected by purpose-built joints make up the foldable structure of which the geometry and kinematic behaviour is based upon that of foldable 2D-panel structures. The latter consist of a series of triangular panels, interconnected at their edges by continuous joints [Gantes 2001]. By discarding the triangular panels, while at the same time materializing their edges into bars and their end nodes into kinematic joints, we obtain a foldable bar structure with an identical deployment behaviour. Once deployed, the structure takes the shape of a barrel vault. By integrating membrane components into the load-bearing structure before transport to the site, the system becomes a ready-to-deploy space enclosure, well-suited as a temporary shelter.

Folding pattern and geometry

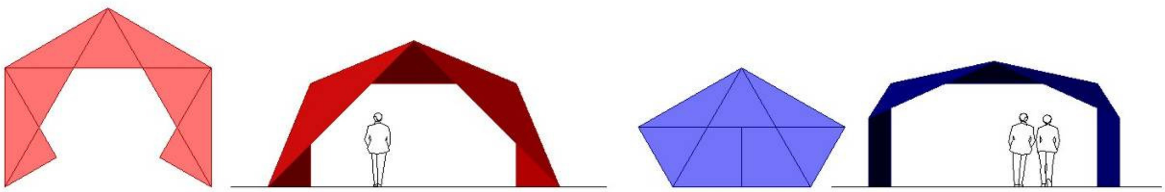
The geometry for the proposed system is derived from a simple folding pattern shown in Fig. 2. The fold lines of the pattern intersect and form triangles with an apex angle β of 120°. Other apex angles are possible, as long as they comply with the foldability condition $\pi/2 \leq \beta < \pi$. Figure 2 shows the wireframe model consisting of triangles with an apex angle of 120° in three consecutive deployment stages.



(a) (b) (c)

Figure 2. Three stages of deployment for a basic regular foldable structure consisting of triangular 2D-panels: (a) folded flat, (b) erected position and (c) fully compacted for transport

We can easily change the geometry by increasing or decreasing the number of panels in the span, leaving the apex angle identical throughout the structure. Such a 'regular structure' is depicted in Fig. 3a. But not all triangles have to be identical: by changing the apex angle of only the outer most modules to $\pi/2$, we obtain a structure that looks somewhat different. It is simply called a 'right-angled structure' (Fig. 3b). In its fully compacted form a right-angled structure demonstrates increased compactness compared to the equivalent regular structure shown in Fig. 3a, while in its fully erected position the side panels are perfectly vertical. This leads to increased inner space and makes it easier to incorporate an entrance door. As a downside, comparing the regular and the right-angled structure side by side, one can imagine the latter being structurally less efficient. This corresponds with what we can gather from our initial models.

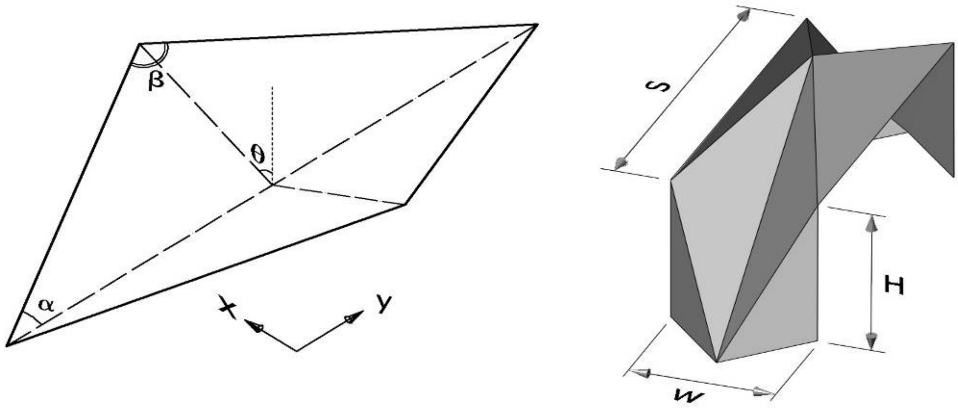


(a) (b)

Figure 3. For n=4: side view of compacted and unfolded configuration of (a) a regular and (b) a right-angled structure

Parametrization

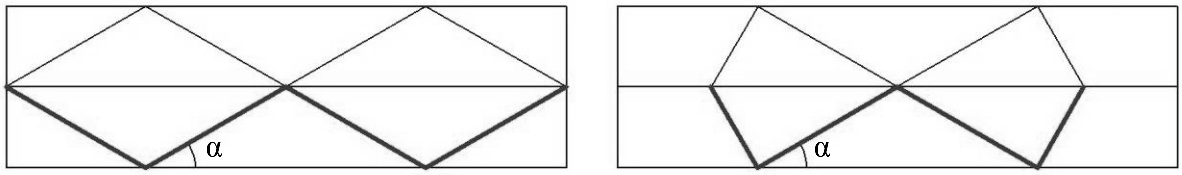
In order to design these structures, a complete parametrization of a single module (Fig. 4a) and the structure as a whole (Fig. 4b) is needed. This provides us with a description of all relevant design parameters such as the apex angle (β), bar length (L), the span (S), height (H), width (W) of the structure and the number of bars (n) in one section of the span. The single most important parameter is the deployment angle θ, measured between a triangular face and the vertical axis, as shown in Fig. 4a. Since θ determines to what degree a single module is opened or closed and because every module in the structure is identical, θ solely determines the deployment of the structure, with values ranging from $\pi/2$ (folded flat configuration, Fig. 2a) to 0 (fully compacted configuration, Fig. 2c). The value for θ we are interested in is the one that corresponds with the fully erected position, i.e. a semi-circular shape for the regular structure. For the right-angled structure we are looking for the configuration whereby the side walls are standing perfectly vertical.



(a) **(b)**

Figure 4. Relevant design parameters used in the parametrization of (a) a single module and (b) the whole structure

By using trigonometry we can derive the relationship between the apex angle, the number of bars and the deployment angle θ [De Temmerman 2005]. Note that in formulas (i) and (ii) all parameters are independent of the bar length. The parameter 'n' stands for the number of bars in the span (this number matches the number of edges of the triangles in the original folding pattern). These are represented by bold lines in Fig. 5.



(a) **(b)**

Figure 5. Folding pattern for the smallest possible structure showing the number of bars in the span: n=4 for (a) a regular structure and (b) a right-angled structure

We can write the formulas for calculating the deployment angle θ, for $n \geq 4$; $0 \leq \alpha \leq \pi/4$; $0 \leq \theta \leq \pi/2$:

(i) For a regular structure (Figs 5a and 6a):

$$n \text{ ArcTan } [\text{Tan}(\alpha) \text{ Cos}(\theta)] = \pi/2$$

(ii) For a right-angled structure (Figs 5b and 6b):

$$2 \text{ ArcTan}[\text{Cos}(\theta) \text{ Cot}(\alpha)] + (n-2) \text{ ArcTan}[\text{Cos}(\theta)\text{Tan}(\alpha)] = \pi/2$$

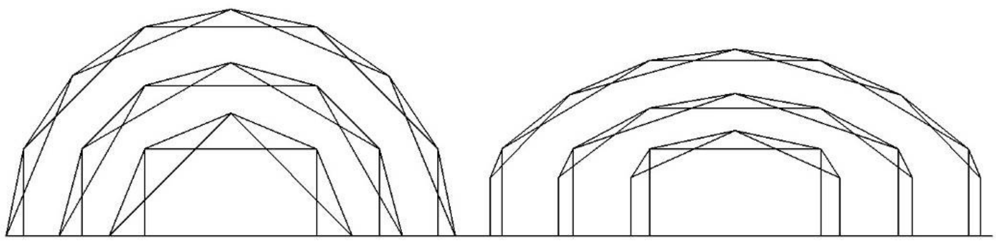


Figure 6. For n= 4, n=6 and n=8: side view of (a) regular structures and (b) right-angled structures, all with the same apex angle β =120°

Modularity

When we look at the smallest structures in Fig. 6 (n=4) we can see that they share a characteristic that sets them apart form the other: they have identical edges in the vertical plane. This implies that they can be linked together along that edge to form a chain of structures, i.e. a barrrel vault (Fig. 7). This way, a structure emerges posessing all advantages of the right-angled structure without neglecting the overall structural performance.

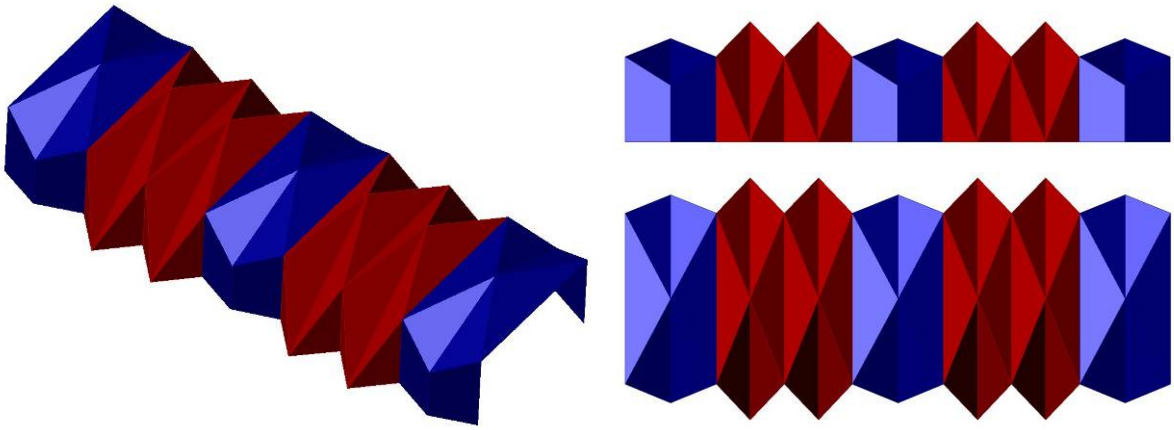


Figure 7. When n=4, regular structures and right-angled structures can easily be linked together

From wireframe model to foldable shelter

Once the gobal geometry of the structure is outlined in a zero-thickness wireframe model, elements with discrete dimensions are introduced: the edges of the initial triangular panels are materialized into bars, connected by a kinematic joint as shown in Fig. 8. This purpose-built connector is a joint which is constructed in such a way that the original kinematics of the system are preserved and movement during deployment is not hindered by the thickness of the elements. For the regular structure, all connectors are identical: this is connector A shown in Figure 8. But for the right-angled structure the altered apex angle requires additional connectors B and C. Figure 9 shows where they are applied in the structure. Note that connector C consists of only 4 hinged parts as opposed to 6 for connector A and B.

Figure 8. Five stages in the deployment of connector A

Off course, for the system to be employable as a fully-fledged architectural structure, a suitable cover to protect from bad weather conditions has to be incorporated, as shown in Fig. 1. The foldable bar system can either accept stiff panels or a supple membrane as cladding material, each leading to particular detailing issues which will have to be addressed at a later stage. When a membrane is chosen with a very simple cutting pattern, we have shown that an acceptable level of pretension can be introduced by unfolding the structure to its final position [Mollaert 2005].

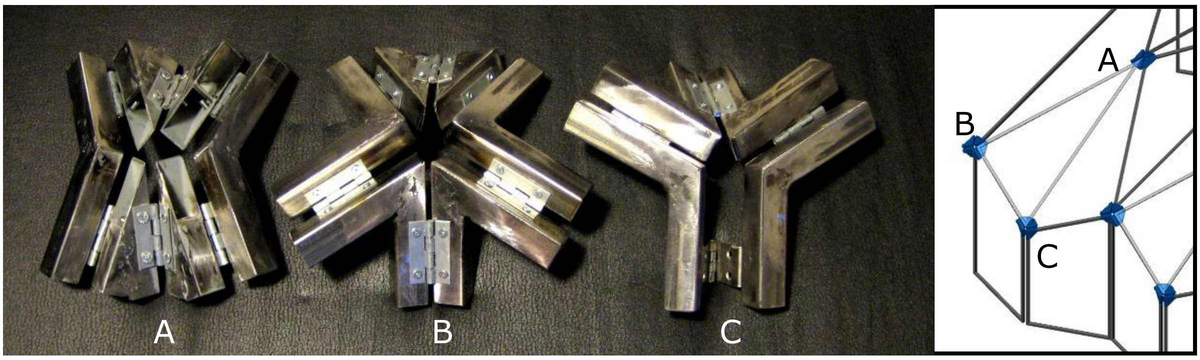


Figure 9. Full scale models of hinged connector A, B and C, made from welded steel

In order to make sure that the resulting kinematic behaviour is indeed the desired one a 1/5 scale model is constructed out of polyacetal connectors (as shown in Fig. 10) and aluminium bars, in which a supple membrane can be incorporated.

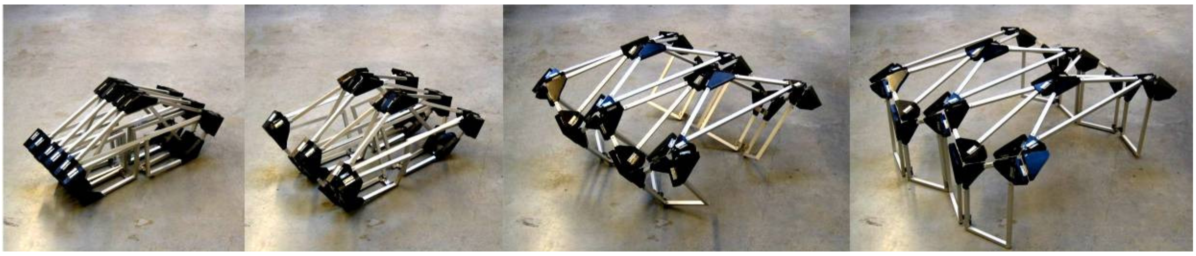


Figure 10. Four stages of deployment of a 1/5 scale model of a right-angled structure with 4 bars in the span (n=4) and an apex angle of 120° (β=120°)

Next step in the design process is to perform a structure analysis on a FEM-model to allow for a preliminary dimensioning of the bars and joints. Also we'll investigate the possibilty of strategically incorporating scissor units to help providing a certain level of pretension in the membrane in the fully deployed configuration, thus enhancing structural performance [Mollaert 2005].

Acknowledgments

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