Design of Scissor Structures for Retractable Roofs

T. Van Mele, M. Mollaert, N. De Temmerman,
L. De Laet

Vrije Universiteit Brussel
Pleinlaan 2, 1050 Brussel, Belgium
tvmele@vub.ac.be

KEYWORDS

Kinetic architecture, Retractable roofs, Scissor structures

PAPER

1. Retractable roofs

In the last few decades retractable roofs have become a popular way to provide flexibility to sports and entertainment facilities, as they can be opened or closed in response to changing environmental or programmatic conditions [Ishii 1999].

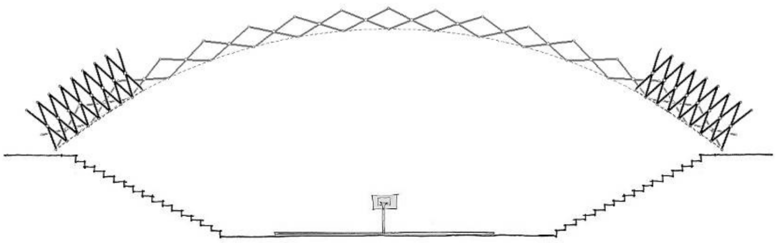

Figure 1: scissor hinged systems can be transformed from a compact configuration to a larger pre-determined form. They provide an interesting solution for the load-bearing structure of a retractable roof.

Scissor structures are a special type of bar structures that present an interesting solution for the load-bearing component of these retractable roofs; their inherent kinetic capabilities allow them to be transformed from a compact configuration to a larger pre-determined form. Scissor structures can be combined with plates or structural membranes to form a fully-fledged roofing solution [Block Van Mele 2003].
This paper presents a specific approach to the analysis of the behaviour of scissor structures and identifies specific configurations in their deployment process that are of particular interest from a designer's point of view. The results of the analysis are integrated in a research and design tool.

2. Scissor structures

All scissor structures arise from the concatenation of scissor-like elements (SLE's). An SLE consists of 2 bars connected by an intermediate hinge or pivot point, which allows the rotation of the bars around a single axis.

SLE's can be divided into three categories [De Temmerman 2002]: translational, polar and angulated (or hoberman) units (Figure 2). Although the geometry of these SLE's can be highly irregular, it can be stated that in a translational unit the lines that connect the top and bottom hinges always remain parallel throughout the deployment process, whereas in polar and in hoberman units these imaginary lines always intersect.

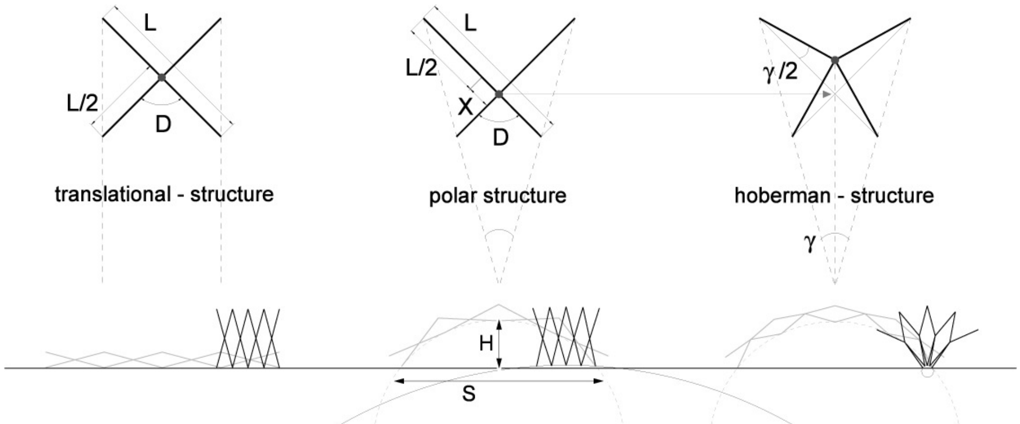

Figure 2: (top) scissor units can be divided into three basic categories: translational, polar, hoberman. (bottom) typical two-dimensional configurations with respectively translational, polar and hoberman units.

These units can be put together into almost every imaginable two or three-dimensional configuration but, in general, we could say that translational units are used to create structures with arbitrary curvature (and therefore also to create structures without curvature), that polar units can be used to create structures with circular curvature, and that hoberman units are especially suited for structures with radial expansion; both translational and polar structures expand linearly.
Of course, as all these structures are supposed to be transformable, they need to comply with a specific set of geometrical conditions that guarantee them to be either foldable or deployable.

3. Foldable vs. deployable

The foldability equation was derived by Escrig and guarantees a stress free condition during deployment for two-dimensional structures [Langbecker 1999]. The equation uses a purely geometrical approach, and ignores the effect of joint size. Therefore, from a structural point of view, the equation imposes no limitations on member sizes and materials and hence does not guarantee that stresses in joints and members will be kept to an acceptable level during the deployment process. It should also be noted that the equation was derived for units composed of straight bars and therefore does not apply to units composed of angulated bars such as hoberman units.
For three-dimensional configurations, two different design philosophies seem to exist. The first, and most general method, guarantees that the structure is stress free only in the compact and deployed configuration. In these structures a snap through usually takes place during the deployment process. They comply with the foldability equation and have been described extensively by Gantes [1991]. In the second methodology, the geometry and configuration of the structure are such that the structure remains stress free throughout the deployment process. This condition restricts the available geometric configurations that can be achieved and has been formulated by Langbecker [1999].
Although these three equations provide sufficient boundary conditions to make working scissor structures, doing so still demands a great deal of insight in their behaviour. This paper, therefore, proposes a complementary approach that incorporates and respects these rules but also provides designers with the necessary insights and enables them to make educated choices.

4. Polar scissor structures as retractable arches with variable curvature

Consider, as an example, a sports facility with a grand stand that needs to be fitted with a retractable roof.

We will use polar scissor units to form a parallel series of two-dimensional retractable arches. Modules of structural membranes can then be fixed in between to create a closed surface [Block Van Mele 2003]. A two-dimensional scissor structure with polar units produces curvature because of the specific position of its intermediate hinges, which is eccentric in relation to the middle of the bars. Such a structure is nearly flat in its compact, folded configuration and becomes more and more curved as it unfolds.

5. Geometrical analysis of the deployment process of a polar scissor structure

We can determine the relations between the geometry of the global structure, the geometry of a single unit and the number of units in the global structure.

A single polar unit can be described by the length of its bars (L) and by the eccentricity of its pivot point (X); 'eccentricity' is defined as the distance measured from the middle of the bars to the actual position of the intermediate hinge. The angle between the bars of a unit is called the deployment angle (D). The global structure of a polar scissor hinged system is completely determined by its main dimensions, span (S) and height (H).

$$\mathrm{S} = \frac{1}{2\sqrt{2}}\left(\sqrt{\frac{(L-2X)^2\,(L^2+4X^2+(L^2-4X^2)\cos(\alpha))}{X^2}}\ \sin\left(U\sin^{-1}\left(\frac{2\sqrt{2}\,(L-2X)\sin(\frac{\alpha}{2})}{\sqrt{\frac{(L-2X)^2(L^2+4X^2+(L^2-4X^2)\cos(\alpha))}{X^2}}}\right)\right)\right)$$

$$\mathrm{H} = -\frac{1}{4\sqrt{2}}\left(\sqrt{\frac{(L-2X)^2\,(L^2+4X^2+(L^2-4X^2)\cos(\alpha))}{X^2}}\ \left(\cos\left(U\sin^{-1}\left(\frac{2\sqrt{2}\,(L-2X)\sin(\frac{\alpha}{2})}{\sqrt{\frac{(L-2X)^2(L^2+4X^2+(L^2-4X^2)\cos(\alpha))}{X^2}}}\right)\right)-1\right)\right)$$

Figure 3: Span and Height as a function of the design parameters (X, L, U) and the kinematical parameter (D)

'X, L and U' are considered design parameters: "different values define different structures". 'D' is the kinematical parameter: "different values define different configurations of the same structure". Therefore, varying D takes a specific structure - defined by a set of design parameters - through its deployment process.

Through this mathematical approach we can plot and analyze the kinematical behaviour of polar structures in a graph as a function of the deployment angle, identify categories of structures with similar kinematical properties, and relate the architectural qualities of polar structures to the design parameters.

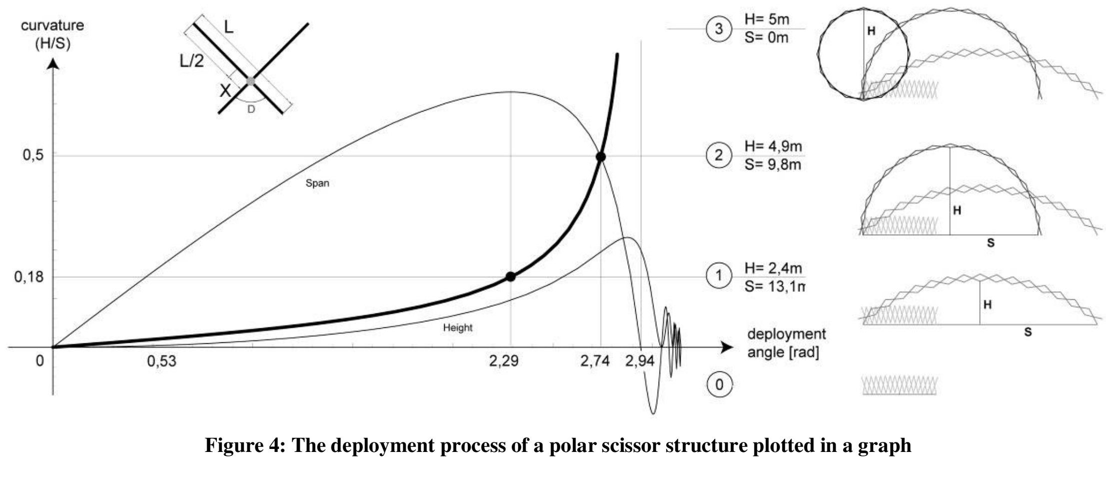

Figure 4: The deployment process of a polar scissor structure plotted in a graph

On the graph we find the evolution of span and height, and of the ratio of height to span. We will call this ratio the shape of the structure. Furthermore, a number of special stages in the deployment process are marked by a series of vertical lines.
Stage 0 (D= 0.53rad) depicts the compact folded configuration of the structure. Notice that we do not consider D= 0rad to be the most compact configuration. This is because of the actual dimensions of the scissors, the fact that the cladding needs a sufficient amount of space to be fitted, and because we want to preserve a minimal covered surface (for example, over the grandstands). At stage 1 (D= 2.29rad) the structure is at its maximum span. Notice the importance of this configuration as it defines the length of the structures bounding box.
At stage 2 (D= 2.74rad) the span of the global structure is exactly twice its height; the structure forms a half circle. Stage 3 (D= 2.94rad) is where the structure forms a full circle. Notice that all configurations past this point have overlapping elements and therefore would not be feasible in an actual application.
All scissor structures with polar units have a similar deployment process with stages 1, 2 and 3 as their characteristics. The shape of the structures at these stages and the angles at which they occur depend on the specific combination of the design parameters.

6. Influence of scale, polarity and the number of units

Obviously, structures of different scale but with exactly the same geometrical proportions have exactly the same deployment process. Hence different structures can be compared by their shape-curves, regardless their actual dimensions or measurements.

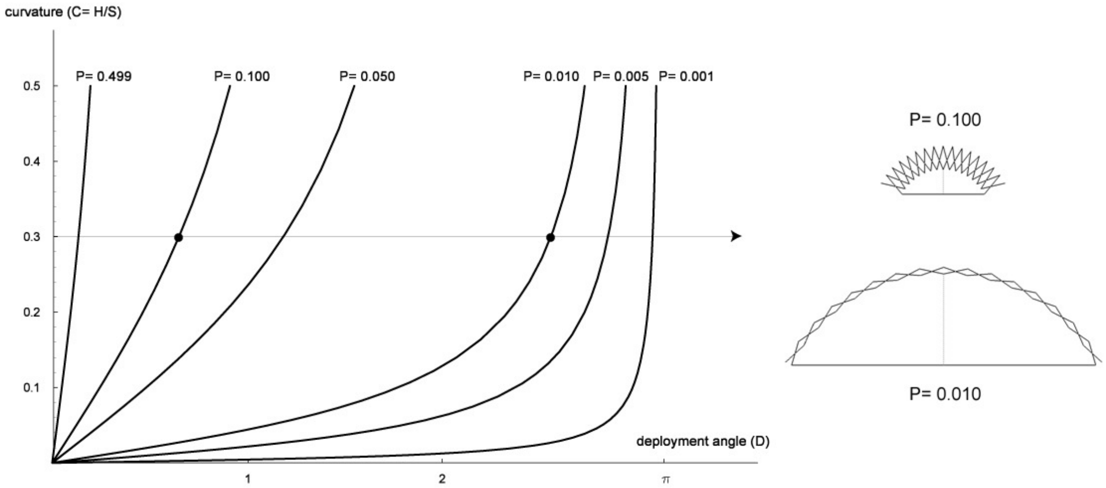

Figure 5: Different structures can be compared by their shape-curves

If we define polarity as ‘the ratio of the eccentricity of the pivot points to the length of the bars’ (P= X/L), then ‘P’ represents the potential of a unit to produce curvature.
For higher values of polarity the shape-curves shift to the left and become much steeper. Such structures curl up much faster and therefore reach their maximum span at much lower values of D. Hence, they generate a shorter span for a given bar length and number of units, and are therefore less performing in terms of deployability.
The example in figure 5 shows two structures with the same number of units and the same length of bars. Both structures produce an underlying space of the same shape but the span of the structure with P= 0.1 is much smaller. As the addition of units would alter the shape of the structure, a larger span can only be obtained by longer bars.

7. A research tool for geometrical design

The structure of the tool is based on the process of designing a scissor structure and has three different stages.
First the boundary conditions for the global structure have to be set. This means that the designer has to choose the desired curvature (or shape) of the structure in a specific state of service. This state of service corresponds with an angle of deployment (D_{design}) that lies between the chosen minimum and maximum values of D. In most cases $D_{design} = D_{max}$ because D_{max} represents the roof in its completely unfolded (closed) configuration.
A graph then depicts the different solutions for these boundary conditions as a function of the number of units. Solutions with lesser units have a higher value for polarity and longer bars.
During the final stage the deployment process of a specific solution is evaluated. Based on this evaluation the entire process is either repeated, if the characteristic configurations of the structure do not suit the specific needs of the project, or finalised by the determination of the actual dimensions of the scissors corresponding to the scale of the project.
As all parameters can be changed interactively, using this tool should improve the understanding of the behaviour of scissor structures in general.

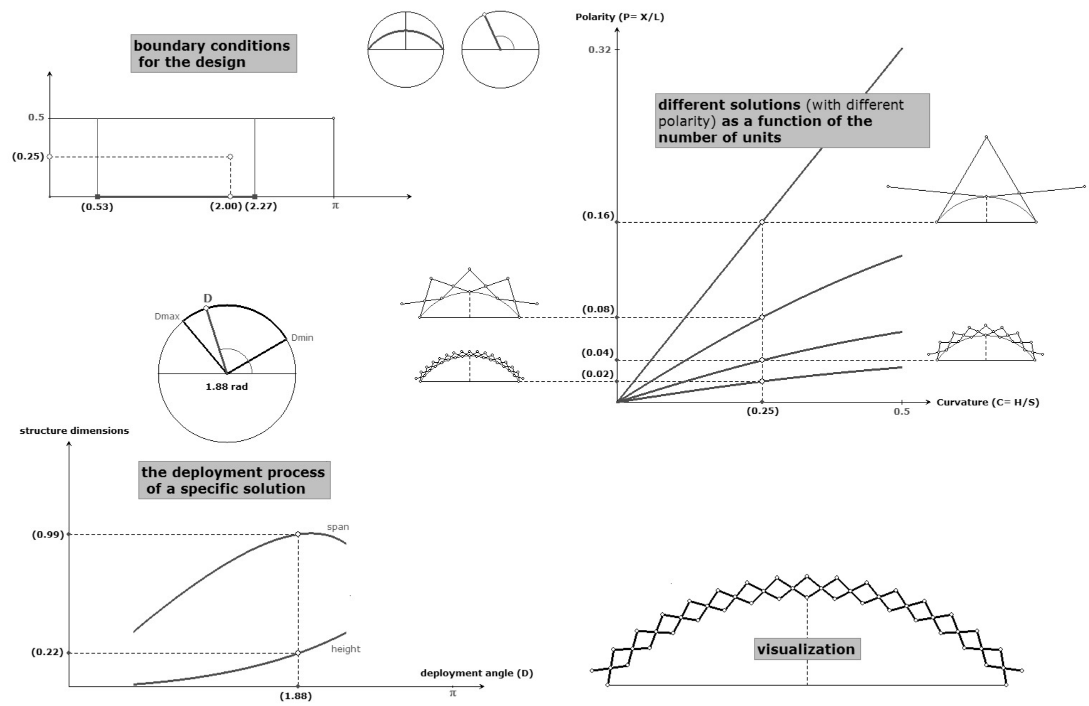

Figure 6: Screenshot of the graphical interface of the research tool

The geometrical analysis of the deployment process, the analysis of the influence of the design parameters and the interactive research tools will be available online at the time of the conference for polar structures as well as for translational and hoberman structures.

REFERENCES

Ishii, K., 2000, Retractable Roof Structures, Witt Press, Southampton, Boston.

Langbecker T., 1999, Kinematical Analysis of Deployable Scissor Structures, International Journal of Space Structures Vol. 14 nr. 1.

De Temmerman, N., 2002, Analyse van schaarstructuren ifv een ontwerpopdracht, Masters Thesis, Department of Architecture Vrije Universiteit Brussel, Brussels.

Gantes C., 1991, A Design Methodology for Deployable Structures, PhD Thesis, Department of Civil Engineering MIT, Massachusetts.

Block, P., Van Mele, T., 2003, Scissor Hinged Deployable Membrane Structures Tensioned by Pleated Pneumatic Artificial Muscles, Masters Thesis, Department of Architecture Vrije Universiteit Brussel, Brussels.