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Expandable origami for architectural applications: layers of ORIGAMI-SCISSOR hinged deployable structures

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Abstract
Origami and scissor-hinged had been different types of deployable structures out of many others that exist. The author of this research unified both types and made a diamond origami-scissor hinged pattern, and therefore created a new hybrid type of deployable structure. Origami-scissor hinged patterns are lattice expandable origami structures that can fold and unfold as the thick origami, and expand and contract as a scissor structure; this therefore provides an extra degree of freedom to the thick origami. This paper tests the geometric compatibility of several possibilities of thicknesses of the scissor pantographic layers of the origami-scissor hinged pattern. The purpose of this research is to ascertain what are the geometric constraints and allowances in the design of the layers of origami-scissor hinged deployable structures, and to investigate whether an origami-scissor hinged pattern can be done with an overall reduction in thickness, which would allow a more efficient ratio of stowed to deployed configuration. This new technology has potential applications for mobile or transformable architecture, aerospace, robotics, industrial design and kinetic art.

Keywords: Deployable, transformable, expandable, thick origami, architecture, scissor-hinged, pantograph, geometry.

1. Introduction
The diamond origami-scissor hinged pattern unified origami and scissor hinged deployable structures, which had so far remained separate types within the field [1]; this signified the birth of a hybrid new type of deployable structure: origami-scissor hinged, invented by Rivas-Adrover [2]. This was achieved by applying the 'form generation method of relative ratios' (FGMORR) for 2-bar scissor-hinged structures by Rivas-Adrover [3] to the 'origami of thick panels' by Chen et al. [4].

Advances have been made in zero thickness (paper model) such as the symmetry based method that allows modifications in origami design by Sareh [5]. However, in order to build origami in large scales for architecture and engineering applications, a rigidity and thickness of the material is required. Applications of thick origami include space applications such as the solar array designed by BYU which is inspired on the origami flasher pattern by Zirbel et al. [6].

Various methods have been suggested in order to make thick origami using its zero-thickness kinematic model by De Temmerman et al. [7], Edmondson et al. [8], Hoberman [9] and Tachi [10]. 'Origami of thick panels' by Chen, Peng and You [4] demonstrates that origami of thick panels can be devised by mechanism theory alone, and propose a method that can be extended and generalized to different types of origami.

Scissor-hinged deployable structures are made by units of bars joined by a pivot. While a single scissor mechanism is relatively simple, its replication to create large structures that can expand and contract is highly complex. Scissor-hinged projects include the transportable pavilion for exhibitions by Pérez Piñero [11], the swimming pool cover in Seville by Escrig, Valcárcel and Sanchez [12], and the Iris Dome by Hoberman [13]. Recent advancements on scissor grids include the research by Roovers and De Temmerman on grids done with polar and translational units [14] and [15].

2. Form generation method of relative ratios (FGMORR)

Scissor hinged surfaces have been made by replicating scissor units to make grids that make triangles or squares. The 'form generation method of relative ratios' (FGMORR) [3] can be applied to an indefinite number of combinations of lines, and therefore allows for potentially infinite scissor structures to be made with optimum deployment; this therefore opens a significant space for innovation.

The fundamental principle of the FGMORR is that in any given combination of lines, a ratio for a scissor unit (or various ratios for different sizes of scissor units with equal angles of motion) can be found, that distributed throughout the segments and subsegments results in geometrically compatible scissor hinged structure, as long as the following conditions are satisfied: the combinations of lines must intersect so that it can be translated in pantographs that intersect and join at the end nodes; the combination of lines is interpreted as a plan view; all the scissor units of all different ratios, must have equal angles of motion; the relative position of the scissor units in space must also remain constant and proportional throughout the deployment; the different ratios allow for scissor units with bars of different lengths (with equal angles of motion), and the smaller bars have to be at least half or longer than the bars of the first ratio to allow a good mobility of the structure; all the different ratios for different lengths of bars must mirror another scissor unit of the same ratio, by doing this the geometric deployability constrain defined by Escrig is guaranteed [16]. These conditions can be satisfied when using translational scissor units. This method enables for the scissor structure to be made with the minimum number possible of different sizes of bars, as well as achieving an optimum expansion and contraction.

The premise that the method can be applied to any given combination of lines was tested by applying it to a pattern derived from the geometry of the Alhambra in Granada, and resulted in the proposal of the Alhambra transportable pavilion in Cambridge Market Square [17].

3. ORIGAMI-SCISSOR hinged deployable structures

The diamond origami-scissor hinged structure [2] made by applying the 'form generation method of relative ratios' (FGMORR) [3] to the origami of thick panels [4]. This is done with two bar scissor hinged translational units. The origami panels are translated in virtual lattice thicknesses that can expand and contract while retaining the angles of the origami intact. Where in the diamond thick origami, one triangulated face would be made of two panels, in the diamond origami-scissor structure one triangulated face is made of 77 bars and 124 nodes. The diamond origami-scissor prototype was made of six triangulated faces. This prototype is made of 744 nodes and 462 bars (with six different types of bars). The prototype is structurally stable and it is kinematically compatible without any deformation of parts. While the diamond origami of thick panels has one degree of freedom, the origami-scissor structure has two degrees of freedom.

The origami-scissor hinged geometry method was also applied to the waterbomb origami of thick panels where the theoretical model was also geometrically compatible, and it also provides an extra degree of freedom to its thick origami counterpart [18]. Research indicates that this method could be extended and generalized to other types of thick origami patterns.

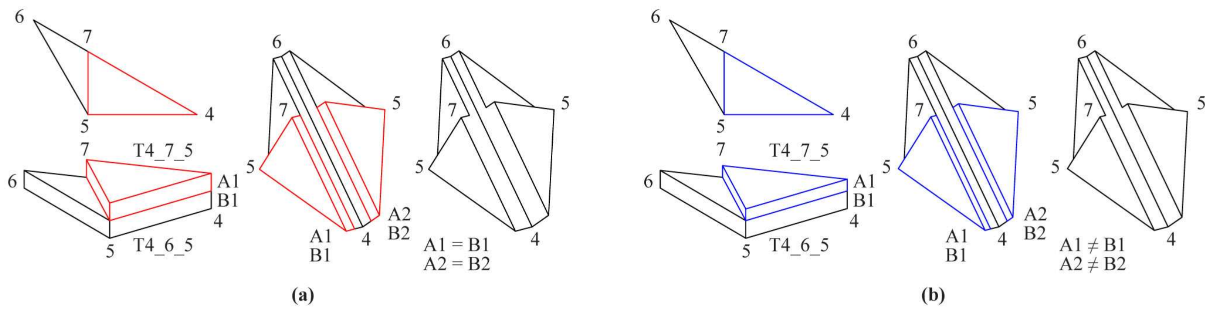

Figure 1: Thicknesses of the diamond origami panels. (a) Panels of equal thicknesses; (b) panels of different thicknesses.

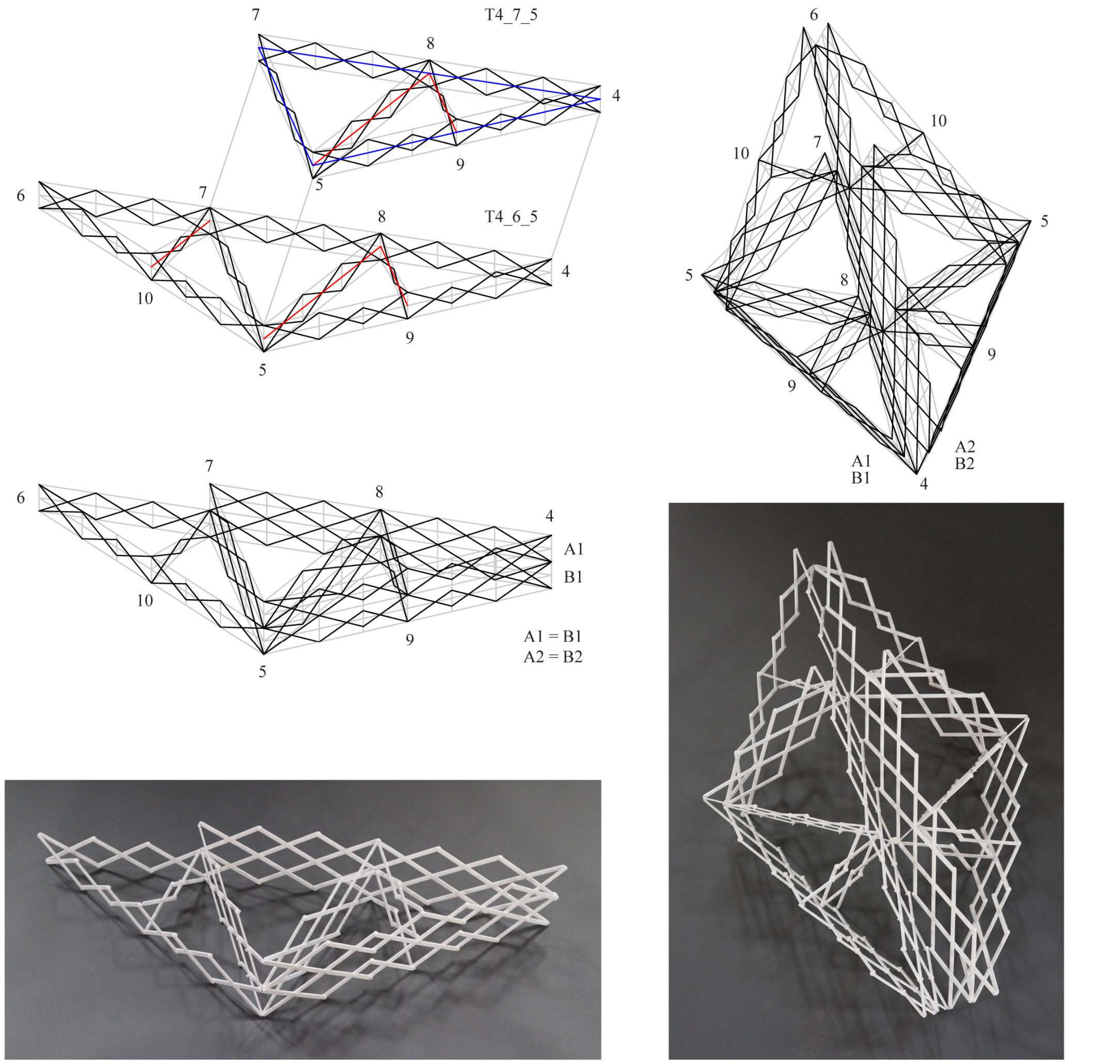

Figure 2: Diamond origami-scissor hinged structure made with panels of equal thicknesses (thickness A is equal to that of B). Theoretical model and built prototype.

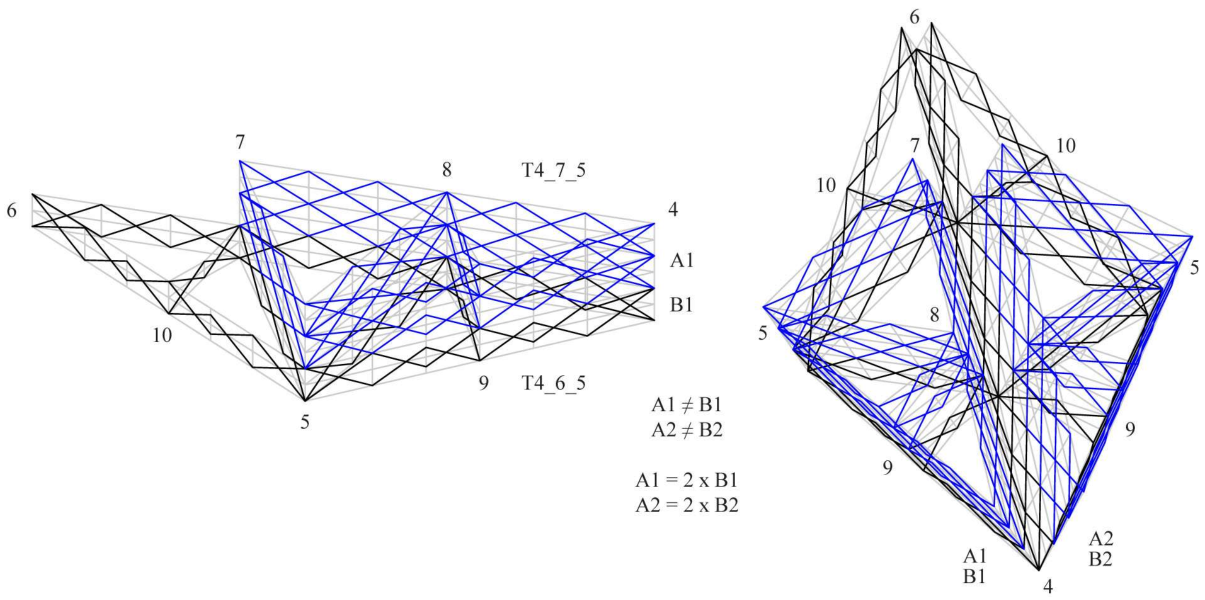

Figure 3: Diamond origami-scissor hinged structure made with panels of different proportional thicknesses. Thickness A is twice that of B.

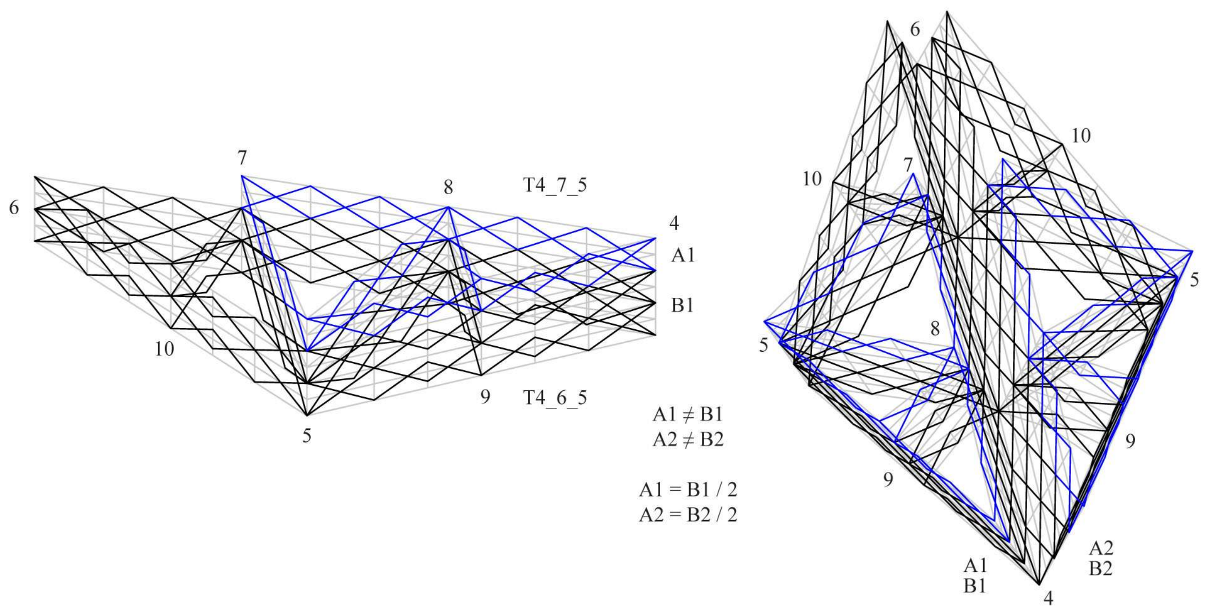

Figure 4: Diamond origami-scissor hinged structure made with panels of different proportional thicknesses. Thickness A is half that of B.

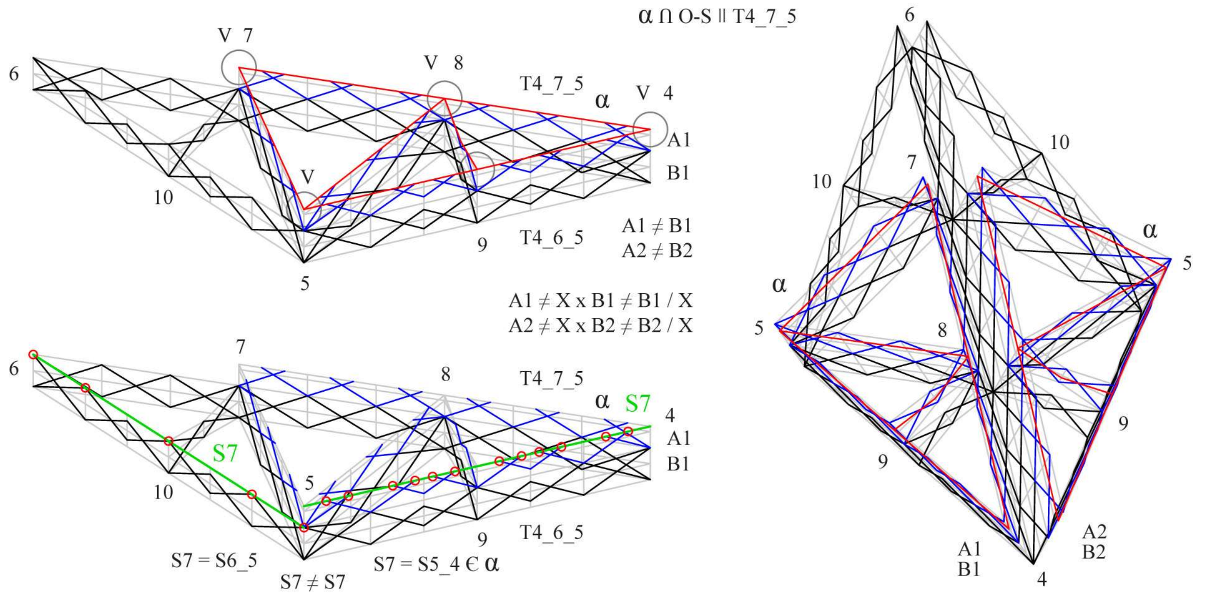

Figure 5: Diamond origami-scissor hinged structure made with different non-proportional thicknesses.
Intersecting plane alpha.

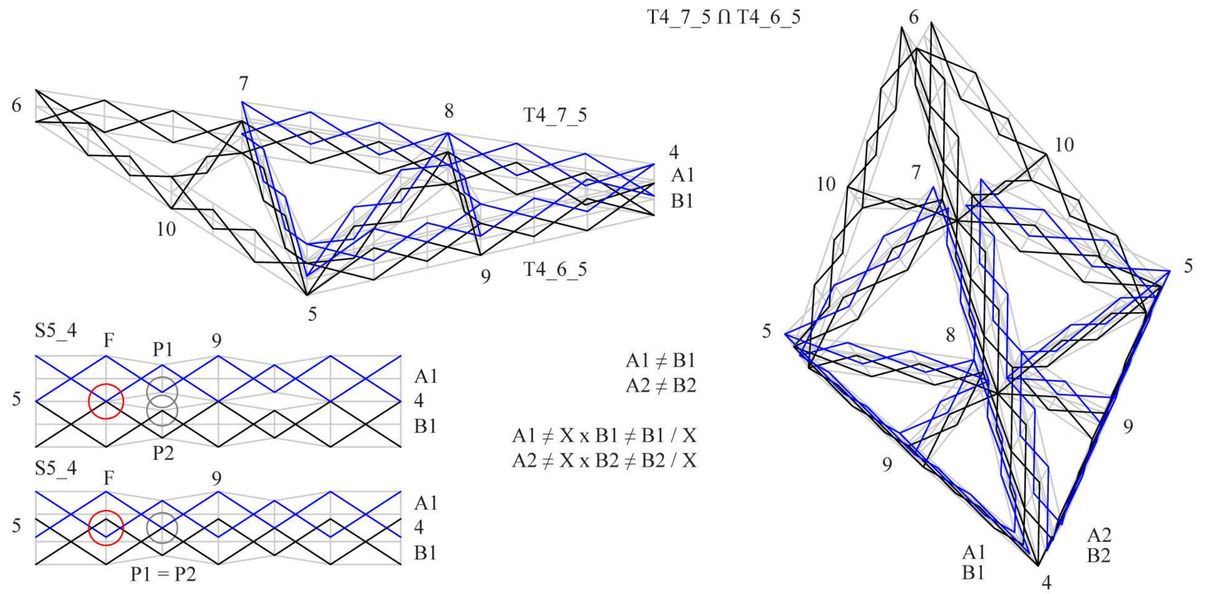

Figure 6: Diamond origami-scissor hinged structure made with different non-proportional thicknesses.
Interweaving layers of scissor hinged pantographs.

4. Thicknesses of origami-scissor hinged layers

The diamond origami-scissor structure was made of two panels of equal thicknesses superimposed; this facilitated placing one triangle of pantographs on top of another, where both triangles were made of equal sizes of scissor units. The following research will test whether the method could be extended to origami of thick panels made with different thicknesses, therefore with different lengths of bars for the scissor pantographs.

The thicknesses of the origami panels will dictate the relative lengths of the bars of the scissor units to make the pantographs; therefore, a determination of its precise geometry is required in order to unify thick origami and scissors. The geometry consequence of applying mechanism theory to origami of thick panels, is that in some origami types, if certain ratios of thicknesses of panels apply, the origami type could be made with various options of thicknesses. For instance, in the case of the diamond origami of thick panels, each triangulated face is made of two thicknesses: A1 and B1, which are dictated by triangles T4_7_5 and T4_6_5. This mirrors another identical triangulated face made with: A2 and B2 (Figure 1). If the thicknesses of the diamond origami pattern made with thick panels comply with the following geometry conditions, the thick origami will have a fluid deployment:

$$\begin{aligned} A1 + B1 &= A2 + B2 \\ A1 &= A2 \\ B1 &= B2 \end{aligned} \tag{1}$$

However, as long as the above conditions are satisfied, the panels A and B may or may not be of equal thicknesses:

$$\begin{aligned} A1 &= B1 \\ A2 &= B2 \end{aligned} \tag{2}$$

$$\begin{aligned} A1 &\neq B1 \\ A2 &\neq B2 \end{aligned} \tag{3}$$

The option of equal thicknesses of panels expressed in (2) is represented in Figure 1 (a). The option with different thicknesses panels expressed in (3) is represented in Figure 1 (b). The following is an investigation of three main possibilities of thicknesses of panels made with pantographs for the diamond origami-scissor hinged pattern: equal thicknesses, different proportional thicknesses and different non-proportional thicknesses. This aims to determine the form generation capabilities of the origami-scissor hinged geometry method, which could then be applied to other origami patterns.

4.1. Equal thicknesses

Figure 2 represents the option used to build the diamond origami of thick panels where A and B have equal thicknesses and correspond to equations (2) and Figure 2 (a). Wherever possible this will be the preferred option, as equal thicknesses translates in equal lengths of bars in the different layers of pantographs that can therefore be joined at the nodes. Therefore, instead of building the pantographs as separate layers, the bars are extended throughout the different layers and joined as a trellis for structural stability and efficiency during assembly.

4.2. Different proportional thicknesses

Where different thicknesses are used (3) that are proportional, the layers of scissor pantographs can be arranged that have equal length of bars and can therefore be replicated using the same principles described in the previous option. Figure 3 displays an option where thickness A is twice that of B (4), and Figure 4 represents an option where the thickness A is half of B (5):

$$\begin{aligned} A1 &= 2 \times B1 \\ A2 &= 2 \times B2 \end{aligned} \tag{4}$$

$$\begin{aligned} A1 &= B1 / 2 \\ A2 &= B2 / 2 \end{aligned} \tag{5}$$

Although both options are geometrically compatible, it is important to consider that in scenario (4) illustrated in Figure 3, triangle T5_6_7 is half of T4_7_5 and would be susceptible to considerable pressure during unfolding and the structure would have to be designed to withstand this. Therefore option (5) represented in Figure 4 would be structurally more stable.

4.3. Different non-proportional thicknesses

Two options are here investigated for origami of thick panels made with scissor pantographs with different non-proportional thicknesses, both of which satisfy:

$$A1 \neq X \text{ x } B1 \neq B1 / X$$
$$A2 \neq X \text{ x } B2 \neq B2 / X \tag{6}$$

4.3.1. Intersecting plane

By intersecting a plane α through the top layer A1 of the origami- scissor diamond structure parallel to T4_7_5 through a non-proportional plane, one obtains two different and not proportional thicknesses, as expressed in (6) and illustrated in Figure 5. As the plane cuts through the scissor pantographs, single bars are left throughout the length of the edge and nodes V are lost in vertices 4, 9, 5, 7 and 8, therefore the nodes along the segment S7 defined by pantograph S6_5 do not match the nodes along its counterpart segment S7 defined by S5_4 pantograph. This case study therefore highlights the condition for adjoining scissor pantographs to make creases: the adjoining pantographs must not only have the same length, but have the same morphology and bilateral symmetry so that they are geometrically compatible and can be joined at the end nodes.

4.3.2. Interweaving layers of scissor pantographs

Another option to achieve an origami-scissor structure made with different non-proportional thicknesses (6), is to interweave the layers of scissor pantographs. Figure 6 displays how triangle T4_7_5 (thickness A1) is lowered down interweaving T4_6_5 (thickness B1), by doing this both segments S7 (7) remain intact and will be able to be joined to generate the origami scissor structure. In this instance, points P1 and P2 have been aligned so that the bars at these nodes can be made of continuous bars. Where F was previously a single node where the bars of thickness A1 and B1 would coincide, now there are four nodes closely placed, creating shorter bars. These shorter bars could have an impact on the mobility of the structure and would require the design of specific ratio of thickness versus length in order to be viable.

5. Conclusions

Origami-scissor hinged deployable structures [2] [18], built with layers of pantographs, can fold and unfold as the origami of thick panels [4], and simultaneously expand and contract retaining the geometry and the relative angles of the thick origami intact. This paper illustrates a study that tests the geometric compatibility of different possibilities of morphology of origami-scissor hinged layers. If various layers are used, it is preferable to use layers of equal thicknesses as it was done with the diamond origami-scissor hinged pattern [2]. If different thicknesses of layers are used, they can be fully geometrically compatible if they are proportional. A fundamental condition so that they are geometrically compatible in the creases is that the pantographs must have equal morphology and bilateral symmetry; this allows for the different origami faces to be joined at the end nodes.

An interesting option is that of interweaving pantographs. This scenario illustrates how in this instance it would be possible to achieve a geometrically compatible diamond origami-scissor hinged pattern with interweaved layers of pantographs. Therefore, if certain ratios of thickness versus length of bars have been accounted for, interweaving pantographic layers can decrease the overall thickness of the structure, increase is structural strength and allow for new geometric and morphological design possibilities.

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