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Structural comparison of scissor-hinge linkages

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ABSTRACT: Deployable structures can deploy from a compact to an expanded configuration by changing their sizes. The behaviors of these structures depend on some parameters such as geometric shape, member sizes and kinematic properties. To provide the deployment, not only the arrangements of structural members but also some restrictions must be considered. Moreover, contiguous members of the structures must let the large rotations to provide the transformation between different geometric forms from fully folded to fully deployed configurations. These requirements have an important impact on the fundamental properties of the structures related with structural performance, such as stiffness and strength. In this paper, stiffness of different scissor-hinge linkages are analyzed and compared. These linkages cover the same span with almost the same geometry and have the unit elements with same size and same weight. However, the geometry of unit elements is different from each other. The paper investigates the effect of this difference on the stiffness of whole system.

1 INTRODUCTION

Scissor-hinge linkages are the most preferred type of deployable structures since they are easy to assemble and disassemble. Mostly used in portable or temporary applications such as emergency shelters, exhibition areas, bridges, space enclosures and aerospace applications, these linkages provide significant volume expansion. A typical scissor-hinge linkage system consists of scissor units that are composed of two bars connected by a revolute joint on bars. The linkage is formed by connecting the units to each other with revolute joints at their end nodes.

For all types of scissor units, there is an imaginary line between the upper end-point of one bar and the bottom end-point of the other bar, which is called “unit line” (Fig. 1a). Scissor-hinge linkages can be classified into three categories depending on the geometry of unit lines, the dimensions of the bars and the location of the scissor joint on the bar. When the unit lines remain parallel to each other during the deployment process, a “translational scissor unit” is obtained (Fig. 1a). The scissor-hinge linkages made up of translational units can only slide without any rotation. “A polar scissor unit” is created by connecting two straight bars with scissor hinges away from the midpoints of the bars (Fig.1b). The result of connecting polar units to each other is a single curvature arc so they are convenient to form singly-curved structures such as barrel vaults or the more basic scissor arch (Mira et. al. 2014). An “angulated scissor unit” is obtained by connecting two identical angulated bars instead of straight bars, which have a kink with an angle (Fig.1c). The scissor joint is located on this kink of the bar. This property provides structure to make a radial deployment about a center.

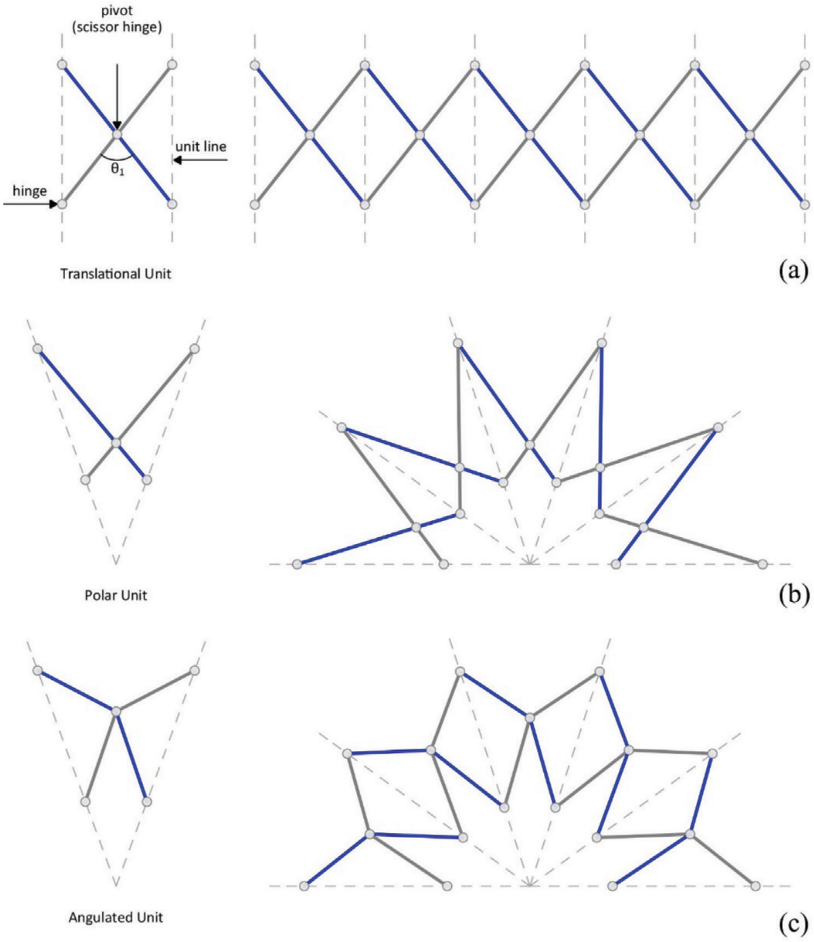


Figure 1. Primary scissor units and the scissor linkages generated by them: a) translational scissor-hinge linkage; b) polar scissor-hinge linkage; c) angulated scissor-hinge linkage

The research on the scissor-hinge linkages started in 1961 by Piñero (1961) and followed by many other researchers until today. After Piñero, these linkages were further developed by Escrig and Valcarcel (1986a, 1986b, 1987 and 1993) as in the forms of new spherical grid structures that are composed of two-way and three-way scissors with several connection details. The roof structure of the swimming pool of San Pablo Sports Centre in Seville is one of the well-known real-life application by Escrig (1996). In addition to these developments, Hoberman made significant contributions to the literature by his designs and patents from architectural applications to the toy industry. He proposed a novel concept composed of angulated elements that led to design of radially deploying closed loop structures (Hoberman 1990, 1991). In the following years, deployable structures were applied to space applications, including antennas and solar panels by Pellegrino and You. They took Hoberman's discovery a step further and discovered generalized angulated elements to be used as a building block (You & Pellegrino 1997). Kassabian et al. (1999) reduced the number of elements of a deployable structure with multi-angulated elements that are used to construct mounted on pinned columns. Van Mele (2008) used scissor arches composed of angulated elements to cover a tennis arena. He designed a vault consisting of two opposite pin connected scissor arches. In addition, a new scissor component called as "universal scissor component" was introduced by De Temmerman and Mira (2010). This component can be used as translational unit, polar unit or angulated unit for different applications and various geometries such as barrel vaults and domes. Studies of Akgün et al. (2010, 2011) are also important for the research on the topic. These studies propose a new scissor unit called "modified scissor-like element" and the developed scissor-hinge linkages can transform their geometries without changing the span length.

As can be seen from the studies in the literature, deployable structures offer transformability and aesthetic advantages but it is well-known that there is a significant price to pay with respect to

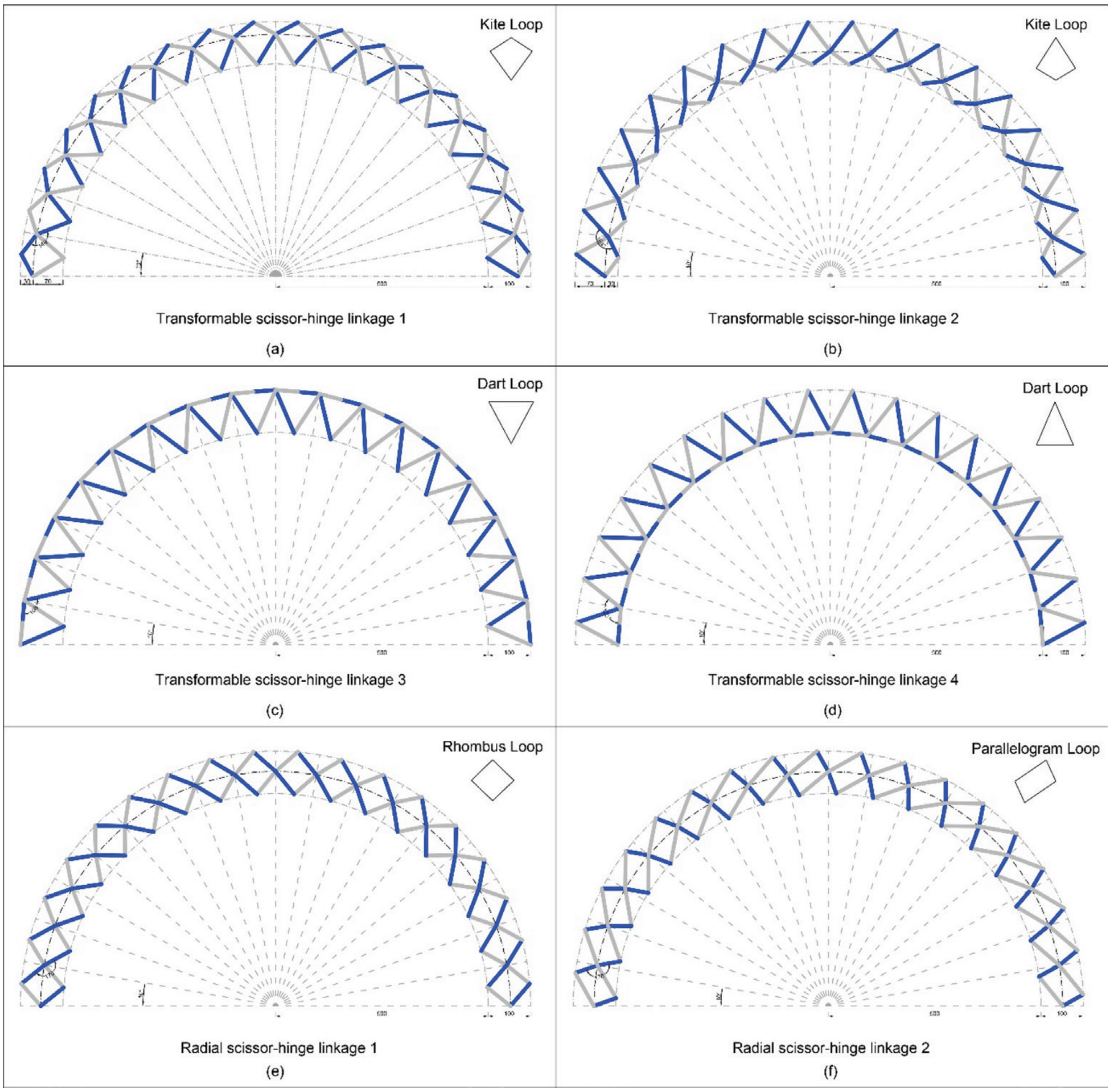


Figure 2. Six scissor-hinge linkages tested in the case study

their structural response and efficiency. This paper aims to investigate and compare the structural behavior and stiffness of various scissor-hinge linkages made up of various primary units, and reveal the best alternative. In order to arrive at this aim, a case study involving six different scissor-hinge linkages are investigated in the paper. These six linkages have the same geometric shape (an arch) with the same span length, same profile sections and same height; only the scissor units and the geometry of the primary units are different from each other. The scissor-hinge linkages tested in the case study are presented in Figure 2.

STRUCTURAL ANALYSIS

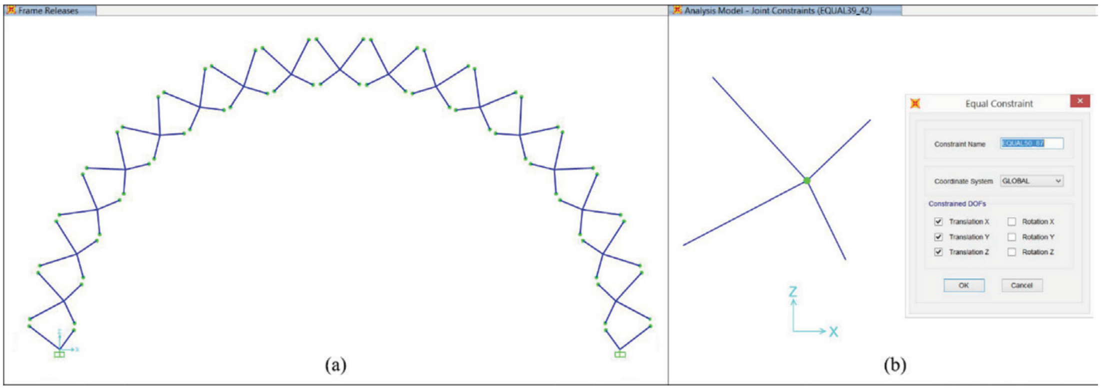
In this study, different configurations of two linkage types are considered which are transformable scissor-hinge linkage and radial scissor-hinge linkage. Table 1 summarizes the analyzed 2D structure types and topographic properties. The analysis and section optimization is done using Sap2000®. Eurocode 3-2005 provision's strength limit states are used without any load combination to determine the sections of members. Although real life design may be governed by the deflection limit checks, it is not considered in this study since the amount of deflection is an indicator of performance level. The selection of frame section is done among European tubular sections between 60x30x3.6 and 120x60x4. In a real life case, the member sections would be grouped for manufacturing and assembly purposed. However, to compare the top displacements of the arches at their minimum possible weight would provide a better comparison. Hence, each member is assigned to minimum applicable section (in terms of weight) individually. The sections are assumed to be S275 grade structural steel.

Two end-nodes of the structures are assumed to be fixed to simply compare the arcs although a fully fixed connection may not be obtained in real application. However, a stiff connection at the base is required to keep the structural deflections in an acceptable range. Moreover, the connections at the ends of the units are modelled as pinned connection as shown in Figure 3a. Similarly, midpoint connection between the members are defined as pin connection but by defining equal constraint between two members. So that each member would transfer the moment forces through but not to coinciding member (pair). Only translational forces are transferred between the coinciding members. Figure 3b shows the equal constraint definition.

2.1 *Loading of the Arc*

All structures are loaded in same way with 1kN/m projected gravity direction load as shown in Figure 4. Frame members with none section property (no stiffness, no weight) are used to transfer loads on the structural members. Self-weights of the sections are considered automatically by the software.

Wind loads and other actions are taken into consideration in this work, to be able to compare performance results in a simpler manner. Likewise, the vertical load and dead load is linearly added without combination coefficients.



Constraint Name: EQUAL50_87

Coordinate System: GLOBAL

Constrained DOFs

☑ Translation X ☐ Rotation X

☑ Translation Y ☐ Rotation Y

☑ Translation Z ☐ Rotation Z

Figure 3. a) End releases (pin joints) of structural model; b) scissor joint constraint

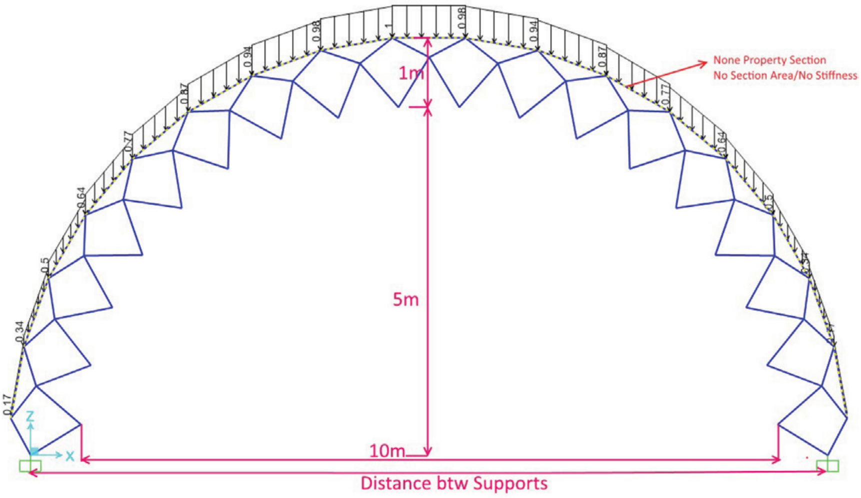


Figure 4. Characteristic dimensions and loading of the arc

2.2 *Results*

All the structures have 10m of inner span and 5m of inner height with 6m of outer height. The results of analysis and design are provided in Table 1. Weight of the structure and the maximum top displacement are normalized with respect to average of all structures and combined by simply multiplying as given in Equation 1.

$$Rating = \frac{\Delta_i}{\frac{\sum_i^n \Delta i}{n}} * \frac{W_i}{\frac{\sum_i^n Wi}{n}} \tag{1}$$

where Δ_i = max top displacement for structure *i*; W_i = self-weight of structure *i*.

2.2.1 *Transformable Linkage structures*

For transformable linkage (TL) type structures, it is clearly seen that when the angular sides are outwards and inner side follows a smooth arc (Fig. 6d), 10m inner span may be obtained with 10m support distance. Shorter support distance obviously decreases the forces on members and the top displacement. Moreover, when TL1 and TL3 (Figs. 6a & 6c) are compared, although the distance between the supports of TL 3 is more, it performs better in terms of top displacement with a slightly higher weight. TL2 (Fig. 6b) is a middle form of TL1 and TL4. TL2 is slightly smoothed version of TL1 at the inner side of arc that improves the performance significantly especially in terms of top displacement without much difference in distance between supports. To sum up, for transformable linkages, a smooth form at any side of the arc would highly increase the structural performance, since the forces would be transferred axially through the frames. On the other hand, if smoothness of the arc is provided inside, required support distance for the needed inner span would be shorter and results in lower deflection.

2.2.2 *Radial Linkage*

Two Radial linkage (RL) arches are considered in this work. RL1 (Fig. 6e) is a symmetric and similar to TL1 where RL2 (Fig. 6f) is composed of parallelogram loops which is not symmetric in terms of load transfer to base. The asymmetry in RL2 results difference of deflections/forces between right and left sides of arc. At the right top side, longer edges of parallel are positioning horizontally which results in higher moments (Fig. 5) and less stiff area. Hence, the top displacements are higher and shifted to right.

Table 1. Properties and performance of structures (low the rating, better the performance)

Linkage Type	Distance btw Supports m	Inner Span m	Inner Height m	Max Height m	Max Top Displacement m	Weight of Structure kN	Disp./ Avg.Disp	Weight/ Avg.Weight	Rating
Radial Linkage 1	11.04	10	5	6	-0.280	3.07	1.06	1.09	1.15
Radial Linkage 2	11.03	10	5	6	-0.317	3.35	1.20	1.19	1.42
Transformable Linkage 1	10.87	10	5	6	-0.340	2.67	1.29	0.95	1.22
Transformable Linkage 2	10.60	10	5	6	-0.249	2.43	0.94	0.86	0.81
Transformable Linkage 3	12.00	10	5	6	-0.250	2.77	0.94	0.98	0.93
Transformable Linkage 4	10.00	10	5	6	-0.152	2.60	0.57	0.92	0.53
				Average	-0.265	2.81			

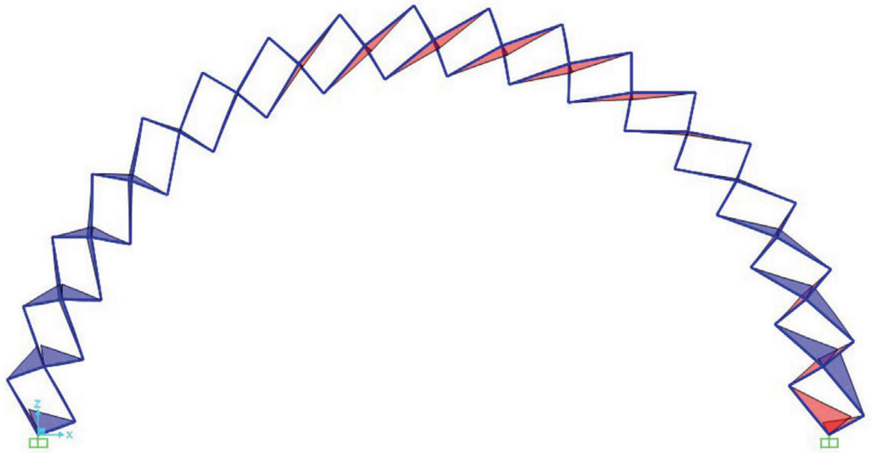


Figure 5. Moment diagrams on the frames for RL2 under self-weight and 1kN/m projected loading

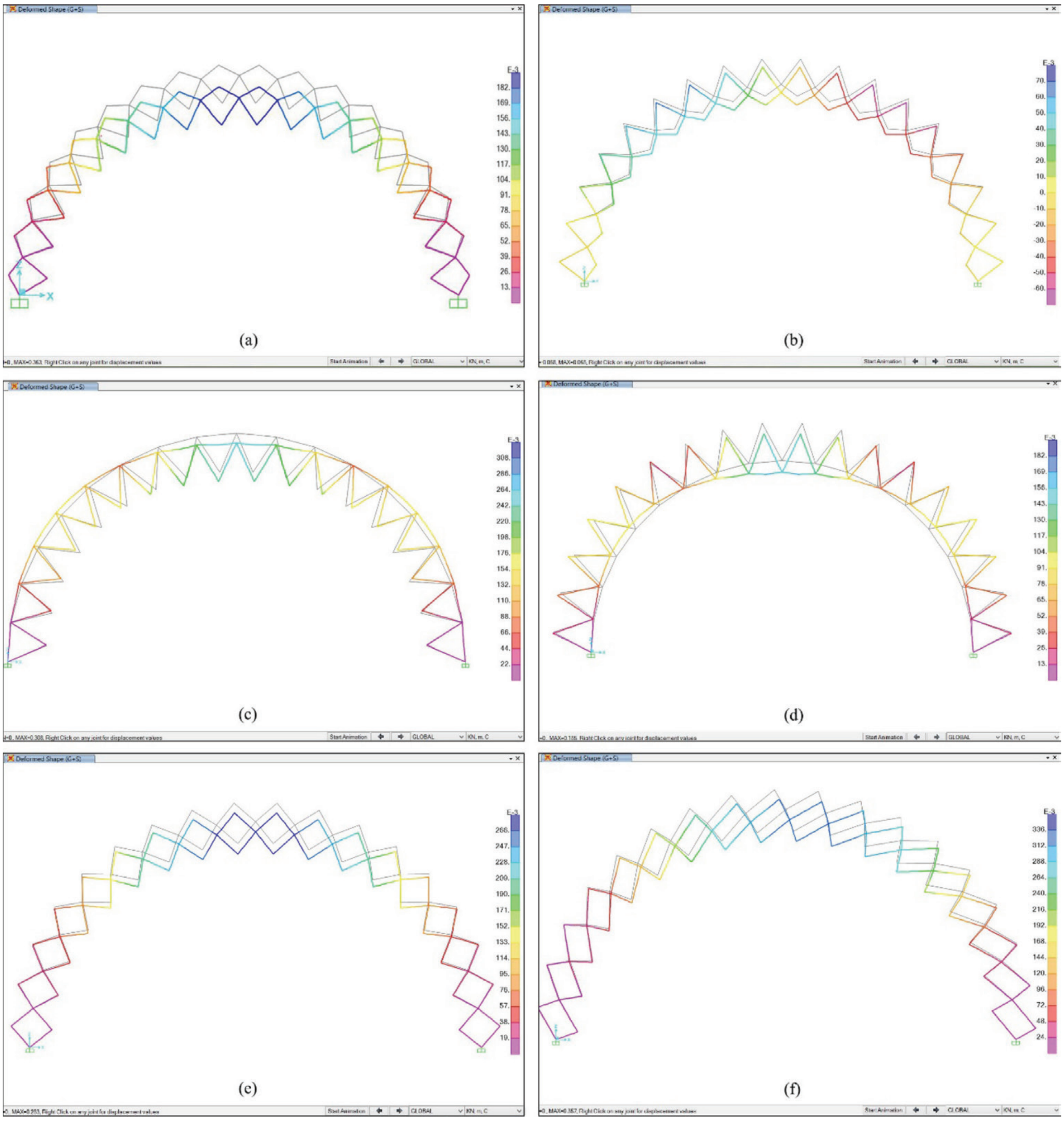


Figure 6. Deformed shapes of structures a) TL1 b) TL2 c) TL3 d) TL4 e) RL1 f) RL2

2 CONCLUSIONS

In the present paper, an initial effort for the quantification of the carrying capacity of scissor-hinge linkages with different primary units has been made. In order to achieve this aim, a case study has been carried out. The scissor-hinge linkages presented in this case study cover the same span with almost the same geometry. Although the size and weight of the unit elements are same, their geometry are different from each other. According to the conducted structural analysis, it has been found that there is a significant difference in stiffness according to the used primary scissor unit. It can be concluded that choosing the proper scissor unit at the initial stage is very important to design a load bearing structure, because the geometric shape of the unit directly affects the structural response of the scissor-hinge linkage.

3 ACKNOWLEDGMENT

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4 REFERENCES

Akgün, Y., Gantes, C.J., Kalochairetis, K. and Kiper, G. 2010. A novel concept of convertible roofs with high transformability consisting of planar scissor-hinge structure. *Engineering Structures* 32: 2873-2883.

Akgün, Y., Gantes, C.J., Sobek, W., Korkmaz, K. and Kalochairetis, K. 2011. A novel adaptive spatial scissor-hinge structural mechanism for convertible roofs. *Engineering Structures* 33: 1365-1376.

De Temmerman, N. & Mira, L.A. 2010. Design and analysis of a universal scissor component for mobile architectural applications. In Proceedings of the international IASS symposium on spatial structures – temporary and permanent, Shanghai, China, 815-826.

Escrig, F. & Valcarcel, J.P. 1986a. Analysis of expendable space bar structures. In Proceeding of IASS Symposium on Shells, Membranes, and Space Frames. Osaka: Elsevier Science Publishers. 269-276.

Escrig, F. & Valcarcel, J.P. 1986b. Great size umbrellas with expendable bar structures. In Proceedings of the 1st International Conference on Lightweight Structures in Architecture, Sydney, University of New South Gales, 676-681.

Escrig, F. & Valcarcel, J.P. 1987. Curved expandable space grids. In Proceedings of the International Conference on the Design and Construction of Non-conventional Structures. London: Civil-Comp Press.

Escrig, F. & Valcárcel, J.P. 1993. Geometry of expandable space structures. *International Journal of Space Structures* 8: 71-84.

Escrig, F. 1996. General survey of deployability in architecture. *Transactions on the Built Environment* 21: 3-22.

European Committee for Standardization. Design of Steel Structures-Part 1-1 General Rules and

Rules for buildings. Brussels: European Committee for Standardization, 2005. ICS 91.010.30

Hoberman, C. 1990. Reversibly expandable doubly-curved truss structure. U.S. Patent 4,942,700, July 24.

Hoberman, C. 1991 Radial expansion/retraction truss structures. U.S. Patent 5,024,031, June 18.

Kassabian, P.E. You, Z. & Pellegrino, S. 1999. Retractable roof structures. In Proceedings of the Institution of Civil Engineers-Structures and Buildings, 134: 45-56.

Mira, L.A. Thrall, A.P. & De Temmerman, N. 2014. Deployable scissor arch for transitional shelters. *Automation in Construction* 43: 123-131.

Piñero, E. 1961. Project for a mobile theatre. *Architectural Design* 12: 154-155.

Van Mele, T. 2008. Scissor-hinged retractable membrane roofs. Ph.D. Thesis. Vrije Universiteit Brussel.

You, Z. & Pellegrino, S. 1997. Foldable bar structures. *International Journal of Solids and Structures* 34: 1825-1847.