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Dynamic shelter structure

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ABSTRACT: Dynamic building envelopes have entered the mainstream practice of architecture in the last decades. Such dynamic systems are capable of changing their geometric configurations repeatedly and reversibly relative to environmental conditions and occupant requirements. Thus, they may offer innovative building solutions by folding, expanding or curling. This study proposes a dynamic shelter structure that provides several shape options in response to the changing needs. In order to generate the shelter structure, first, loop assembly method used for developing the structure is introduced. Then, a parametric model is built in Grasshopper® not only to analyze the geometric properties of the loops and their alternative geometric forms but also to develop a flexible tool allowing changes at topological, geometrical and structural levels. Based on the geometric analysis, the structural mechanism is constructed. Transformation capability and possible configurations are studied. The proposed structure can transform itself into multiple forms (from planar configuration to S-shaped and reversed S-shaped configurations) with single DOF although the existing single DOF scissor structures can deploy between two geometric shapes.

1 INTRODUCTION

For centuries now, an architecture to respond specific needs has been sought. Migrating tribes created their way of lightweight and transportable architecture in the form of tents and Yurts (Kahn 1973). As there were different situations, adaptable systems arose as well. In antique arenas, the solution to weather conditions was found with deployable membrane canopies (Escrig 1996). On the other hand, a drawbridge leading into a city needed to allow citizens in and out while it had to be folded away to protect the city. As the tools were primitive, so were the solutions. With the advances throughout time, we are now able to develop more complex structures to accommodate more sophisticated needs.

Today the demand for a more dynamic architecture has increased even more. The already packed cities without much space, rapidly changing usage scenarios of spaces, emergency conditions, material and effort consumption and the environmental harm caused by buildings are just some of the reasons making the subject even more worth the attention. In the last century, both architects and engineers searched for novel structures to answer the demand.

Adapting to different climates and landscapes, being able to take many forms depending on the requirements of users and their capacity to meet rapidly changing circumstances and needs are what makes transformable/deployable structures so promising. As a temporary construction, a structure that is lightweight, can be stacked, transported and reused also has a lower impact on the environment. These characteristics also go parallel with the aims of sustainable design.

A deployable structure incorporating a mechanism has at least one kinematic degree-of-freedom (DOF). This gives the structure the ability to change configuration, such as transforming from compact to expanded forms. Most of the time this is a reversible action and they perform their architectural function only in the fully deployed configuration. Architectural examples of such structures are typically temporary lightweight structures like emergency shelters (Thrall & Quaglia 2014), exhibition and recreational structures and retractable roofs (Kassabian et al. 1999).

Various structural systems in a wide range have been proposed as deployable/transformable systems such as scissor (or pantographic) structures (Van Mele et al. 2010), deployable tensegrity (Fuller & Applewhite 1975), structural origami (Trautz & Cierniak 2011), foldable membrane structures (Otto & Rasch 2001) and -more recently- tensairity (De Laet et al. 2009). In their work, Hanaor and Levy (2001) sorted the most common ones into groups according to their morphological and kinematic properties. The proposed shelter structure in this paper belongs to the structural group with rigid links composed of scissor elements.

The scissor structures that are extensively used as deployable structures today were first introduced by Pinero (1961). The first dome structure utilizing scissor units was exhibited by Zeigler in 1974. Using planar translational scissor-like elements (SLEs) in various directions to form grids, another pioneer in the field, Escrig generated three-dimensional structures. Using two-way and three-way scissors, he also developed spherical grid structures (Escrig & Valcarcel 1986, 1987). One well-known real-life application by Escrig is the roof structure of the swimming pool of San Pablo Sports Centre in Seville (Escrig 1996). Using curved translational scissor units, Langbecker & Albermani (2000, 2001) formed doubly-curved synclastic and anticlastic structures. On the other hand, using the angulated scissors, Hoberman (1990, 1991) developed many structures such as arches, domes and spheres; also some well-known structures such as his trademark toy sphere, Iris Dome at EXPO 2000 and Hoberman Arch which was presented at 2002 Winter Olympics at Salt Lake City. Hoberman's angulated scissor unit was further examined in detail by You & Pellegrino (1997). They expanded their research forming rings of scissors and adding inner rings to achieve a structure that can radially close and retract like an iris. Kassabian et al. (1999) developed a structure that rests on columns with pin joints. Van Mele (2008) is another researcher who proposed a barrel vault made up of two angulated scissor arches carried by pin connected arches.

Previous works are mostly composed of structures, which have only two modes either open or closed, and they transform from one to another to be utilized. Recently, the studies by Maden have expanded the adaptability and form flexibility of adaptive shelter structures (Maden et al. 2015, Maden 2017) in which the structures have multi DOF allowing various geometric configurations from plane geometry to doubly-curves geometries. This allows the structures to be configured dynamically and utilized in any state in between these modes.

In this paper, a dynamic shelter structure is proposed which has the ability to change its geometric shape into different forms with single DOF. The novelty of the structure is its generation method and varying forms. Rather than using the current design approaches in the literature, another approach called loop assembly method is used to generate the structure that is composed of kite loops.

2 GEOMETRIC DESIGN METHOD

In the literature, the scissor structures are mostly created using primary scissor units that are translational, polar and angulated units (Fig. 1). The desired geometry is formed by connecting the predefined scissor units to each other. Due to the geometric compatibility conditions of the

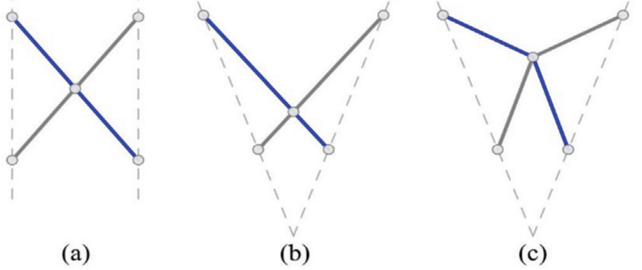

Figure 1. Primary scissor units: a) translational unit; b) polar unit; c) angulated unit.

scissor units, the solutions proposed for architectural applications are generally restricted to certain geometric forms such as vaults and domes although there are some proposals for more free forms and hypar geometries. Further, the generated forms are able to deploy only between two geometric shapes with single DOF. There is no other form possibility.

However, in this paper, the structure is generated by loop assembly method in which the type and number of the scissor elements are determined later based on the type of the loops. Compared to first aforementioned method, the loop assembly method allows generating transformable structures with single DOF, which can transform to different geometric forms more than two.

2.1 *Loop types*

The loop types are identified based on the quadrilaterals. In Euclidean plane geometry, a quadrilateral is defined as a four-sided polygon with four vertices (Johnson 1929) which has three topological types as convex, concave and crossed quadrilaterals (Fig. 2a). Interior angles measure less than 180^0 in convex quadrilateral whereas one interior angle exceeds 180^0 in concave quadrilateral. On the other hand, the sum of the interior angles on both sides of the crossing are equal in crossed quadrilateral. Rhombus, square, rectangle, parallelogram, kite, dart and trapezoid are the basic geometric shapes that fall under the quadrilateral category (Fig. 2b). Using these shapes, different types of scissor loops can be generated.

2.2 *Loop assembly method*

Loop assembly method is based on constructing the scissor structures by using aforementioned loop types. In the literature, this method was first used by Hoberman (1990) to design radially deploying closed loop structures. On an arbitrary polygon, he placed the rhombus loops and then created the elements. Similarly, he developed straight rhombs, arch-hinged rhombs and circle-hinged rhombs. Rhombus loops were also used by Liao & Li (2005) and Kiper & Söylemez (2010). Bai et al. (2014) used kite, parallelogram and tetragon loops. On the other hand, Yar et al. (2017) used kite and dart loops whereas Gür et al (2017) used anti-parallelogram loops.

In this paper, kite loop is chosen among the aforementioned examples of quadrilaterals to construct the dynamic shelter structure. First, identical kite loops are assembled on a plane (Fig. 3a) and then scissor element is drawn on the edges of the two adjacent kite loops as shown in Figure 3b. The scissor element is angulated-shaped which lies on the long side of the first loop and the short

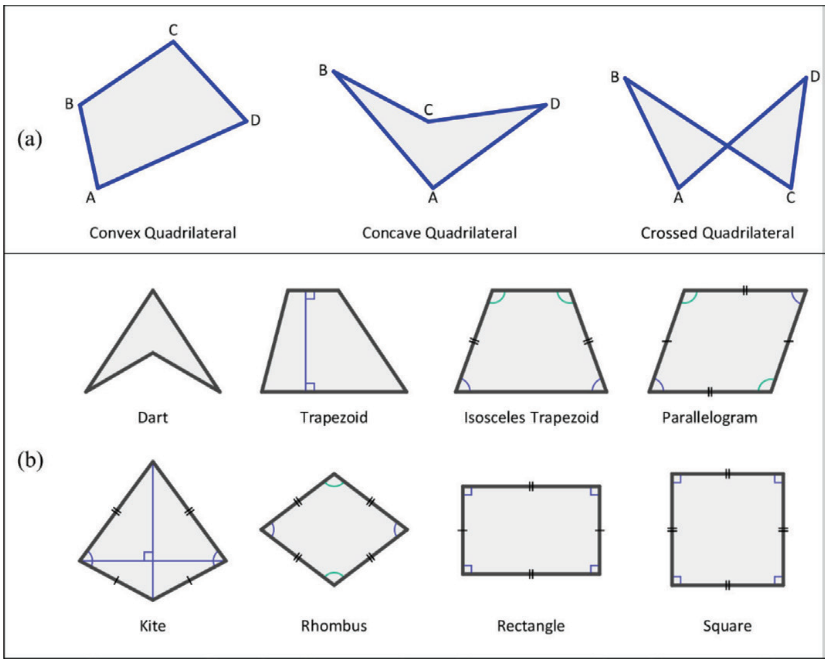

Figure 2. a) Quadrilaterals; b) Types of quadrilaterals.

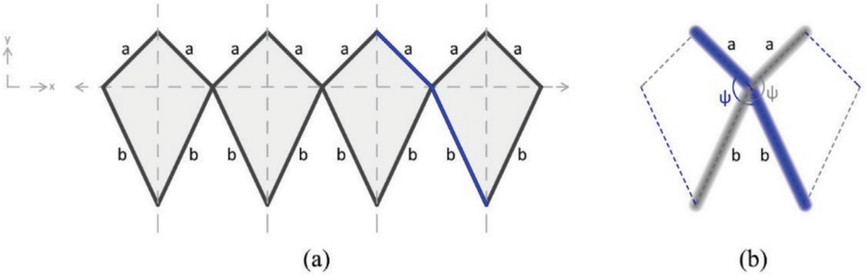

Figure 3. a) Kite loops; b) Generation of the scissor element.

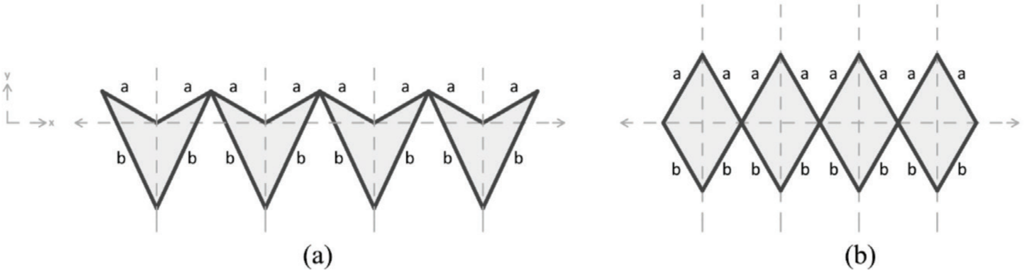

Figure 4. a) Dart loop assembly; b) Rhombus loop assembly.

side of the second loop. The kink angle of the angulated element defines the transformation behavior of the loop assembly. To generate a kite loop assembly, the kink angle should be in between $90^0 < \psi < 180^0$. If it is equal or less than 90^0, a dart loop assembly is obtained as illustrated in Figure 4a. On the other hand, if it is equal to 180^0, the elements become straight and a translational loop assembly with rhombus loops is created (Fig. 4b).

3 DESIGN PARAMETERS AND PARAMETRIC MODEL

In order to study the geometric properties of the loop assembly composed of kite loops, a parametric model is created in Grasshopper®. In the parametric model, first, geometric and deployment conditions of the kite loop are defined. Then, different loop assemblies composed of kite loops are generated. Input parameters are different for all loop assembly and configuration types. Because of their hinge points and span-based or module-based geometry creation selections, they require different sets of parameters. However, loop's long and short arm lengths (PropLongArm and PropShortArm), number of loops (Amount) and angle of the element (KinkAngle Ψ) are defined as input parameters at the initial stage (Fig. 5).

Using the kite loops, two different loop assemblies are generated which are arch-shaped loop assembly and S-shaped loop assembly. For both types, input parameters are the same. For arch-shaped loop assembly, span distance of overall structure is also a parameter to define the adequate arm lengths, which makes the lengths the output of the algorithm to optimize. These parameters are only to create one set of dynamic structure on a plane, which is not an array to generate a three-dimensional structure. Planar geometry is generated as an array on a circle defined by algorithm outputs, which uses arm lengths and angles in between them. After generating two-dimensional arms for both assembly systems, for realization of the geometry, additional parameters added as horizontal array of arms (amount) and horizontal distance between arms. All these parameters prepared to be used in geometry optimization of all structures, means they only generate line-weight structure as an imitation of the overall structure in Rhinoceros 5® environment. However, variable parameters are the length and shape of the bars, which are defined to demonstrate the structural properties after completing geometry optimization in line-weight terms in order to reduce the required computational power.

3.1 *Arch-shaped loop assembly*

The arch-shaped loop assembly is composed of identical kite loops, which allows generating three different geometric configurations with single DOF (Fig. 6). In the first configuration, the loops remain in horizontal position and the loop angle (θ) is at the initial value. As the angle θ is changed, the loop assembly changes its geometry and two other configurations are obtained. When θ is increased, the loops curl up and create an arch-shaped geometry. On the other hand, if θ is decreased, the loops roll down and form a reversed arch-shaped geometry.

3.2 *S-shaped loop assembly*

S-shaped loop assembly is created by connecting two arch-shaped loop assemblies to each other. One of the arch-shaped loop assembly is convex while the other one is concave. The S-shaped loop assembly has three possible configurations: linear, S-shape and reversed S-shape. In order to investigate possible applications of this assembly, two alternatives are proposed. It is fixed at one end-point in the first case and at the mid-point of S-shape in the second case (Figs. 7-9). For both cases, same generative algorithm is used. However, to demonstrate the required fixed-point calculations, several transformations on overall geometry are used. These transformations are based on the point which geometry is fixed. Deconstruction of those points in x-, y- and z-axis in virtual environment used to move the geometry to target location, which is fixed point. Then, angle between point (0,0,0 to 10,0,0) and opposite arm point (which is the mirrored point which fixed arm point is located) used to rotate the structure.

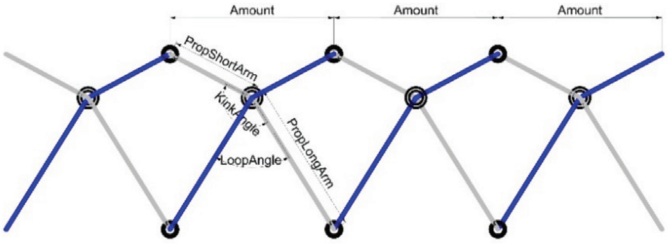

Figure 5. Defined parameters of the kite loops in Grasshopper.

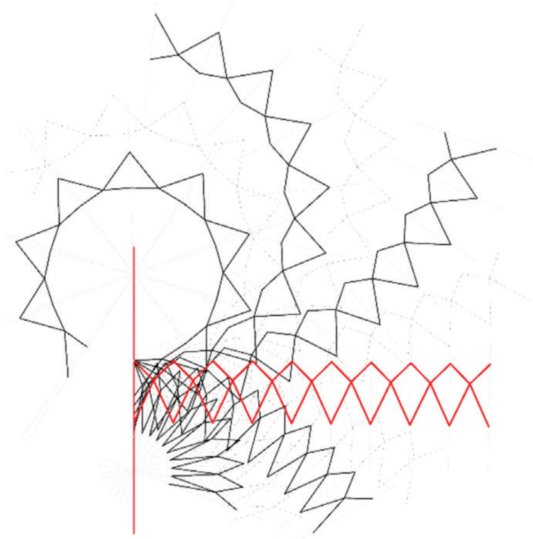

Figure 6. Transformation process of arch-shaped loop assembly.

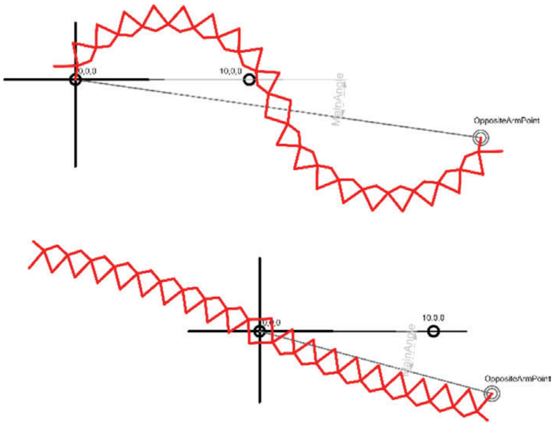

Figure 7. Two alternatives to fix the S-shaped loop assembly.

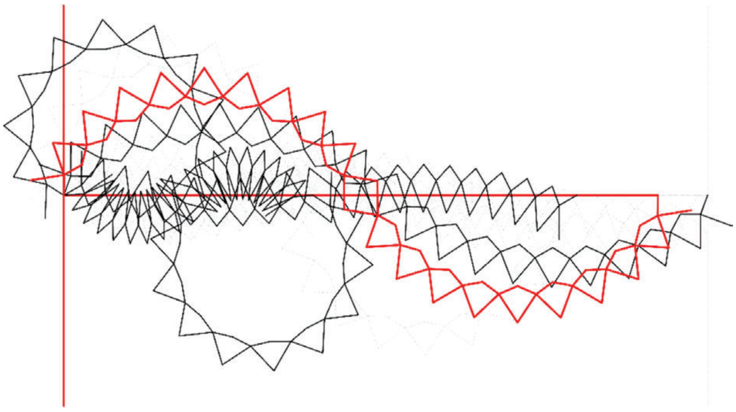

Figure 8. Alternative #1: transformation process of S-shaped loop assembly fixed at one end-point.

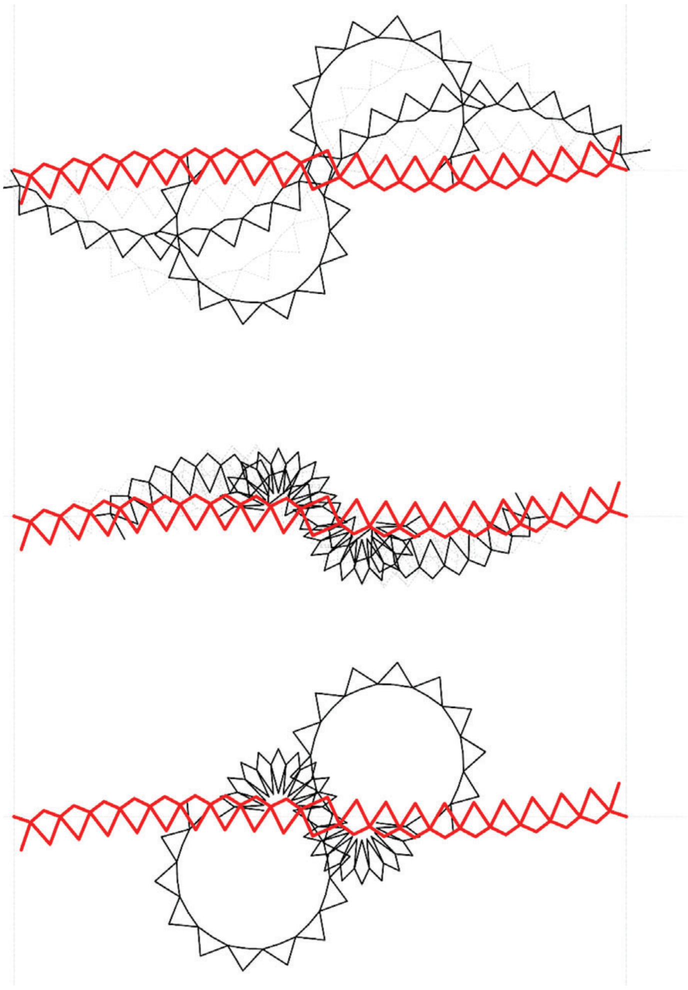

Figure 9. Alternative #2: transformation process of S-shaped loop assembly fixed at mid-point.

4 THE DYNAMIC SHELTER STRUCTURE

Covering approximately 140m^2, the proposed structure is implemented as a dynamic shelter that can serve for different temporary or permanent activities. To create the dynamic shelter structure, aforementioned S-shaped loop assembly is used. The structure is composed of eleven S-shaped modules that are connected to each other by X-shaped elements. Each S-shaped module is composed of nine kite loops. The kite loops comprise of angulated elements (PropLongArm= 70cm and PropShortArm= 35cm) that are hinged at their mid- and end- points.

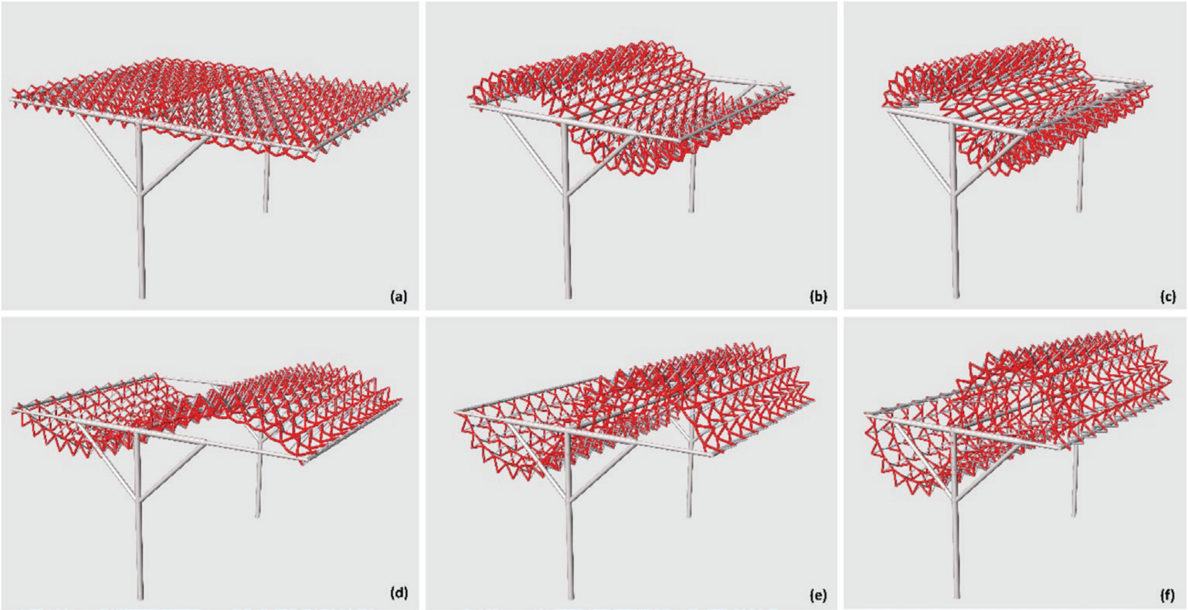

Figure 10. Transformation process of dynamic shelter structure.

Because the generated system behaves like a mechanism, it is required to convert the created structural mechanism into a load bearing structure. For this purpose, telescopic beam elements are added to the system, which allow linear translation of the system in horizontal direction. Those elements are supported by bracing elements and connected to 7m-high columns by pin connections. As the telescopic beam elements extend or shorten, the curvature of the structure changes.

There are revolute joints at the connection points of the loops to the beams and columns, which provide the required rotational motion. By this means, the structure changes its geometry from the S-shape to the reversed S-shape (Figs.10b-f). In addition to these forms, the structure can also remain at planar configuration (Fig 10a) that allows generating a flat surface. As the activity changes underneath the structure, the structure can be adopted to the needs of the users by changing its geometry. Although most of the existing examples are limited to two geometric configurations such as open and closed, the proposed dynamic shelter structure provides more flexibility on form generation.

The motion of the structure can be provided by a single actuator since it has single DOF. Although changing the length of the telescopic beams could provide a change in the form, this method lacks to change the direction of the curves. The other possible actuation strategies are changing the angle between the angulated links of the loops or the translational elements. As the translational elements' unit thickness increase, the structure folds more compact and assumes an S-shape and as the unit thickness decrease, the structure unfolds to cover a greater distance in translational scissors' direction while the form becomes reversed S-shape.

5 CONCLUSIONS

In this paper, a dynamic shelter structure has been presented which has the ability to transform itself into different geometric shapes. The structure has been created using the loop assembly method that allows more flexibility on form transformation with single DOF even though it is required to use more DOF in the existing examples to generate different geometries. This reveals the superiority of the proposed structure over the existing ones since the dynamic shelter structure not only transforms from S-shaped geometry to the reversed S-shaped form, but also provides a planar configuration. According to the changing circumstances, the structure responds to the user needs by geometric transformations. In order to validate the feasibility of the proposed shelter structure, it is necessary to conduct structural analysis. As a future work, the structural performance of the shelter structure will be tested considering the design loads and principal limit states.

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