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A Case Study on the Selection of Optimum Loop Units for the Deployable Arch Structures Exposed to Lateral and Non-uniform Gravity Loads

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Abstract

Radially deployable arches may be created by using various types of units. However, for any deployable structure to be constructed in real life, it should satisfy the structural regulations and codes. Despite various advantages from architectural perspective, deployable structures are weak to satisfy the operational code limits when compared to trusses with similar height and span. Therefore, weight minimization is very important to reduce the dead loads of the structure which facilitates the code-conformance of the structure. The optimization of the deployable structures requires an initial selection of the loop types to define the structure parametrically. An initial selection strategy depending on the loads on the structure is important to increase the efficiency of optimization process. Under uniform gravity loads, optimum arrangement for each unit type converges to a similar point. However, in the real world, the loads on the arches are not always uniform and the structure is exposed to non-uniform loadings such as point loads or lateral loads. This work focuses on the performance of various arches with different unit types under lateral and non-uniform vertical loads. Different lateral load and non-uniform gravity loading scenarios are created. For each scenario, the arches with different units are analyzed. In all cases, clear span and height are kept as same. The performance of an arch with a specific unit type for a given load is measured with a score that includes the deformations and the weight of the structure. All the members are assumed to be circular hollow sections with variable diameter and thickness to have a meaningful weight comparison between structures. This work intends to define an initial selection guide for deployable arches under typical non-uniform and lateral loading conditions.

Keywords: Deployable, Structures, Scissor, Lateral, Load, Structural Analyses

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1. Introduction

Deployable structures are increasingly becoming popular in architectural applications as they provide geometrical and spatial change. Considering the usage requirements of the architectural spaces, deployable structures may also offer multi-functionality to the design. Scissor-hinge linkages are one type of the deployable structures that can be used as temporary shelters or protective covers for outdoor activities, emergency shelters or bridges after natural disasters, retractable roofs for sporting fields, pavilions, exhibition halls, and similar purposes.

A scissor-hinge linkage is composed of scissor units having two bars that are connected by a joint. A unit is defined by unit lines that are imaginary lines between the ends of two bars on the same side (Fig.1-a). Depending on the position of these unit lines with respect to each other, unit type is defined. When the two-unit lines are parallel, it is called translational unit. Linkages of translational units can only move through a straight line [1].

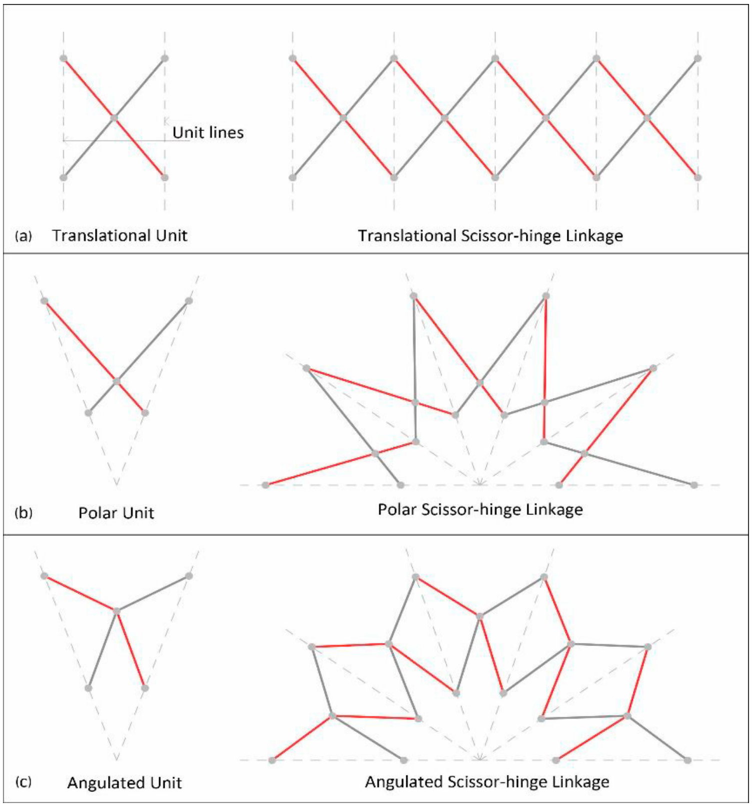


Fig. 1. (a) Translational unit; (b) Polar Unit; (c) Angulated Unit

If the unit lines are coincident, then the structure may form different shapes. Coincident bar unit types may be split into two categories as polar unit (Fig. 1-b) and angulated unit (Fig. 1-c) depending on the geometry of the bars. A polar unit always forms a single radius arc. In spite of that, the angulated units may form different deployment shapes by changing the point of kink and angle. In addition, multi angulated members are used within same structure to decrease the used number of units [2]. There are studies on angulated members that are used to cover large spans such as tennis courts [3].

1.1. Structural performance and optimization

Despite the advantages of scissor-type structures, they have drawbacks to structural performance. The bars of a unit experience moment, shear and axial forces. In this way, these structures are different from a classical truss.

Especially the bending moment is the main source of deflection on the members. Consequently, cumulative deflection of a scissor arch may exceed the serviceability levels. Control of the deformation would require deeper bar section which would increase the weight. Weight is then increasing the deflections and element forces.

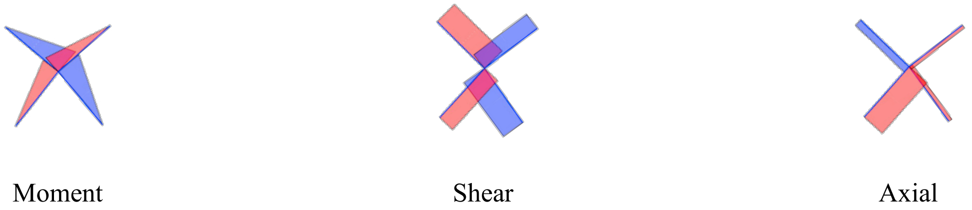


Fig. 2. (a) Moment diagram of bars of a unit; (b) Shear diagram of bars of a unit; (c) Axial force diagram of bars of a unit

Therefore, weight optimization of the structure is important and through the optimization process the deflection is a major criterion. However, weight optimization alone may not be applicable to real life if it cannot meet the expectations of the industry. An optimization tool should be fast, providing clash-free solutions that industry can apply rapidly. Because a rework or a possible problem on site may wipe out all the savings of optimization. Predefinition of some standard scissor types would increase the optimization performance of the code and decrease the possibility of clashes due to the accumulation of experience on these predefined types. By predefined scissor types, the code may perform an initial selection according to the applied loads on the structure.

Previously a case study was conducted on the uniform gravity loads representing the structures that are not exposed to environmental actions such as indoor structures [4]. However, these structures may also be used for outdoor applications. Possible major lateral load sources for these structures are wind and earthquake loads. Due to lighter self-weight of these structures, they are not much affected by earthquakes. On the contrary, wind loads are dominant since they may be used to close large areas.

For the optimization of a deployable arc structure, the architectural constraints should be defined in advance. These constraints may be the inner span, clear height of the structure and the number of loop units. The kink angle of the bar and the length from one end to the kink (|DE| or |BE| in Fig. 3) are the variables.

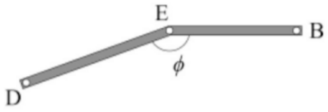


Fig. 3. Angulated bar

This paper presents a case study that is conducted to understand the behaviour of arc structure with different linkage-type under horizontal and non-uniform gravity loads.

2. Case Study

A case study with six different loop configurations is performed to understand the behavior of the arc structure. The six configurations are shown in Fig. 4. All configurations are basically composed of angulated units; but, the kink location and the kink angle are different. Fig. 5-a shows the typical geometry of the configurations. All have 5m inner height, 10m inner span and 1m of section depth. The spacing of frames in third dimension is assumed to be 5m to calculate the tributary wind load acting on the frame. The analysis is performed in two groups. First, with uniform dead load and lateral wind load for each configuration. Secondly, a point load is acted on the arch at different points to observe the response of the structure to non-uniform gravity loads. The structures are assumed to be stiffened after deployment by placing two truss bars at both supports which would bring the deflections to a reasonable level. The analyses are done in SAP2000® software. At every unit, the connection between the bars are moment free and translationally constraint to each other.

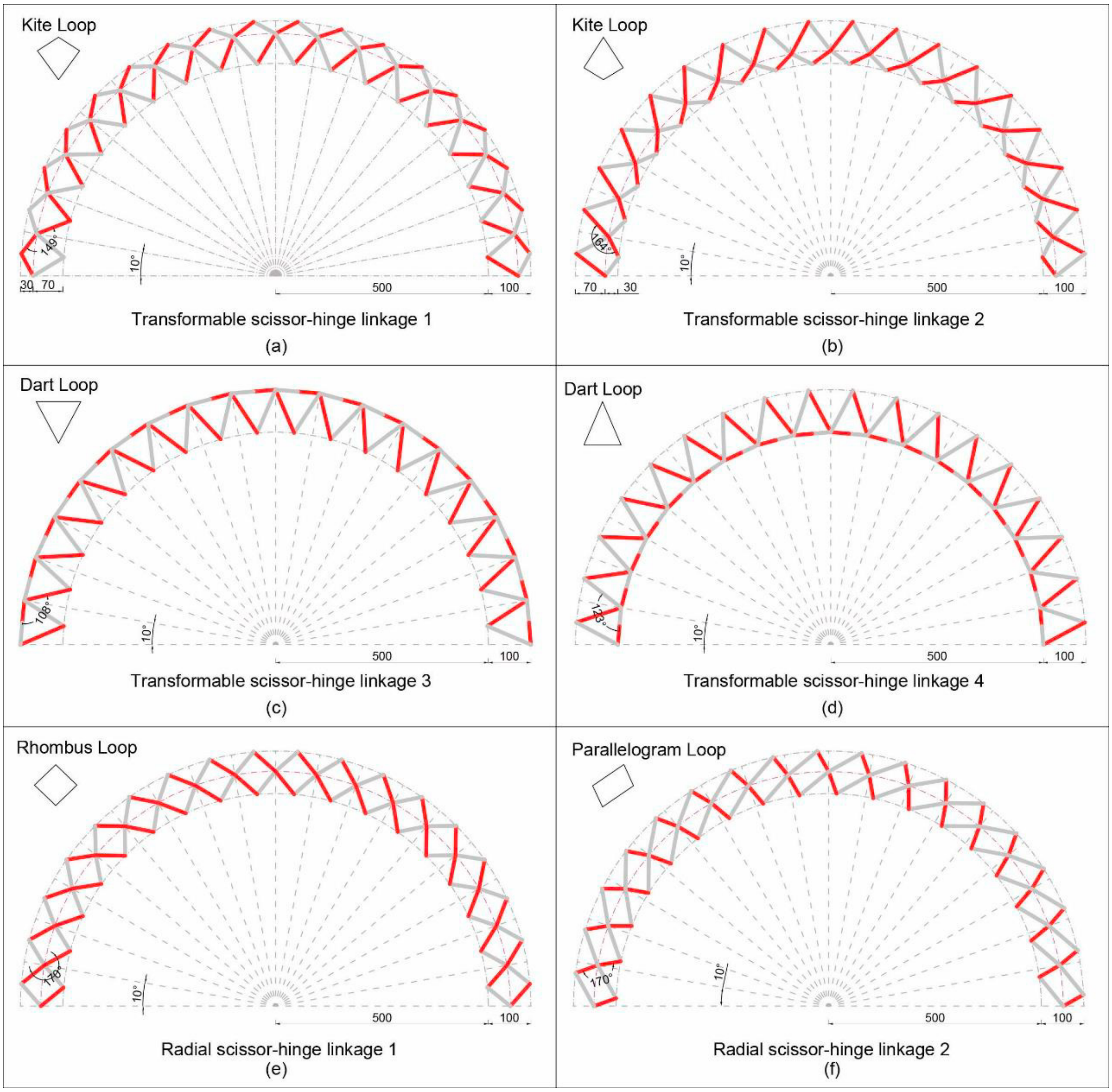


Fig. 4. Case Study Configurations

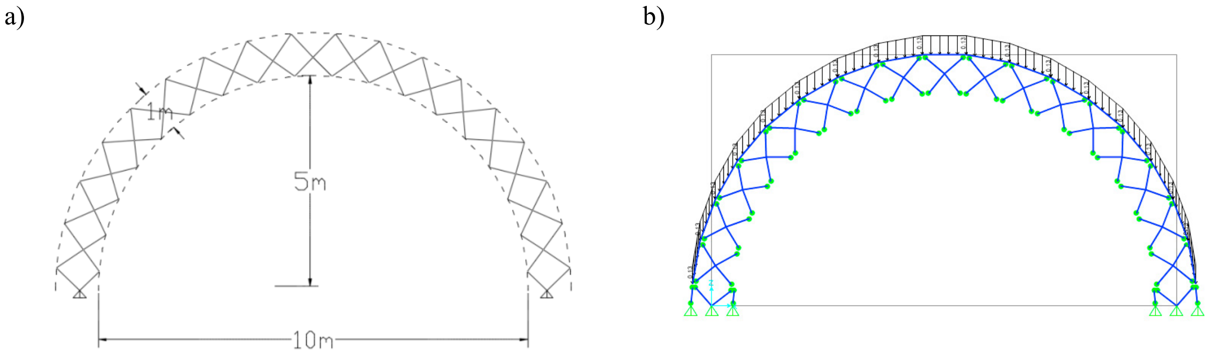


Fig. 5. (a) Typical geometry of configurations (b) Dead load application on the model

2.1. Loads

Dead Load:

The temporary and transformable structures such as tents are covered with a membrane. 2.5 kg/m^2 of area load in addition to dead load of the frame is assumed to account for the membrane and appurtenances. That is equivalent to 12.5kg/m (0.125kN/m) for 5m spacing. Application of dead load is given in Fig. 5-b.

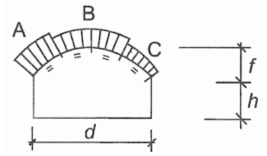
Live Load:

Live loads may be presented on these structures due to appurtenances or any other hanged load. However, these loads are considered separately as non-uniform gravity load.

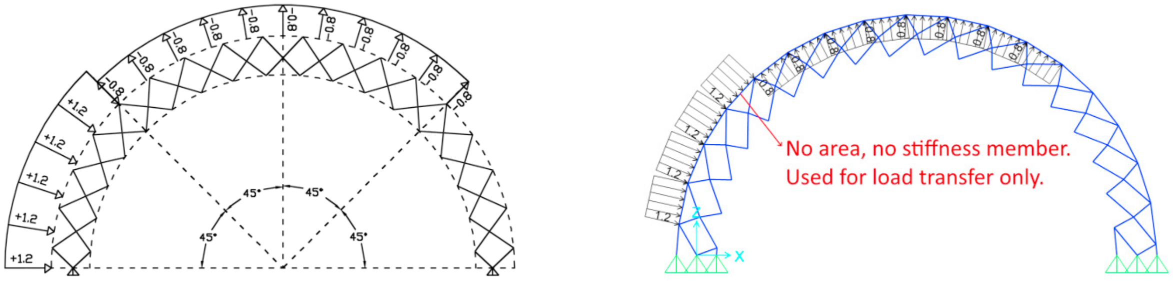
Wind Load:

Wind loads acting on the arch type structures are defined in section 7.2.8 of Eurocode 1.4. Internal pressure coefficient (C_{pi}) is taken as -0.4 by assuming it is closed structure with little air leakage. The resultant of the external and internal pressure is applied to the outer side of structure. For the application of tributary load on the structure, frames with "none" section property is defined between the outer nodes. These frames do not introduce any stiffness or weight into the model and just transferring the loads to nearby nodes. The coefficients that are defined in the Eurocode are used as given in Table 1.

Table 1: Pressure area for arches acc. to Eurocode

Pressure Area	**C_{pe10}**	
A	0.8	
B	-1.2	
C	-0.4	

Above pressure coefficients are applied on the arch as shown in Fig. 6-a and these loads are multiplied with 5m spacing while applying in the model. Due to the symmetry wind loads are considered only from one side that is representative of both sides. Fig. 6-b shows the member end releases, support conditions and load application in model.



No area, no stiffness member.
Used for load transfer only.

a) b)

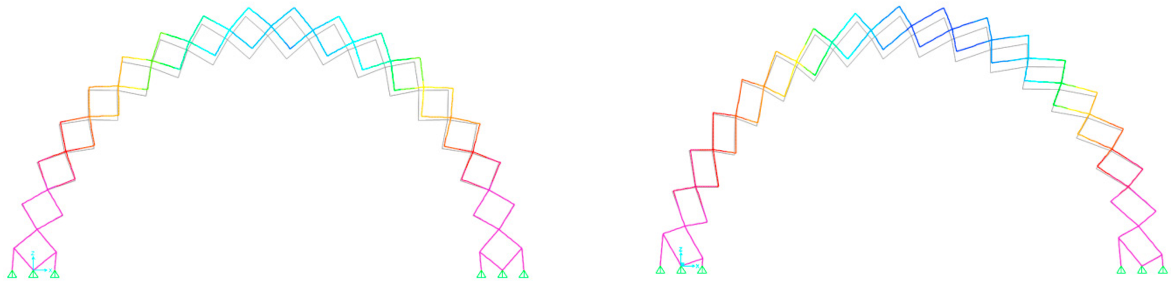
Fig. 6. (a) Wind loads pressure on arch, (b) Application of wind load and member end releases

2.2. Design of members

The design of the members is done according to Eurocode strength limits under unfactored combination of Dead + Wind loads for comparison purposes. Deflections are not limited by serviceability limits since the deflections are used as an input for the ranking of different loop types. Members are not grouped and each bar is designed individually with the possible minimum section. Only European rectangular tubular sections are used in design not to take advantage of section shape and to be able to rank the performances equally between the loop types. Steel grade of S235 is used.

2.3. Analysis

Final minimum sections are selected through SAP2000® design tool. The deflected shapes of the arches with the displacement contours are given in Fig. 7.a-f. It can be observed that the arches tend to direct the deformations upwards except the dart loops. Upward deformation is dominant due to the pressure distribution of the wind on the arch as well. With increasing uniform vertical downward loads, the deflections are orienting to horizontal.

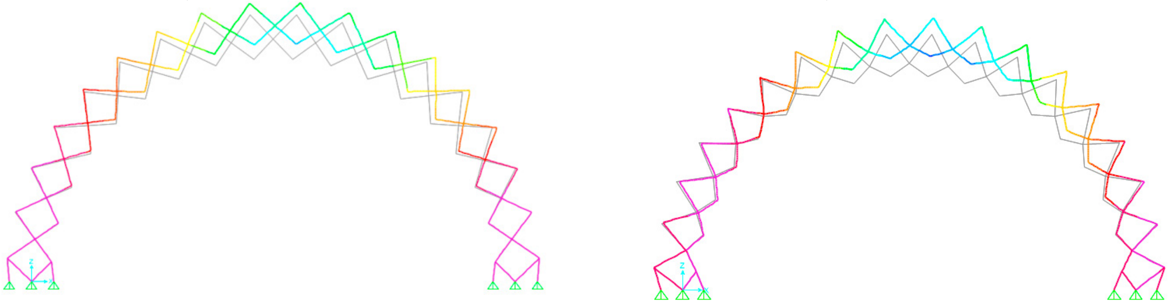


a) Radial 1

Rhombus Loop

b) Radial 2

Parallelogram

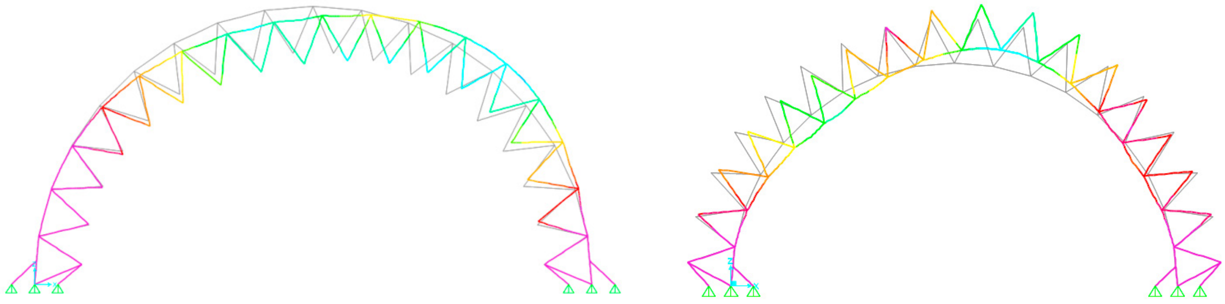


c) Transformable 1

Kite Loop

d) Transformable 2

Kite Loop



e) Transformable 3

Dart Loop

f) Transformable 4

Dart Loop

Fig. 7. Deformation gradient of (a) Radial-Rhombus loop, (b) Radial-Parallelogram, (c) Transformable-Kite Loop, (d) Transformable-Kite Loop 2, (e) Transformable Dart Loop, (f) Transformable Dart Loop 2

2.4. Rating

A rating system is required to quantitatively compare the loop performances. For comparison, the horizontal displacement, the vertical displacement and the weight of structure are combined.

$$Rating = \frac{\Delta h_i}{\frac{\sum_i^n \Delta h_i}{n}} * \frac{\Delta v_i}{\frac{\sum_i^n \Delta v_i}{n}} * \frac{W_i}{\frac{\sum_i^n W_i}{n}} \qquad (1)$$

$\Delta \mathrm{h_i} = \text{max horizontal displacement of structure}$
$\Delta \mathrm{v_i} = \text{max vertical displacement of structure}$
$\mathrm{W_i} = \text{self} - \text{weight of the structure}$
$n = total\ number\ of\ compared\ arch\ structures$

The proposed rating in Eq. 1 treats the horizontal and vertical deflection separately. It should be noted that the displacement values are absolute values. Lower weight and lower displacements compared to other configurations would result in a smaller rating number; therefore, lower the rating better the performance. Despite the importance of displacement or weight may differ due to the applications, for a basic comparison Eq. 1 is found to be useful. The results of the analysis and the design under Dead + Wind loads are given in Table 2.

Table 2. Comparison of loop configurations under Dead+Wind load

Linkage Type	**Distance btw Supports m**	**Inner Span m**	**Inner Height m**	**Max Height m**	**Max Vertical Displacement m**	**Max Horizontal Displacement m**	**Weight of Structure kN**	**Ver Disp./ Avg.Disp**	**Hor Disp./ Avg.Disp**	**Weight/ Avg.Weight**	**Rating**
Radial Linkage 1	11.04	10	5	6	0.267	0.150	8.15	0.97	0.82	1.12	0.89
Radial Linkage 2	11.03	10	5	6	0.247	0.054	8.17	0.90	0.30	1.12	0.30
Transformable Linkage 1	10.87	10	5	6	0.356	0.222	6.81	1.30	1.22	0.94	1.48
Transformable Linkage 2	10.60	10	5	6	0.163	0.093	6.51	0.59	0.51	0.89	0.27
Transformable Linkage 3	12.00	10	5	6	0.347	0.327	7.45	1.26	1.79	1.02	2.32
Transformable Linkage 4	10.00	10	5	6	0.269	0.248	6.60	0.98	1.36	0.91	1.21
				Average	0.275	0.182	7.284				

From the ratings, transformable linkage 1, 3 and 4 are found to be performing poor. Although they are the lightest options among others, their displacements, especially in horizontal direction, are high compared to other configurations. Radial linkage 2 (Parallelogram Loop) and Transformable Linkage 2 (Kite Loop) have the best rating with the contribution of their lower horizontal displacement.

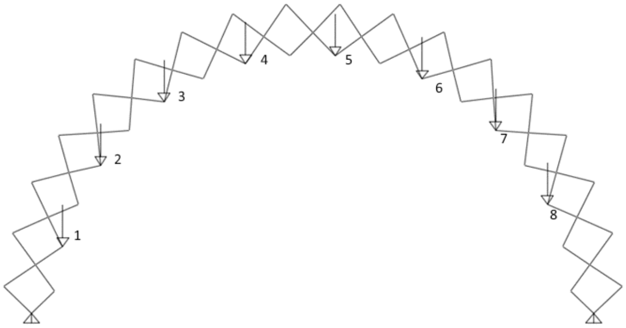


Fig. 8. Sample configuration for the vertical loading nodes

2.5. Arbitrary vertical point load application

The arch structures may expose to vertical non-uniform loads such as hanging equipment, decoration etc. Arc shape, by nature, is well performing against the loads that are directed to their center of radius. However, concentrated loads that are not directed to the center may be dangerous depending of the magnitude of the load. Thus, all the case configurations are loaded with single 2 kN (200kg) of concentrated load at the inner nodes one by one at each run. As a result of these consecutive analyses, single concentrated loads at 2kN level do not show a significant effect in deformation profile or member sizes. Only some replacements at the neighboring members of load application is necessary that would be handled in design process. However, at the preselection of the loop type for optimization purposes, this concentric loads are not a selection parameter.

3. Conclusion

This case study compares the different linkage unit types for their performance under wind actions. Comparison is done by using a rating method mentioned in Section 2.4. According to rating of each linkage unit, a set of preselection may be done to decrease trial set for the optimization algorithm.

When the performance of each loop type is reviewed, the dart loops are not performing well under wind loads although they were found to be better under uniform gravity load [4]. The bars that are tangent to the circumference of arc results in high bending moments since they do not have an axial resisting component in radial direction. Any optimization code should not start with a similar configuration. Moreover, Transformable linkage 2 type is performing very well with its low weight and satisfactory displacement. The bars of this linkage are oriented in a way that does smaller angle with the radial line of the arch. Therefore, the wind action does not create high moment, but axial force. This characteristic is found to be common in the well performing arches. So that, a limitation on the angle with the imaginary radial lines may be defined within the optimization algorithm to decrease sample subspace.

On the other hand, concentrated vertical loads of simple decorations and equipment are not a major issue for the selection of loop type. A comparative result could not be found. But, it is important for the sizing of members around the hanging locations.

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