Folding/unfolding of tensegrity systems by removal of self-stress

Ali Smaili, René Motro

FOLDING/UNFOLDING OF TENSEGRITY SYSTEMS BY REMOVAL OF SELF-STRESS

A. Smaili, R.Motro
Laboratoire de Mécanique et Génie-Civil - UMR5508, Université de Montpellier II, cc048, Place E. Bataillon, 34095 Montpellier, France.
smaili.ali@caramail.com, motro@lmgc.univ-montp2.fr

ABSTRACT
This paper deals with tensegrity systems folding, by self stress removal. Two methods are described. Each of them is associated with a basic unit: two way extender on one side, and truss member on the other side. After a description of the folding process for these basic units, the generalization is demonstrated for a flat double layer grid. All the theoretical propositions are validated by physical models.

Keywords: Folding, unfolding, tensegrity, self stress.

1. INTRODUCTION
Foldable systems have potential advantages in the field of adaptable architecture and in aerospace industry (compact storage, adaptability and ease of use). We will therefore look closely at new folding modes for tensegrity structures, depending upon the creation of finite mechanisms. The design of finite mechanisms in tensegrity systems is a crucial step in the system conception. This step relies on the understanding of two characteristics of tensegrity systems: finite mechanisms and self-stress [1].The understanding and investigation of these fundamental basics have enabled us to elaborate two modes for finite mechanisms creation in tensegrity structures:

1- Introduction of finite mechanisms associated with self-stress removal.

2- Introduction of finite mechanisms dissociated of self-stress. This mode requires a specific geometrical configuration and a specific assembly of the components. In this case, self-stress is still active during the folding process but one has to assess the incidence of such mechanisms on the structural behavior of the structure [2].

In this communication, we look at the first mode, which is applied to a double layer grid (see figure 1) [3].

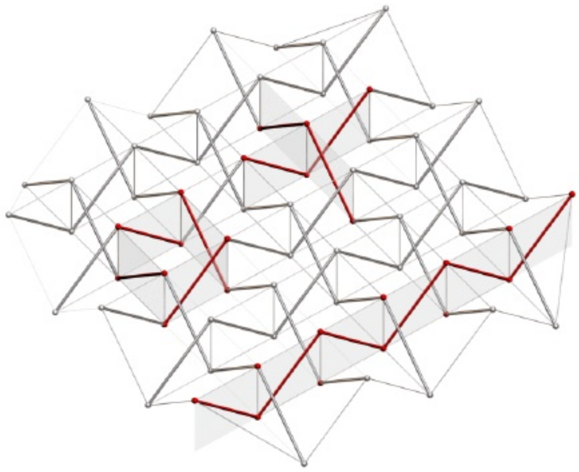

Figure 1. Flat double layer tensegrity grid

The creation of mechanisms rests on the way of lengthening vertical cables, which are the active cables. Two folding methods are possible and depend upon the elementary unit which is considered for folding purpose:

- Basic '2V' module (see figure 2) by using specific active cables in place of normal vertical ones
- Truss member method: each one of the truss member is activated independently by one cable.

2. FIRST FOLDING METHOD

2.1 Basic 2V Module (Extender)
This basic module can be described by the bidirectional assembly of 4 identical cubes (Figure 2). It has two

planes of symmetry which intersect each other along the vertical cable. This module has one state of self-stress and two finite mechanisms related to the unilateral rigidity of cables.

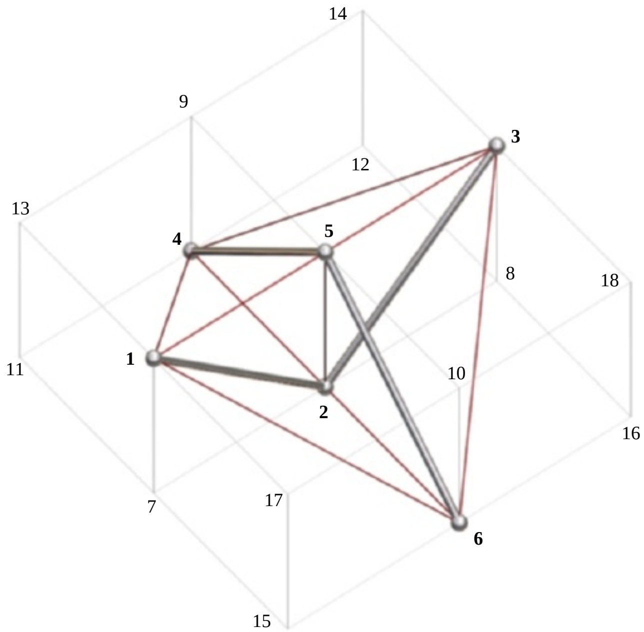

Figure 2. Basic 2V module (extender)

2.2 Folding Process

The introduction of mechanisms is achieved by self-stress removal, which is realized in this case, by the lengthening of the cable 2-5 (Figure 2). In order to apply this method in the grid folding, it is necessary to double the cable in its vertical portion, by introducing two pulleys respectively at nodes 2 and 5. The cable has also to rune inside the struts

The module is folded, in three steps according to the following order.

- The cable is fixed at the starting end node 3.
- Pulleys at nodes 2 and 5 (without friction or blockage, if possible) allow the cable to move freely in the vertical direction. This action is made possible by a pulley mechanism designed to avoid unwanted Frictions.
- The final node, number 1, is equipped with a blocking mechanism which grips the cable at a given length thereby fixing the geometry of the structure.

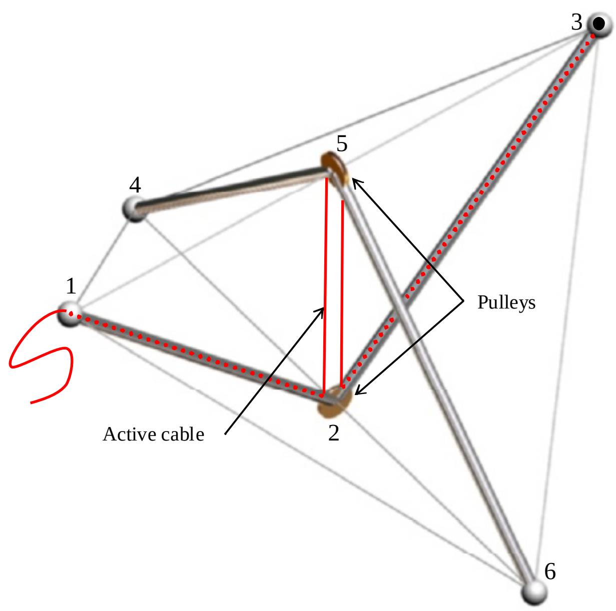

Figure 3. Cable path (1-2-5-2-3)

The mechanism is activated by bringing together nodes 1 and 3 toward the folding plane P1 by exerting forces along the mechanism direction (Figure 4a) then completing the folding process by bringing in turn joints 4 and 6 together toward the folding plane P2 by exerting appropriated forces (Figure 4b). This action progressively lengthens the cable 2-5.

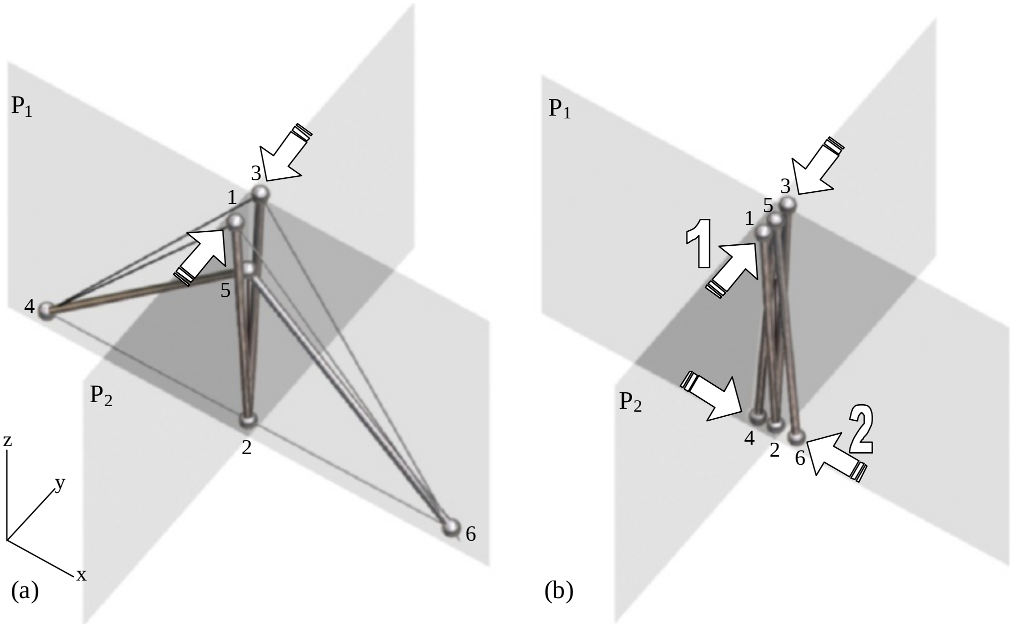

Figure 4. Mechanism activation by acting on the nodes: (a) nodes 1 and 2, (b) nodes 4 and 6

2.3 Stiffening of Unfolded Configuration

The stiffening of the module (unfolding) is created by the reverse process. The cable is shortened until the value corresponding to the "**null self stress equilibrium**". One question arises for this state and concerns the introduction of additional states of self-stress to the 2V module.

Concerning new states of self-stress, the fact that we added a cable inside the struts has introduced additional forces on the original module. Mechanically, we therefore have 3 states of self-stress: 2 local states of self-stress and one global state of self-stress (Figure 5).

To conclude, both struts 1-2 and 2-3 act like pre stressed struts inside a self-stressed structure. The cable ensures the structure stability, but also creates additional states of self-stress in the struts.

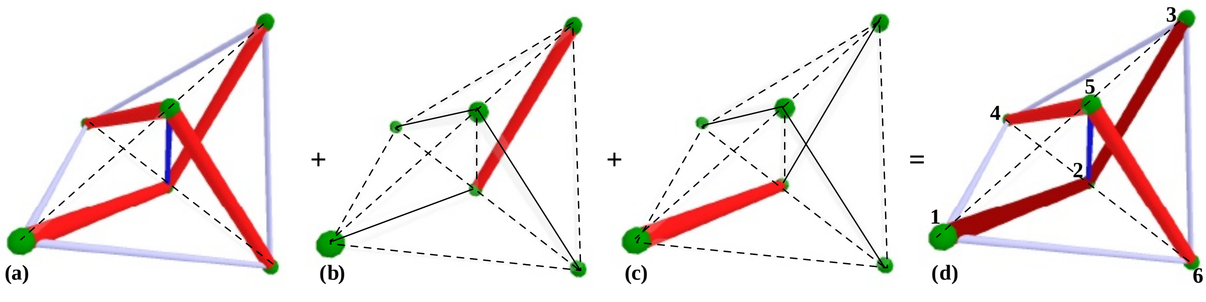

Figure 5. Various states of self-stress in module 2V taken from the computer simulation generated by the T2000 program, (a) global self-stress, (b,c) local self-stress, (d) total self-stress

2.4 Grid Folding

The grid is a bidirectional assembly of the 2V module that have been presented previously. This paragraph will therefore only be a generalization the previously found results. The assembly of the foldable 2V modules, requires a new node design. These nodes have to authorize the replacement of vertical spacer cables by active cables. The complete active cable, based on (1-2-5-2-3) path, will run inside the grid according to the general path illustrated in figure 6. All the vertical single cables in the plane of the vertical trusses are replaced by one double cable.

There is no significant difference with the module folding, since there is a continuity of cables in the truss planes.

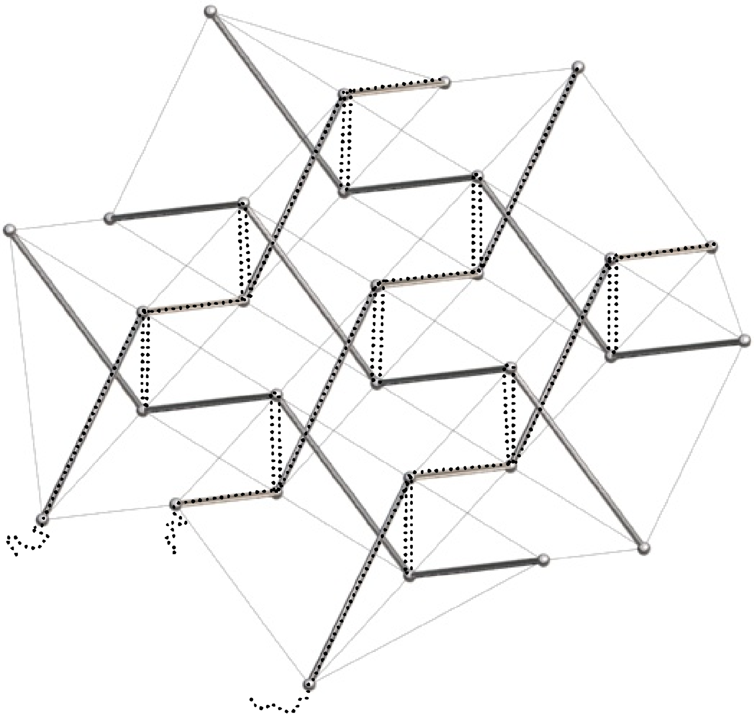

Figure 6. Active cable paths

Any movement in space can be described as the combination of a rotation and a translation. One can also make a translation in space by successive and/or simultaneous rotations. This combination is difficult to achieve. As soon as the active cables are released, each truss member moves independently from the whole which makes it impossible to predict the node cinematic trajectories. Tests carried out on real physical models have demonstrated that even if the method is compatible with the geometry, some restrictions have to be made for folding the structure on a plane by bunching together the elements. The found difficulties result from the lack of self-stress during the folding process. As the grid is made up of identical modules arranged according to two directions, the folding method adopted is chosen in consequence: a simultaneous translation of all the elements

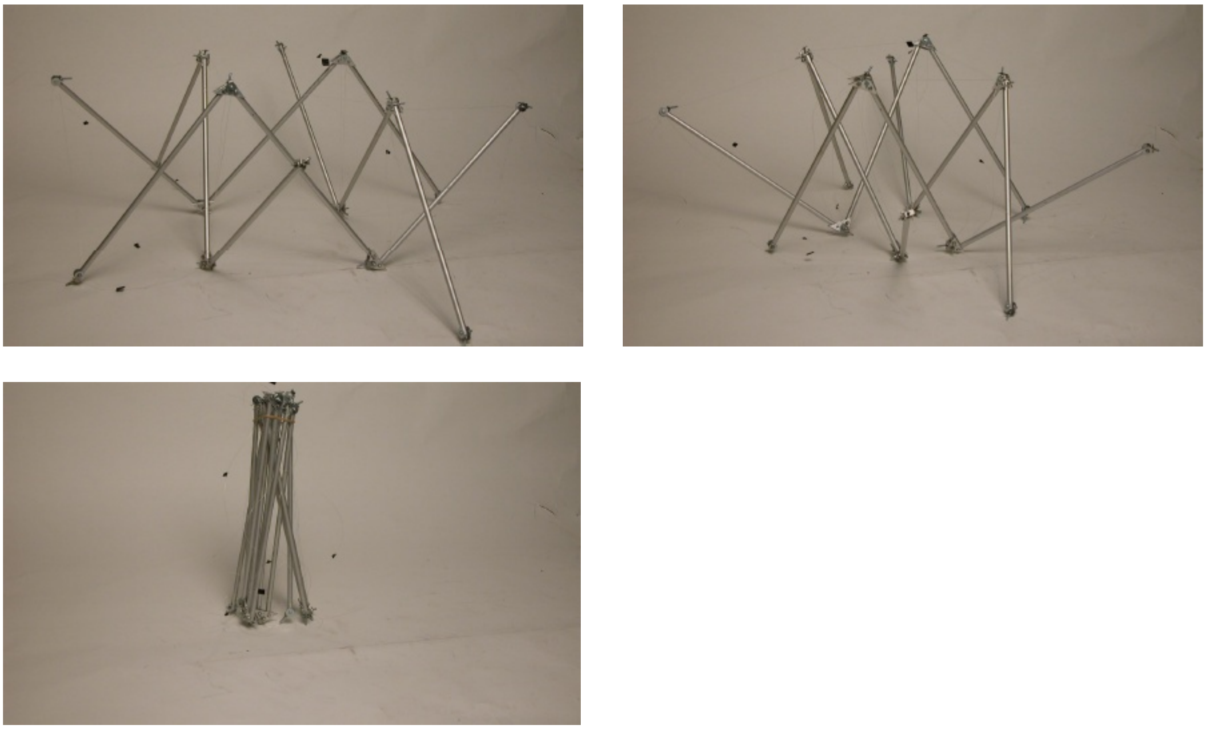

Figure 7. Folding of the physical model

according to the two directions to achieve a bundle of members. This method requires the introduction of finite mechanisms in the whole structure, loosening of all the elements at once time (see figure 7).

3. SECOND FOLDING METHOD

3.1 Truss Member Component

The double layer grid can be seen as an assembly of truss members. A truss member is formed by a collection of 2V half modules assembled according to the two main directions of the grid. In isolating this truss member, it can be noticed that it is made up of alternating struts. Mechanically, none of its constituent members are under any state of self-stress, except the one which could be implemented by the vertical cables (see figure 8). The equivalent actions can also be exerted on the nodes from the outside towards the inside (Figure 9b). Having isolated a truss member, we can create self-stress by replacing all the vertical cables by a single cable which stitches the membrane (Figure 9d).

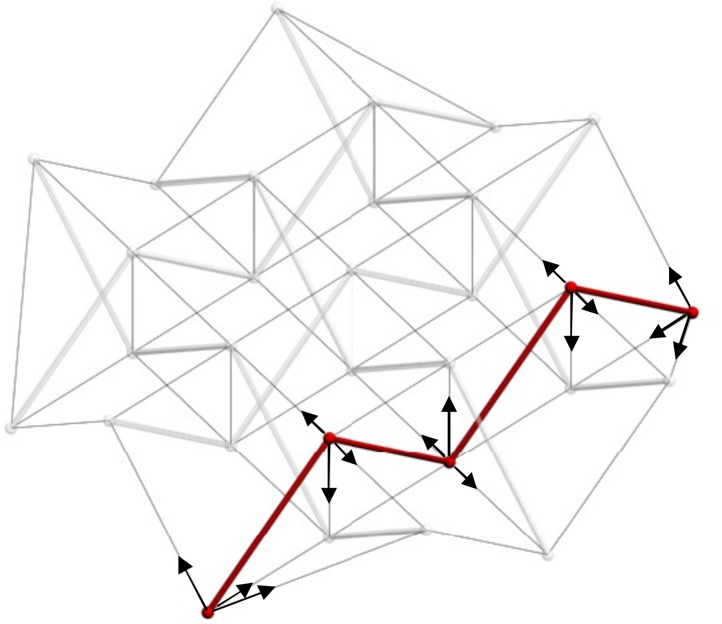

Figure 8. Applied forces on a truss member

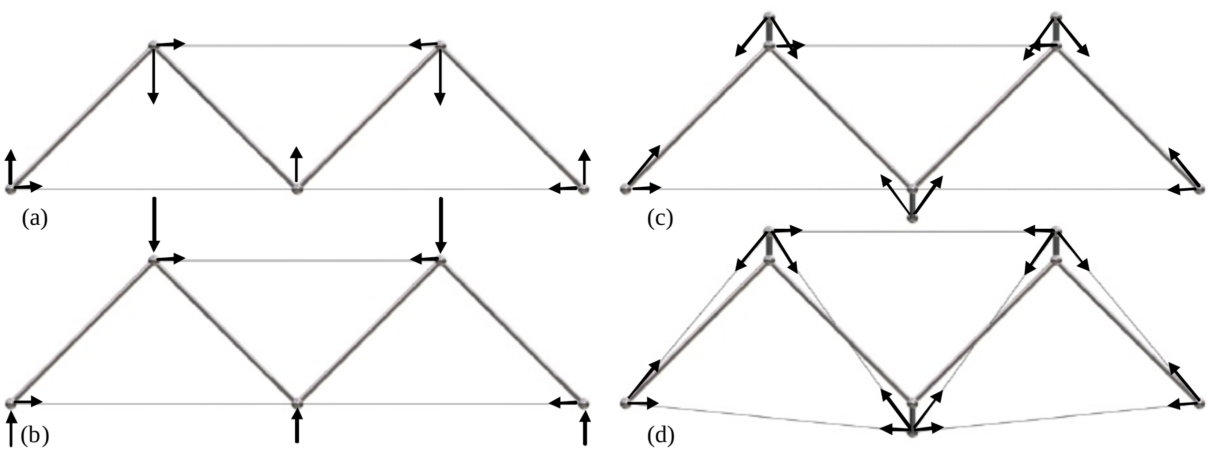

Figure 9. How to self stress the truss member with a peripheral cable

3.2 Truss Member Folding

The basic truss member has only one component in compression (with several elements:1-2,2-4,2-3,3-5,3-6,6-7 and 7-8), one active cables (1-4-5-7-8) running alternatively along the modules of the system.

The folding of a basic truss occurs when a cable 1-4 is loosened. This process can introduce finite mechanisms; this method seems to work better with these types of structures. Loosening the cables causes a lack of stability for extra elements like 2-4, 3-5 and 6-7 relatively to the associated struts (see figure 10).

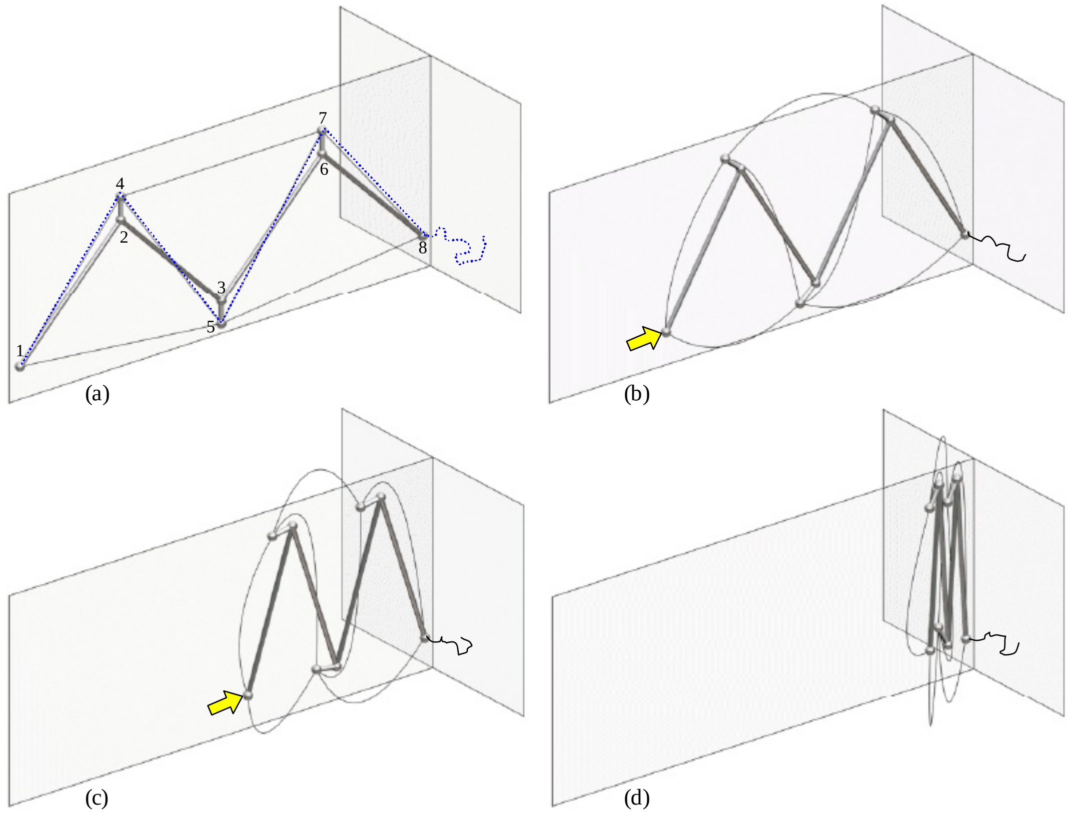

Figure 10. Folding process of the truss member: (a) unfolded configuration, (b, c) intermediate configuration, (d) folded configuration

3.3 Folding the Grid

In order to enable the folding of the grid, which is a truss member assembly, we may take advantage of the simplicity of the assembly along only 2 orthogonal directions (see figure 11). Each of the truss members is assembled to its neighbor without affecting its state of self-stress. This assembly method does not require any additional members or peripheral system to achieve a state of self-stress.

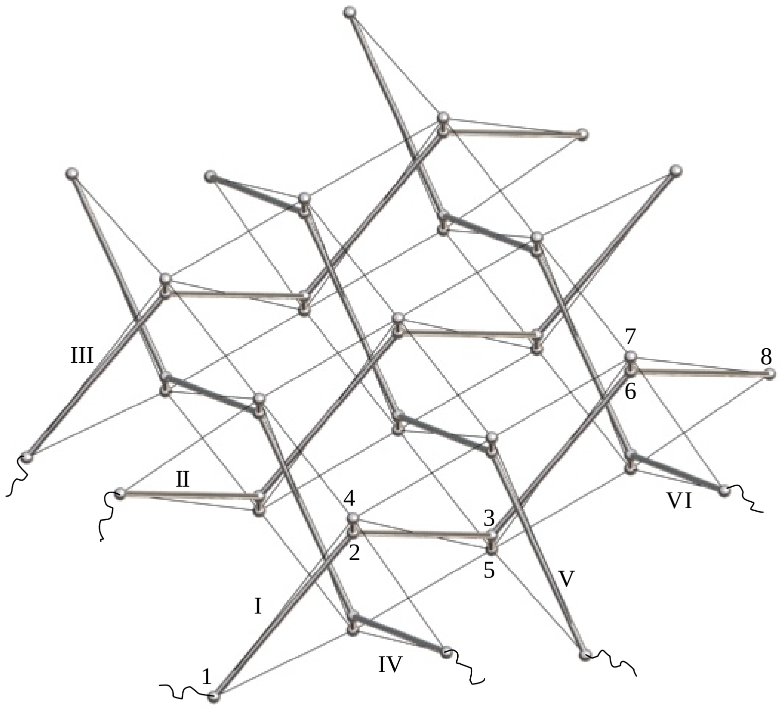

Figure 11. Self-stress truss member assembly (bidirectional grid)

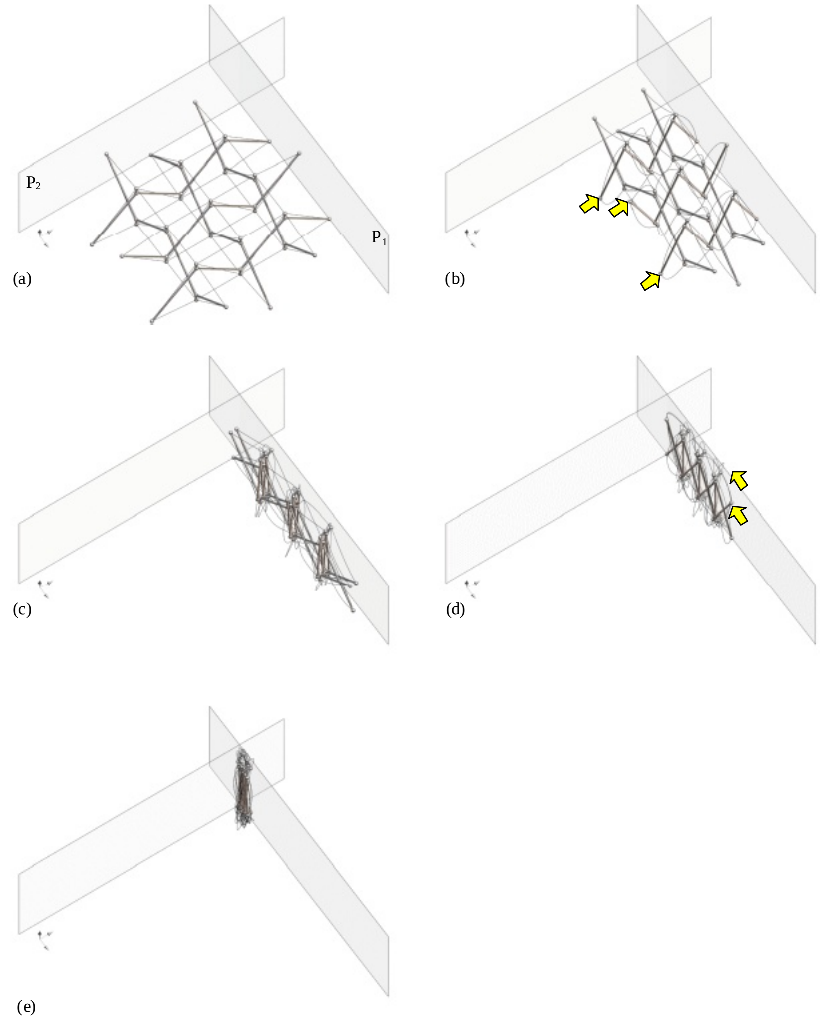

Figure 12. Folding process of the grid

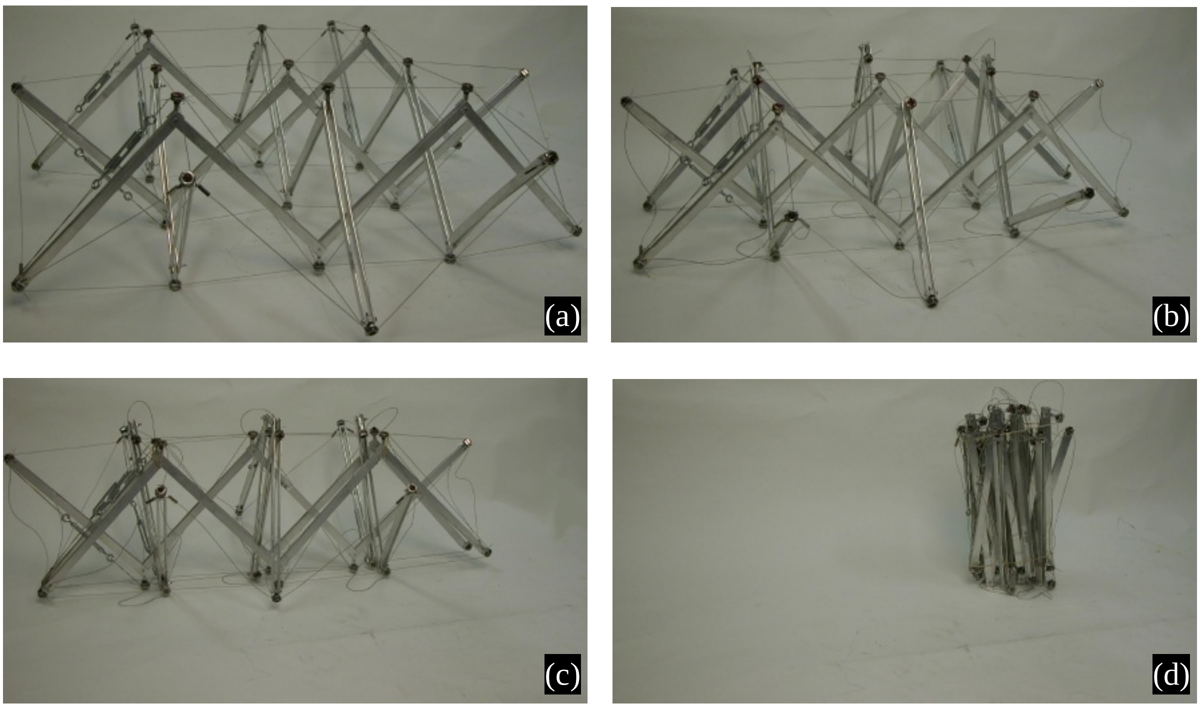

Figure 13. Folding of the grid, physical model

3.4 Physical Models

All the properties that have to be met by the module have been developed in order to achieve the folding compatibility of the grid. The physical model has validated the fact that the assembly of basic modules, in the grid, meets perfectly the geometric and mechanical requirements (see figure 13).

4. CONCLUSION

We have observed the effects of mechanisms which are activated by the self-stress removal to achieve motion of the members. The main characteristic of this method is a reduced volume at the end. The simplicity of mechanisms creation in tensegrity systems for folding/unfolding, by way of active cables, is interesting for some applications. We add also, that by reducing the volume in the folded configuration without the need of having anchorage devices, makes this type of folding process suitable for aerospace applications. The architectural applications are not so obvious.

REFERENCES

[1] A. Smaili, *Systèmes légers pliables/dépliables: cas des systèmes de Tenségrité*. Thèse de Doctorat, directeur de thèse: Motro R., Université Montpellier II, Montpellier, France, Septembre 2004.
[2] A. Smaili , R. Motro, V.Raducanu, *New concepts for deployable tensegrity systems*, IASS Symposium: Shell and Spatial Structures from models to realization, 20-24 Septembre 2004, Montpellier, France.
[3] V. Raducanu, *Architecture et systèmes constructifs: Cas des systèmes de tenségrité*. Thèse de Doctorat, directeur de thèse Motro René. Université Montpellier II, Montpellier, France,septembre 2001.