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The effect of minimized orientation of members in connections on the structural behavior of free-form lattice space structures

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Abstract

In free-form space structures, the orientation of structural members is adjusted by the local geometrical properties of the free-form surface that cause twist angles in the connections. A basic approach to minimize these twist angles is to change the orientation of the members. Therefore, the main purpose of this research is to review different methods for changing the orientation of members and to investigate the effect on the stability behavior of free-form space structures. In this study, a single-dome and a double-dome free-form space structures with different grid patterns have been selected and initial and optimal orientation of the members have been calculated in their configuration using programming in MATLAB. Then the selected structures are designed and analyzed using SAP2000 and the stability behavior has been investigated using ABAQUS. The results show that changing the orientation of members in order to minimize twist angles on grid lines, improves stability behavior in most cases.

Keywords: Free-forms, Space structures, Minimized orientation of members, Twist angles, Connections, Stability behavior.

1. Introduction

In contemporary times, the utilization of free-forms in the construction of lattice space structures is of great interest. These complicated structures need special considerations in design and fabrication process. The internal forces within members of free-form space structures vary from axial forces to significant bending moments, as evidenced by their structural behavior. So in most free-forms, members have rectangular cross sections. In this structures, the orientation of each member is adjusted by the local geometric properties of the free-form surface that cause twisting angles in the connections [1-3]. Figure 1 shows the middle planes of the members on a grid line of a lattice structure. As shown, the different orientations in different positions have caused twisting angles on a grid line, which makes the manufacturing process of jointing system complicated and expensive. Manipulating and minimizing these twisting angles to achieve the twist-free connections is ideal for construction (Figure 2).

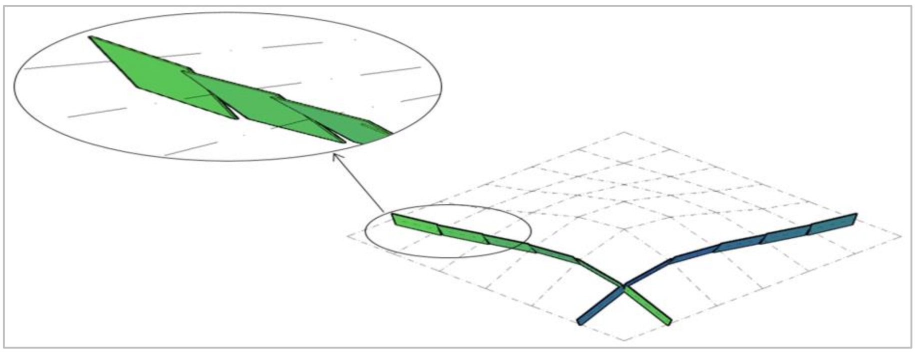


Figure 1: The middle planes of the members on a grid line of a lattice space structure

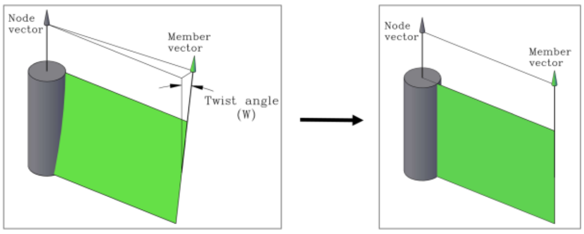


Figure 2: The twist-free connections is ideal for construction

Extensive research has been conducted on minimizing twist angles for traditional space structures, with geodesic domes serving as a prominent early example. However, there have been few advancements in optimizing twist angles for free-form grid shell structures. (A comprehensive overview of these methods can be found in reference [3]). One of the practical approaches to minimize the twist angles is the changing orientation of members. This approach has also been used in the construction of great free-form structures, Similar to the YAS Viceroy in Abu Dhabi (Figure 3) and had a positive impact on costs, load-bearing capacity and aesthetics [2-4].

Figure 3: YAS Viceroy Hotel in Abu Dhabi (2008); structural design by schlaich bergermann and partner [2]

It is obvious that changing the orientation of the members in order to minimize the twist angles in the connections will be effective on the structural behavior of free-form space structures, Nevertheless, there are queries that require clarification. In what way and to what extent? In general, published researches in this regard, such as Xiongjue [5], ignore the effect of reducing twist angles in connections and only focus on the orientation of members. Therefore, considering the importance of minimized orientation of members in connections in the practical process of design and fabrication of free-form space structures, this research will be beneficial.

2. Optimized orientation of members in connections

According to Figure 4, the orientation of a member is defined by vector that is placed in the middle of the panel vectors located adjacent to that member and it is obtained from the mathematical averaging of these panel vectors [1]. The resulting orientation, in addition to matching the geometry of the freeform configuration, also enables direct glazing [2]. This particular orientation is referred to as the "Panel-mean" orientation in this context. Figure 1 shows these orientations for the middle planes of the members on a grid line of a lattice space structure. This process of determining the orientation of members will cause huge and non-uniform twist angles in the joints and complicated jointing systems [6-7].

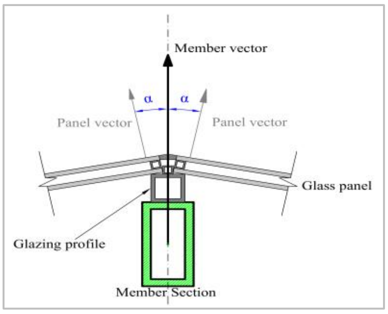


Figure 4: Direct glazing of glass panels to members

It is practically possible to change the orientation of the members in order to reduce the twist angles in the connections. According to Figure 5, with the rotation of each member individually on their cross-sectional plane, the twist angles can be minimized in a connection. This change the orientations must be carefully considered in the design procedure and also in the installation of cladding system [3]. It is possible to use this approach in order to minimize the twist angles throughout the grid shell configuration with different methods. The methods used in this study are as follows:

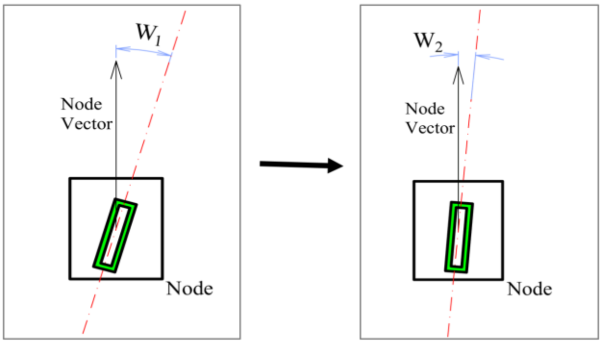


Figure 5: reducing twist angle by rotating the member on its cross sectional plane.

2.1. Uniform-line method

In this method, the same orientation is applied to all members located in a grid line. With this method according to Figure 6, twist-free connection is possible for the members on that grid line. To achieve this uniform orientation, for example, it is possible to average the orientations of members in a grid line and apply this average value uniformly to all members of that grid line. This particular orientation is referred to as the "Line-mean" orientation in this context. Another choice for this, can be the orientation of the member that has the greatest deviation from the vertical direction in the grid line. This orientation is called the “Line-max” orientation in this context.

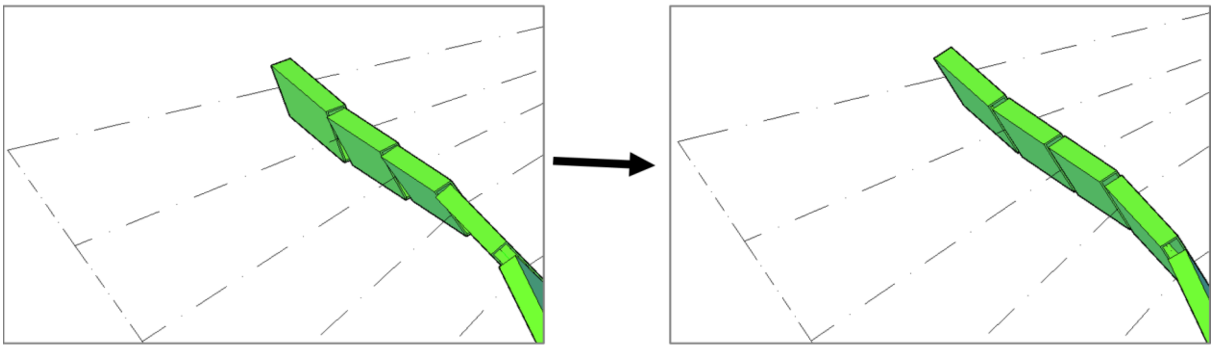


Figure 6: applying the same orientation to all members that are on a same grid line

2.2. Orientation resulting from the relative twist angles (W_n)

According to Figure 2, the twist angle in a connection is defined as the angle between the member vector and the node vector which may also have different values in adjacent nodes. As seen in Figure 7, if the vector of a member is rotated and placed in the middle of two adjacent node vectors, the resulting angles will be the same on both sides [8]. Here, this angle in a connection is called the relative twist angle of that connection, and the corresponding orientation is called the “W_n” orientation.

This orientation is calculated and assigned specifically for each member of the free-form configuration and in addition to equalizing the twist angles on both sides of a member, it also reduces the maximum twist angles in all connections of the structure.

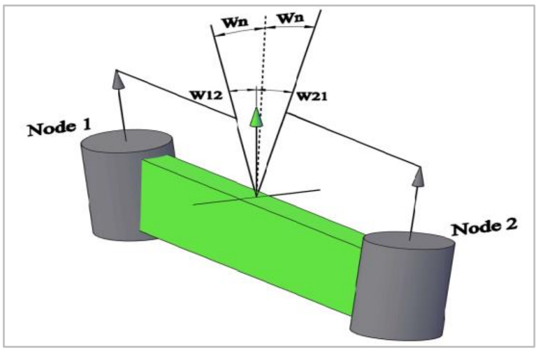


Figure 7: relative twist angles “W_n” at adjacent nodes

3. Generation, design and analysis of models

Figure 8 shows the steps of preparing models to study the structural behavior of free-form space structures. In this paper, Formex configuration processing is used for generation of information about various aspects of free form space structures such as element connectivity, node coordinates, joint number and support arrangements [9], [10]. After configuration processing, initial and optimal orientation of the members are calculated in the configuration of the grid shells using programming in MATLAB software and S2K text files are created for design and analysis in SAP2000 software. Finally, the structural models are transferred to ABAQUS software to study stability behavior.

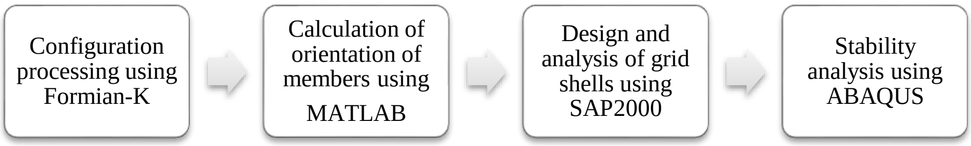


Figure 8: Steps of generation, design and analysis of models

St37 steel and rectangular beam sections are used in the design of all structures and the orientation of the members as “Panel-mean”, “Line-mean”, “Line-max” and “W_n” has been calculated for each gird shell structure and applied to its members. For simplicity, all supports in all models are assumed to be fixed, and the connections between the members are rigid. Each structure is designed and analyzed for each orientation of the members. The loading and design was under common loads based on Iranian Code of Practice for Spatial Structures [11]. Due to the lack of sufficient information, wind load has not been considered in the design process of free-form space structures. Table 1 gives the loading assumptions considered in the design of studied models.

Table 1: Loading assumptions

Load Type	Assumptions
Dead	50 kg/m2
Snow	Moderate Snow (Pg=150 kg/m2)
Wind	Not considered
Earthquake	Area with intense seismic and soil type II
Temperature	±25ºC

In order to study the stability behavior, non-linear geometric and material analyzes were carried out considering large deformations and to trace the equilibrium path, the “modified Riks method” based on the arc-length approach was used. Timoshenko beam element (B31) is assigned for all members [12] and the loading condition in stability analysis are dead load and symmetrical snow load.

4. Verification of the finite element modeling

IM. Kani & RE. Mcconnel model [13] has been used for verification. As shown in Figure 9, it is a star-shaped dome with steel rod members (diameter = 67.4 mm). The dome has fixed supports at six nodes and concentrated load is applied at the central node of the model. Figure 9 also shows the results of the finite element analysis in present study using the proposed algorithm and IM. Kani & RE. Mcconnel study. It can be seen that load-displacement diagrams in the present study have sufficient accuracy.

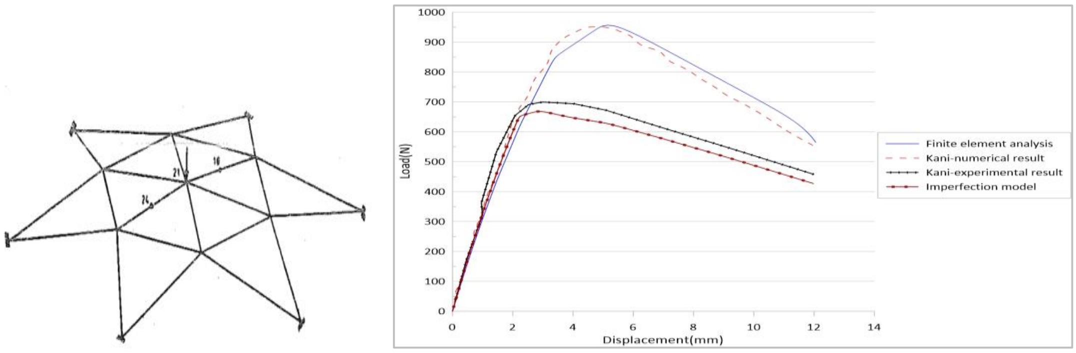


Figure 9: The star-shaped dome in IM. Kani et al. [13] and Verification of the finite element modeling

5. The effect of minimized orientation of members in connections on the structural behavior of free-form space structures

The configuration of the modeled forms is obtained from Formian for levic dome with different patterns and edges held in position (The novation function is used in Formian software) [10]. After calculating the orientation of the members and designing each structure separately, the stability analyses were carried out for the models.

5.1. Single-dome free-form space structure

Figure 10 shows the single-dome configuration with three different patterns. The specifications of the configurations are also shown in Table 2. The information related to the cross-sections assigned to the members and weight of resulting structures for different orientations in design process are also shown in Table 3.

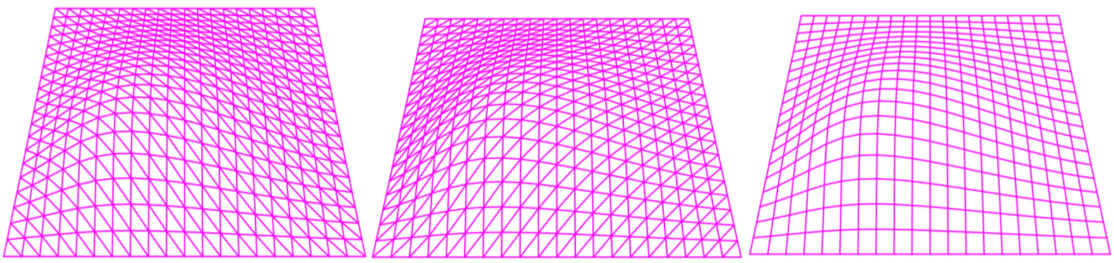


Figure 10: Single-dome free-form space structures: (a). Freeform 1a (b). Freeform 1b (c). Freeform 1c

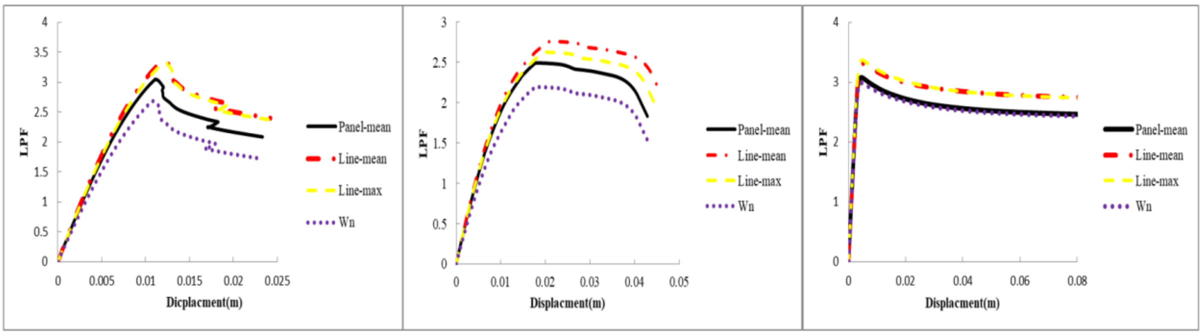
Table 2: specifications of the configurations of single-dome free-form space structures

Configuration	Span (m)	Rise (m)	number of nodes	number of supports	number of members	Max member Length (m)	Min member Length (m)	Average member Length (m)
Freeform 1a	30x30	6	441	80	1240	2.40	1.50	1.70
Freeform 1b	30x30	6	441	80	1240	2.50	1.50	1.70
Freeform 1c	30x30	6	441	80	840	1.90	1.50	1.60

Table 3: The cross-sections and weight of structures for different orientations in design process

Structure	Orientation	Weight (ton)	cross-section of members (mm)
Freeform 1a	Panel-mean	26.20	Box 110*30*4.5, Box 130*35*6, Box 140*40*5
	Line-mean	27.30	Box 110*35*4.5, Box 130*40*6, Box 140*45*5
	Line-max	27.10	Box 110*35.5*4.5, Box 130*35*6, Box 140*45*5
	Wn	25.70	Box 110*30*4, Box 120*35*5.5, Box 140*40*5
Freeform 1b	Panel-mean	26.70	Box 110*30*4.5, Box 130*35*6, Box 140*40*5
	Line-mean	27.60	Box 110*35*4.5, Box 130*40*6, Box 140*45*5
	Line-max	27.30	Box 110*35.5*4.5, Box 130*35*6, Box 140*45*5
	Wn	26.00	Box 110*30*4, Box 120*35*5.5, Box 140*40*5
Freeform 1c	Panel-mean	36.00	Box 270*80*5, Box 260*75*6
	Line-mean	37.20	Box 270*85*5, Box 260*80*6
	Line-max	37.80	Box 270*90*5, Box 260*85*6
	Wn	36.50	Box 260*90*5, Box 245*85*6

Figure 11 shows LPF- displacement responses of the free-form models with different orientation in members in single-dome free-form space structures. Load proportional factor (LPF) is the ratio of ultimate load capacity to design load [14]. As mentioned earlier, “Panel-mean” orientation is the primary orientation of members and “Line-mean”, “Line-max” and “W_n” orientations are also the optimal orientations of members that reduce twist angles in connections. In Figure 11, it is evident that cases which have optimized the twist angle on the grid lines (Line-mean and Line-max) exhibit improved stability characteristics but according to Table 3, these orientations have also increased the weight of the structure to some extent.



(a) (b) (c)

Figure 11: LPF- displacement responses of the models: (a). Freeform 1a (b). Freeform 1b (c). Freeform 1c

Table 4 shows a comprehensive review of weight and LPF of structural models with different orientation of members in single-dome free-form space structures. In this table, in addition to weight and LPF of each orientation in each structure, their percentage of change in comparison to the initial case (Panel-mean) are also presented.

$$\text{Percentage of change} = \frac{New\ value - Initial\ value}{Initial\ value} \times 100 \qquad (1)$$

When considering design aspects, it is important to select an orientation that not only optimizes twist angles in connections but also maximizes LPF while minimizing weight gain in free-form lattice space structures.

Table 4: Summary of weight, LPF and their percentage of change in single-dome free-form space structures

Structure	Orientation	Weight (ton)	LPF	Percentage of change	
				Weight %	LPF %
Freeform 1a	Panel-mean*	26.20	3.05	0.00 %	0.00 %
	Line-mean	27.30	3.36	4.20 %	10.16 %
	Line-max	27.10	3.32	3.44 %	8.85 %
	Wn	25.70	2.7	-1.91 %	-11.48 %
Freeform 1b	Panel-mean*	26.70	2.49	0.00 %	0.00 %
	Line-mean	27.60	2.76	3.37 %	10.84 %
	Line-max	27.30	2.62	2.25 %	5.22 %
	Wn	26.00	2.20	-2.62 %	-11.65 %
Freeform 1c	Panel-mean*	36.00	3.07	0.00 %	0.00 %
	Line-mean	37.20	3.31	3.33 %	7.82 %
	Line-max	37.80	3.37	5.00 %	9.77 %
	Wn	36.50	2.98	1.39 %	-2.93 %

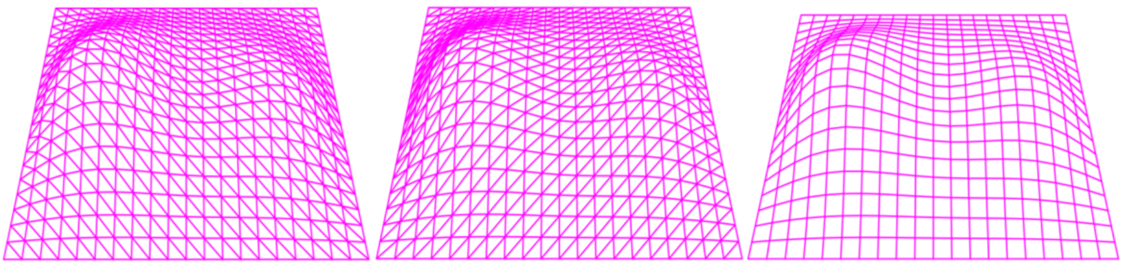
* The Panel-mean values in all structures is considered as the initial values for calculating the percentage of changes.

By reviewing Table 4, the following results are obtained for single-dome free-form space structures:

- The design based on W_n orientations causes small changes in the weight of the structure, while it may reduce the amount of LPF even up to 12%, and this reduction should be considered in the design process.
- Line-max orientations have increased the weight of some structures up to 5%, but the amount of LPF have increased by a maximum of 10%.
- In models with Line-mean orientations, the maximum increase in weight was 4%, while the amount of LPF increased by 11%. Therefore, Line-mean orientations have better efficiency in most structures.

5.2. double-domes free-form space structure

Figure 12 shows the double-dome configuration with three different patterns. The specifications of configurations are also shown in Table 5. The information related to the cross-sections assigned to the members and weight of resulting structures for different orientations in design process are also shown in Table 6.



(a) (b) (c)

Figure 12: double-dome free-form space structures: (a). Freeform 2a (b). Freeform 2b (c). Freeform 2c

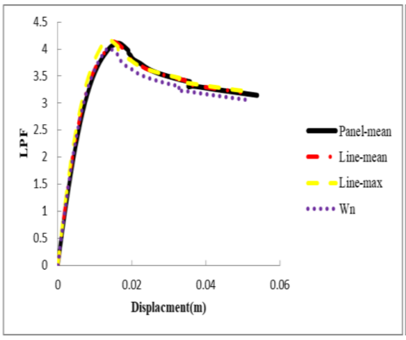
Table 5: specifications of the configurations of double-domes free-form space structures

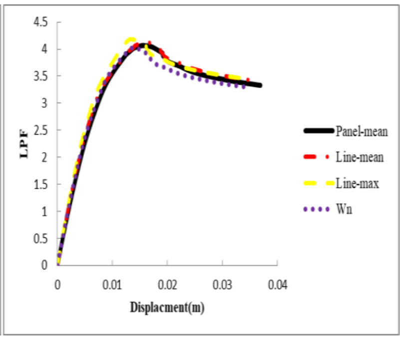
Configuration	Span (m)	Rise (m)	number of nodes	number of supports	number of members	Max member Length (m)	Min member Length (m)	Average member Length (m)
Freeform 2a	30x30	6	441	80	1240	3.20	1.50	1.80
Freeform 2b	30x30	6	441	80	1240	3.20	1.50	1.80
Freeform 2c	30x30	6	441	80	840	2.80	1.50	1.60

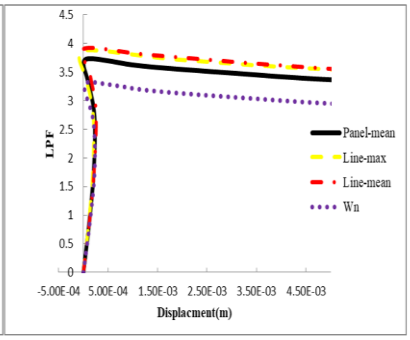
Table 6: The cross-sections and weight of structures for different orientations in design process

Structure	Orientation	Weight (ton)	cross-section of members (mm)
Freeform 2a	Panel-mean	37.00	Box 110*40*5, Box 120*45*6, Box 130*45*7
	Line-mean	37.60	Box 110*40*5.5, Box 120*45*6, Box 130*50*7.5
	Line-max	38.10	Box 110*40*5, Box 130*45*6, Box 135*45*7.5
	Wn	36.80	Box 105*45*5, Box 120*40*6, Box 130*45*7
Freeform 2b	Panel-mean	32.80	Box 110*40*5, Box 120*45*6, Box 130*45*7
	Line-mean	33.40	Box 110*40*5.5, Box 120*45*6, Box 130*50*7.5
	Line-max	34.50	Box 110*40*5, Box 130*45*6, Box 135*45*7.5
	Wn	33.00	Box 105*45*5, Box 120*40*6, Box 130*45*7
Freeform 2c	Panel-mean	33.00	Box 220*70*5.5, Box 230*70*6
	Line-mean	34.30	Box 225*70*5.5, Box 235*70*6
	Line-max	33.80	Box 225*70*5.5, Box 235*65*6
	Wn	32.70	Box 230*60*5.5, Box 220*65*6

Figure 13 shows LPF- displacement responses of the free-form models with different orientation in members in double-domes free-form space structures. Summary of weight, LPF and their percentage of change in double-domes free-form space structures are also presented in Table 7. Considering that the LPF values are higher than 4 in free form 2a and 2b, the sensitivity of these structures to changes the orientation of the members is less than the others and generally LPF- displacement responses of these models are overlapping.







(a) (b) (c)

Figure 13: LPF- displacement responses of the models: (a). Freeform 2a (b). Freeform 2b (c). Freeform 2c

Table 7: Summary of weight, LPF and their percentage of change in double-domes free-form space structures

Structure	Orientation	Weight (ton)	LPF	Percentage of change	
				Weight %	LPF %
Freeform 2a	Panel-mean*	37.00	4.08	0.00 %	0.00 %
	Line-mean	37.60	4.14	1.62 %	1.47 %
	Line-max	38.10	4.17	2.97 %	2.21 %
	Wn	36.80	4.04	-0.54 %	-0.98 %
Freeform 2b	Panel-mean*	32.80	4.08	0.00 %	0.00 %
	Line-mean	33.40	4.14	1.83 %	1.47 %
	Line-max	34.50	4.18	5.18 %	2.45 %
	Wn	33.00	4.03	0.61 %	-1.23 %
Freeform 2c	Panel-mean*	33.00	3.72	0.00 %	0.00 %
	Line-mean	34.30	3.92	3.94 %	5.38 %
	Line-max	33.80	3.84	2.42 %	3.23 %
	Wn	32.70	3.32	-0.91 %	-10.75 %

* The Panel-mean values in all structures is considered as the initial values for calculating the percentage of changes.

By studying Table 7, the following results are obtained for double-dome free-form space structures:

- Optimizing the twist angles in connections based on W_n orientation of members in Free-form 2a and 2b cause very little changes in the weight and LPF of the structures, but it has reduced the LPF value up to 11% in Freeform 2c with a quadrangular grid pattern.
- In models with Line-max orientations, the maximum increase in weight was 5%, while the amount of LPF increased by 3%.
- have increased the weight of some structures up to 4%, but the amount of LPF have increased by a maximum of 5%.

6. Conclusion

In this paper, the effect of minimized orientation of members in connections (in order to reduce the twisting angles) on the structural behavior of a single-dome and a double-dome free-form space structures with different grid patterns were investigated. The selected structures for the initial orientation ("Panel-mean") as well as the optimal orientations ("Line-mean", "Line-max" and "Wn") are carefully designed and their stability behavior were examined. The results of this research show that:

1. Changing the orientation of members in order to minimize twist angles on each grid line (Line-mean and Line-max) of free-form lattice space structures, improves stability behavior in most cases, even in some cases, Line-mean orientation increased LPF value up to 12%, while the amount of weight has increased up to 4%.
2. If the twist angles in the members are optimized individually (W_n orientation) and the change of these angles on the grid lines is not taken into account, the amount of LPF may even decrease by 12% in some models.
3. Changing the orientation of the members have a significant impact on the stability behavior of structures with a low LPF value.
4. In free-form space structures, the cost savings of fabrication due to the optimization of the twist angles in connections is significant. Hence, by selecting the appropriate optimization technique, this advancement can also enhance the structural performance.

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