Reciprocal systems based on planar elements: morphology and design explorations

Conference Paper · September 2013

2 authors:

Olivier Baverel
École des Ponts ParisTech

Alberto Pugnale
University of Melbourne

Reciprocal systems based on planar elements: morphology and design explorations

Olivier Baverel[1], **Alberto Pugnale**[2]

[1] Université Paris-Est, UR Navier, Ecole des Ponts Paris Tech, 77455 Marne-La-Vallée Cedex 2, France, *baverel@lami.enpc.fr*
Ecole Nationale Supérieure d'architecture de Grenoble, Grenoble, France
[2] Lecturer, Faculty of Architecture, Building and Planning, The University of Melbourne, 3010 Parkville, VIC, Australia, *alberto.pugnale@unimelb.edu.au*

Summary: The concept of transferring forces in a reciprocal way has always been related to the use of elongated timber elements. However, planar components can also be considered - circular tiles, squares, triangles and more articulated or irregular geometries are all valid alternatives. This paper proposes an initial study on reciprocal systems based on planar elements in order to guide further morphological research activities. It also presents some prototypes developed by the students of the École des Ponts in Paris during two workshops run in March 2012 and 2013.

Keywords: *reciprocal structures, Reciprocal Frames, Nexorades, timber construction, design workshop*

1. INTRODUCTION

The principle of reciprocity is based on the use of load bearing elements that, supporting one another along their span and never at the extremities, compose a spatial configuration without any clear structural hierarchy [1]. From the conceptual point of view, the development of a reciprocal structure requires: (1) the presence of at least two elements allowing the generation of a certain forced interaction; (2) that each element of the composition must support and be supported by another one; (3) that every supported element must meet its support along the span and never in the vertices (in order to avoid the generation of a space grid with pin-joints).

Such a system has been used worldwide since ancient times. Throughout history, reciprocal systems have been mainly developed with elongated elements. In Europe, the concept of spanning distances longer than the length of the available timber beams was the key reason for the use of such structures, which were therefore called 'short-beams'. In Orient and especially in China, the use of interwoven strips of bamboo for the construction of baskets is an old tradition that was transferred to objects of larger scale, leading to the development of reciprocal configurations based on linear elements too.

In this framework, planar components should also be consider for the development of reciprocal systems - circular tiles, squares, triangles and more articulated or irregular geometries are all valid alternatives. When the reciprocals are made of elongated elements, design efforts are mainly focused on three aspects: (1) the definition of fans to be assembled, (2) the study of their composition possibilities and (3) the selection of jointing system(s). With planar elements, the materiality and jointing system are generally enhanced - width and thickness provide new design possibilities, allowing designers to take advantage of surfaces instead of bars.

In this paper, reciprocal systems based on the use of planar elements are studied and classified according to the shape of the elements and growth possibilities of their assembly. The following section recalls the concept and characteristics of reciprocal structures based on linear beams. Section 3 introduces the concept of reciprocal systems composed of planar elements. Section 4 presents a classification attempt of classification in which several design aspects are taken in account, from the shape of the element to the jointing and growth possibilities of such systems.

2. RECIPROCAL SYSTEMS WITH LINEAR ELEMENTS

From the conceptual point of view, the development of a reciprocal structure requires: (1) the presence of at least two elements that allow a certain forced interaction to be generated; (2) that each element of the composition must support and be supported by another one; (3) that each and every supported element must come into contact with its support along the span and never at the vertices (in order to avoid the generation of a space grid with pin-joints) [1].

Figures 1A-B show an elementary example of a reciprocal structure that respects such conditions. This basic configuration has been developed with linear elements and is generally called 'fan' or 'nexor'. It can be assembled with other similar systems in order to generate more complicated structures [2].

From the geometrical point of view, a reciprocal configuration is defined by:

(1) the eccentricity between elements, which represents the shortest distance between the axes of two connected elements and provides three-dimensionality to the resulting assembly;
(2) the engagement length, i.e. the distance between the bar end of a supporting element and its point of contact with the supported one;
(3) the length of each element;
(4) the style/orientation of the fan, which is called 'right' when it creates a clockwise moment, while it is identified as 'left' for an anticlockwise moment;
(5) the end disposition, which considers whether an element of a reciprocal configuration is placed above or below its support. In the first case, it is positive, while in the second it is negative;
(6) the topology of the chosen grid.

With these parameters, it is possible to describe and automatically generate any basic configuration, as well as more complex ones, by assembling single fans together.

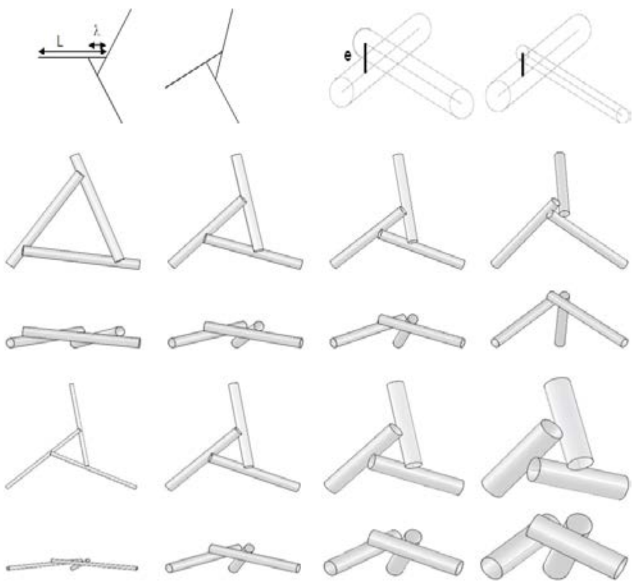

Fig. 1A. Eccentricity and engagement length variations for simple fans.

Fig. 1B. Style and fan orientation.

2.1. Assembly and growth

The assemblies of simple fans, which compose more articulated reciprocal systems, can be classified in several ways. From the morphological point of view, they can generate flat or curved structures. Depending on the shape of the composing elements and their jointing system, flat bridges and slabs can be obtained, as well as spatial structures in which bars are superimposed. From the architectural point of view, they can grow in a 1D or linear way, such as in the case of Leonardo's bridge, or in a 2D way, following the shape of surface-like structures. In a few cases, the final configuration does not belong to the previous two categories and could be considered as growing in a 3D or 'fully' spatial way. From the geometrical point of view, assemblies of reciprocal fans can also be obtained from regular polyhedra. In this family, tetrahedric, cubic and dodecahedric reciprocal configurations can be built with an identical fans aspect ratio.

Fig. 2. Left, 1D reciprocal bridge; Middle, 2D reciprocal roof; Right: 3D reciprocal structure by Olga Popovic Larsen.

3. RECIPROCAL SYSTEMS WITH PLANAR ELEMENTS

When reciprocal systems are designed with elongated elements, design efforts are mainly focused on three aspects: (1) the definition of the fans to be assembled, (2) the study of their composition possibilities and (3) the selection of the jointing system(s). However, as suggested by the rare natural example of the Cocolith, planar panels of different shapes can also be used to transfer forces in a reciprocal way.

This inspires a new research direction, in addition to the three aspects mentioned above: reciprocal systems based on planar elements need a further effort for the design of the element itself. The Cocolith uses circular tiles, but also squares, triangles and more articulated or irregular geometries can be considered.

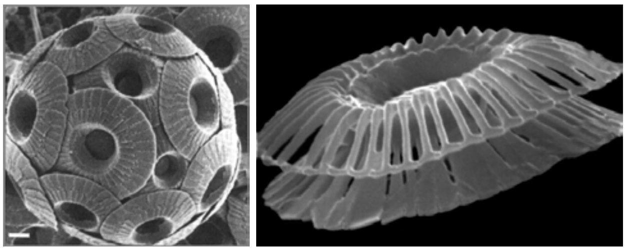

Fig. 3. View of a cocolithophore and an elementary tile.

3.1. Material and Joints

During his career, Werner Blaser designed several pieces of timber furniture using non-elongated elements assembled in a reciprocal way [3]. The materiality and jointing system were generally enhanced compared to structures realized with elongated components. The width and/or thickness of elements provide new design possibilities, and allow designers to take advantage of surfaces instead of bars. However, in most of the examples by Blaser, crafting and aesthetic reasons took priority over structural needs. Let us consider the leg of the table shown in Figure 4A. The cross shape was obtained by composing timber pieces in a reciprocal way in order not to use extra steel elements to join them. The reciprocal node in Figure 4D is again a pure aesthetic solution to a technological issue of assembling – timber elements are arranged with an engagement length equal to zero and are therefore orthogonal to one another. It should be considered that such components also work in an orthogonal position to the ground and that their structural behavior is distant from being reciprocal while the typical aspect of a fan is maintained. A similar comment could be made for the reciprocal node of the table leg shown in Figure 4C. Here, the finger joint is developed to provide architectural form to the technological need of interlocking separated elements in space. Again for the table in Figure 4B, the reciprocal joint interlocks timber elements without resorting to extra steel elements, even though it provides a structural contribute. With the use of planar elements, even a simple joint obtained through the superimposition of panels can offer several design possibilities, which need further investigations.

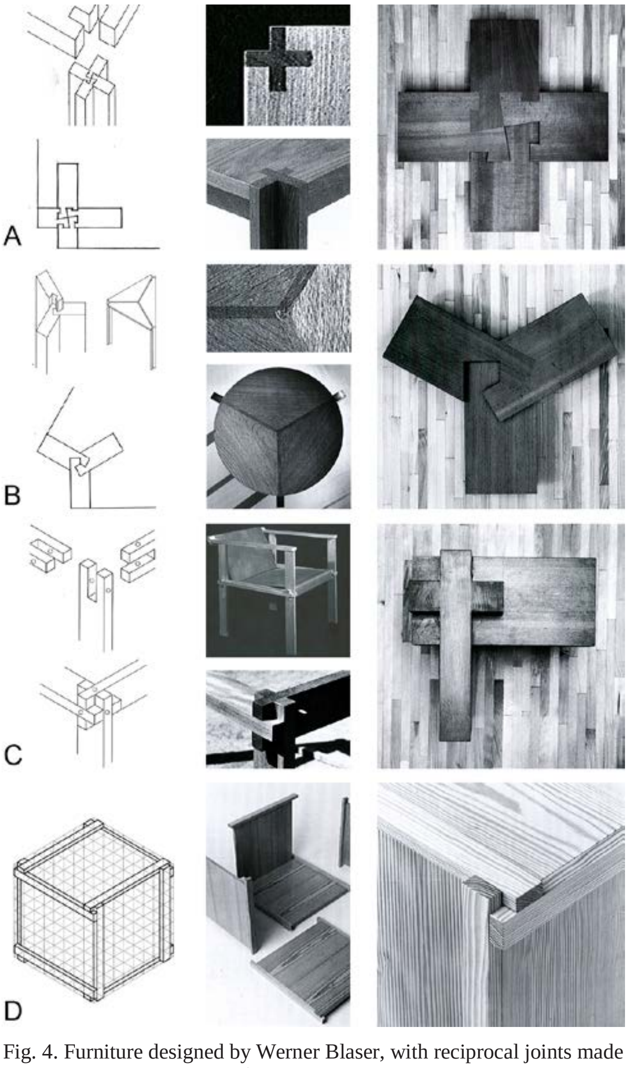

Fig. 4. Furniture designed by Werner Blaser, with reciprocal joints made of planar elements.

4. ASSEMBLY AND GROWTH: A CLASSIFICATION ATTEMP

In order to guide future morphological researches, five categories of reciprocal configurations made of planar elements are proposed.

4.1. Planar elements used as 'thick' linear elements

This category includes all those reciprocal structures in which the composing planar elements are approached and used in the same way as elongated ones. Figure 5 shows a geodesic dome made of planar element with notches. The second picture gives a more detailed view.

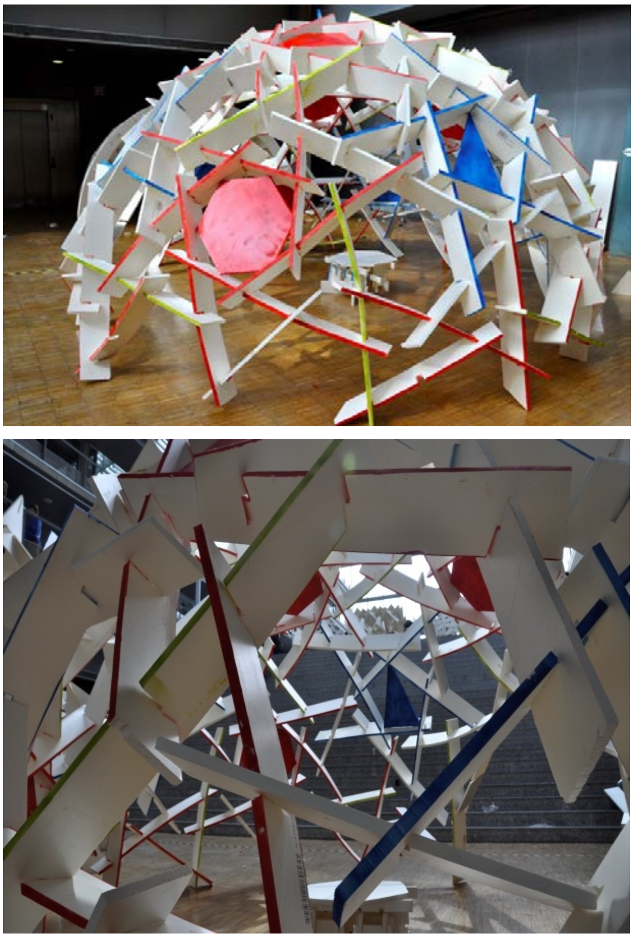

Fig. 5. Left: a geodesic dome made of planar element with notches; Right: Detailed view.

Only a few examples have been designed and built with thick linear elements, of which the Serpentine Gallery 2005, by Siza and Balmond, is probably the most relevant – timber components were used as beams and their thickness allowed interesting interlocked joints to be realized (Figure 6A). Another grid-shell was designed by the students at the University of Melbourne, under the guidance of Eugene Cheah in 2012 (Figure 6B-C). Here, thickness variations of the rectangular sections also allowed the students to introduce integrated cladding elements.

Fig. 6A. Detail of the roof of the Serpentine Gallery 2005.

Fig. 6B-C. A reciprocal structure realized by the students at the University of Melbourne in 2012. The nodes and construction have adopted the same principles used for the Serpentine Gallery 2005.

4.2. Planar elements used as ‘groups’ of linear elements

This second category includes all those reciprocal structures in which the composing planar elements can be substituted by a fan of linear elements, i.e. the planar element conceptually groups linear ones to form reciprocal fans. In this case, focus is on the design of the composing element. Figure 7, Left, shows the simplest example of a reciprocal structure belonging to this category, which is made of triangles that hypothetically replace fans of three linear elements each. Tiles can have three different engagement lengths, while only two are possible for elongated elements. These tiles can be transformed into a configuration with three linear elements that represent the edges of a triangle. The arrangement shown in Figure 7, on the right, is a 6 vertice star element. The star shape is the only solution that can allow the elements to be placed one on top of another, as the tiles would otherwise overlap one another. This type of tile could have 6 different engagement lengths. Figure 7, in the middle, shows a configuration made of crosses that replace fans with 4 linear elements.

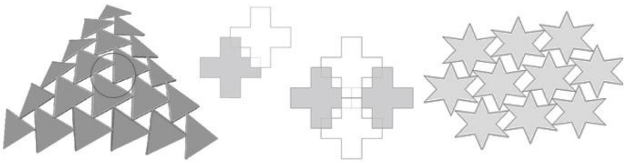

Fig. 7. Reciprocal configurations made with planar elements. Left: triangles; Middle: crosses; Right: star-shaped elements.

Figure 8 shows a reinterpretation by H. Logan of Leonardo’s bridge, developed with planar elements [4]. Here, the tiles are connected by a slot that can be quite simple (Figure 8, Top) but, if the shaping of the composing element is worked on, more complex configurations could be obtained (Figure 8, Bottom). This configuration connects several tiles together and, as shown in the elevation, a truss effect is created. The stiffness of the structure does not therefore depend only on the stiffness of a tile, but also on the equivalent truss.

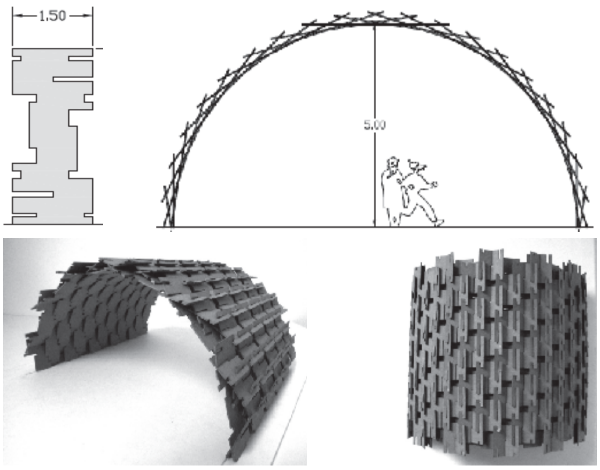

Fig. 8. A complex tile with slots and a possible resulting shape.

Figures 9 and 10 show a system with triangular planar elements. One uses a “flower-shaped”:element, the other uses a cut triangular element.

Fig. 9. Top: example of a 'flower shape' planar element; Bottom: a detailed view.

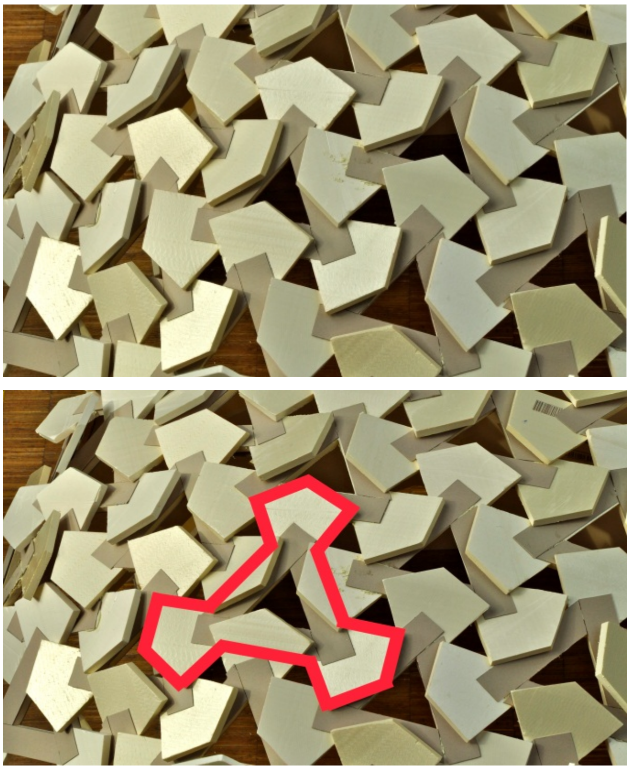

Fig. 10. Top: example of a 'cut triangle' planar element; Bottom: highlight of the composing element.

4.3. Planar elements that transmit bending moment via the notches, and are used in different ways from the previous two categories

In this category, the notch between the tiles transmits a bending moment as shown in Figure 11, Top. The word reciprocal is right to describe this configuration - the assembly permits the bending moment to be transferred and gives structural stability to the configuration (see Figure 11, Bottom).

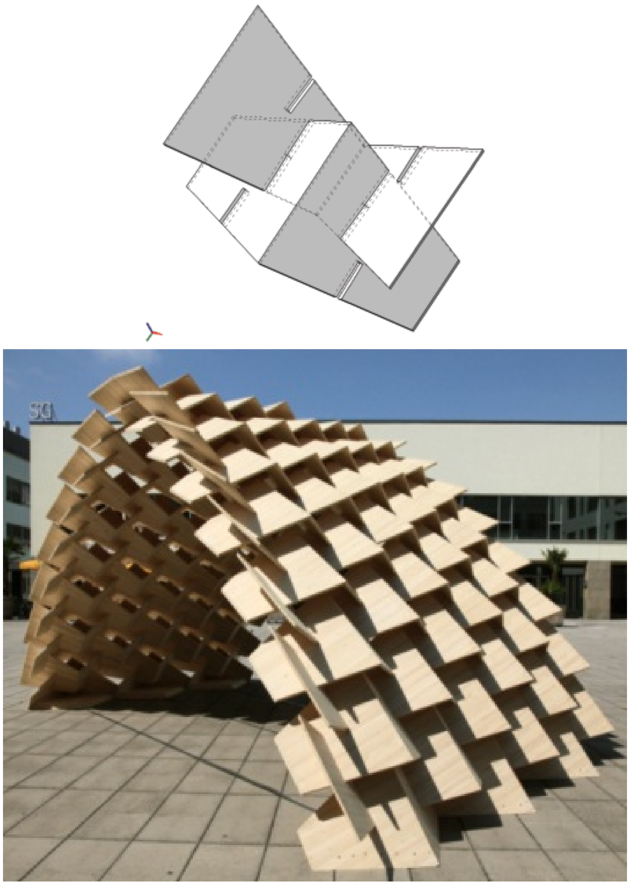

Fig. 11. A tile element and the resulting shape (from IBOIS EPFL).

4.4. Planar elements as part of a truss

In this category, the notches allow the element to transmit traction or compression forces as shown Figure 12, where a truss-like structure is generated.

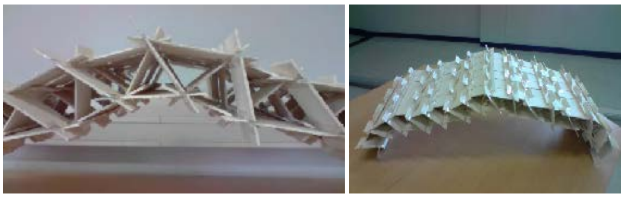

Fig. 12. Configuration where the planar elements are part of a truss.

4.5. Planar elements used in different ways from the previous four categories

A configuration belonging to this category is shown in Figure 13 (the entire sequence). A basic fan is obtained as a reciprocal structure of the first category with a small engagement length. By means of interlocking and superimposition, it can be extended in a surface-like way (Figure 13, in the middle) or as a fully 3D structure (Figure 13, bottom). Figure 14 shows the constructed structure.

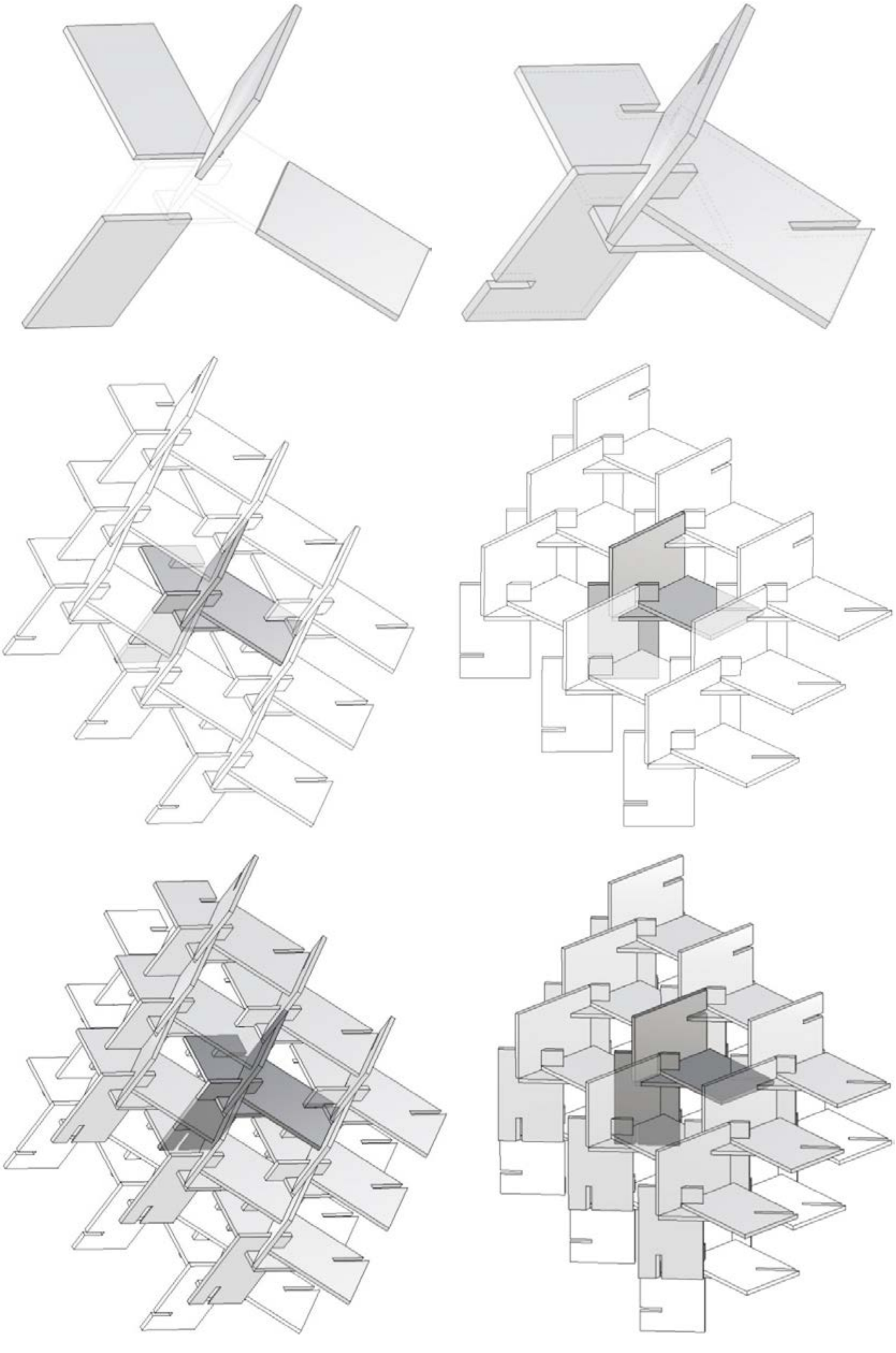

Fig. 13. Reciprocal structure based on planar elements developed with the students of the École des Ponts in Paris. Top: realization of the basic fan; Middle: growth as a surface-like structure; Bottom: growth as a spatial structure.

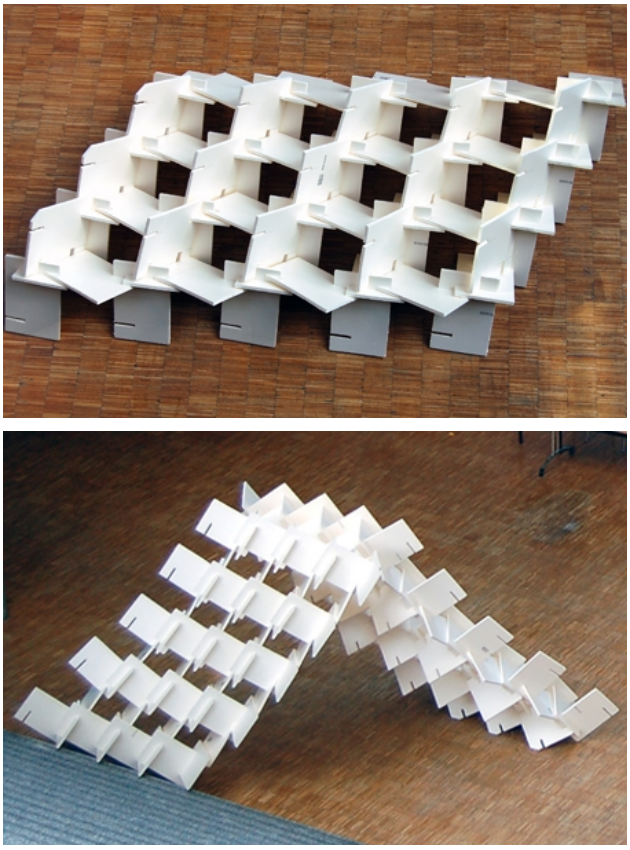

Fig. 14. Prototype in actual scale of the reciprocal structure drawn in Figure 13, Middle part.

5. CONCLUSIONS

The paper has presented a first study of reciprocal systems based on the use of planar elements.

First, the parameters that define a reciprocal system with elongated elements have been mentioned. Then, configurations based on planar elements have tentatively been classified into five categories in which the composing panels can be seen as: (1) ‘thick’ elongated elements; (2) ‘groups’ of elongated elements; (3) notches that can transmit bending moment; (4) noteches that can transmit compression and traction forces; (5) combinaition of some of the previous categories.

It should be underlined that the two first categories stand by friction-only. Several examples have been given for each category and a wide range of resulting geometries has been found.

This investigation and classification attempt had the aim of showing the morphological potential of reciprocal structures based on planar elements. It has also demonstrated the need for further geometrical, structural and construction explorations.

6. REFERENCES

[1] Pugnale A., Parigi D., Kirkegaard P.H., Sassone M., *The principle of structural reciprocity: history, properties and design issues*, In: *Proceedings of the IABSE-IASS Symposium 2011: “Taller, Longer, Lighter”*, London (2011)

[2] Baverel O., Nooshin H., Parke G., Kuroiwa Y., *Nexorades*, International Journal of Space Structures, Vol. 15, No. 2 (2000) pp. 155-159

[3] Blaser W., *Joint and Connection: Trends in Furniture and Their Background*, Birkhäuser (1992)

[4] Logan H., *Recherche de solutions structurelles de nexorades en plaques et ses applications en architecture*, Master’s thesis, ENS Architecture de Versailles (2008)

[5] Baverel O., Boulais L., *Workshop «Nexorades with Composites Materials»*, International Journal of Space Structures, Vol. 26, No. 4 (2011) pp. 363-364.