An approach to design of effective and efficient supports of double-layer grids subject to seismic and thermal loadings

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Abstract— **Double-layer grids are usually erected in regions which suffer from strong earthquakes. Their supporting system has to be designed in such a way to sustain the developed lateral forces, which in turn, must be carried to the substructure. In other words, some of the supports have to be laterally fixed, causing self-strained forces in the double-layer grid due to changes of the ambient temperature. In this paper, a research, approaching the design of supports that would be able to undertake the horizontal forces and simultaneously to permit the free movement of the double-layer grid, is realized. The results show a significant decrease on the magnitude of the lateral reactions, leading to savings on the material of the substructure along with an optimum design of the double-layer grid.**

Keywords: double-layer grids; supports; seismic loadings; thermal loading

I. Introduction

Double-layer grids (DLGs) are 3-dimensional steel structures consisted of a large number of linear members. Usually a bolted connection, free to rotate, is provided to link the adjacent members. Due to the large number of members a great stiffness is achieved along with a high degree of indeterminacy. The grids are loaded by forces that act on the nodes perpendicular either to the top or to the bottom layer. As a result their members are subjected only in axial forces [1, 2] and therefore a full exploitation of the material strength is reached, leading to less heavy structures. In addition, the development of Formex Algebra by Nooshin [3, 4, 5] facilitated the design of elegant and impressive geometrical shapes with excellent aesthetics. The aforementioned advantages along with the industrialized production, easy to assemble by unskilled labor, made them popular to cover large spans without intermediate supports, such as sports and exhibition halls, airport hangars, etc [6].

Many researchers investigated the structural behaviour of a space-truss-roof under seismic excitation. Moghaddam [9] argued that space structures presented exceptional performance in severe earthquakes due to their light weight and large reserved strength. Li and Ding [10] investigated the effect of soil-structure interaction on seismic behaviour of long-span space-truss-roof. It was noticed that the axial forces were significantly larger in the model considered with a soil-structure interaction than that of the model with a rigid foundation. The research of Wang and Zhu [11] was addressing the seismic behaviour of long span space-trusses under multi-support and simple-support excitations. It was observed that the structure was stable in the case of a simple-support excitation whilst it was very unstable at the multi-support case. Yang et al. [12] have proposed a control method to improve the seismic performance of double-layered spherical reticulated shells. The proposed method is based on the use of bar-type dampers which replace selected members of the shell.

The influence of the substructures on the structural behaviour of double-layer grids has been also researched. Alinia and Kashizadeh [13] studied the effect of flexibility of substructures upon thermal behaviour of spherical double layer space-truss domes. They observed that, in rigid supports, the horizontal reactions due to thermal expansion of truss members were significant and increased linearly along with the temperature increase. They concluded that the use of fixed supports should be carefully examined in the design stage. Karamanos and Karamanos [14] stated that two different conditions should be examined, concerning the stiffness of the substructure, which might be either flexible or rigid. In the case of rigid substructures which are very stiff compared to the double-layer grid, laterally fixed supports cause the development of high self-strained forces in the grid, due to the changes of temperature. They proposed some arrangements of supports which were able to undertake horizontal seismic forces and materialize a free movement of grid. However, the double-layer grid could not behave as a diaphragm.

The collapse mechanism of double-layer grids has also been investigated by many researchers. Yu et al. [15] studied the impact of substructures' type (rigid or flexible) on the failure characteristics of steel reticulated domes subjected to strong earthquakes. In the case of a rigid substructure, it was observed that the failure was abrupt and general. On the contrary, in the case of a flexible substructure, any plastic deformation was distributed on the external members of the reticulated dome and then it was extended slightly before it collapsed. Malla et al. [16] argued that the truss structures should be studied using a dynamic analysis, even if they have to sustain loads applied statically. By developing an analysis methodology the inelastic behaviour of the members in the dynamic analysis of the truss structure is taken into consideration. The results showed that, the response of the structure became more critical when considering the actual postbuckling behaviour of members, than assuming the loss of its full load carrying capacity. Jihong et al. [17] investigated the failure mechanism of long-span spatial lattice structures under multi-support excitation (MSE) and uniform support excitation (USE). It was observed that, in both cases, within the first four seconds the total amount of plastic members (damaged and undamaged) was increased rapidly. In the following two seconds the number of damaged members resulted in the collapse of the structure. It was also noticed that the plastic region was generated in the area where the node displacements were significantly increased; this may have caused the collapse of the entire structure.

A key issue which influences the structural behaviour of double-layer grids is the choice of the supporting system. Chilton [18] suggested a combination of lateral restrained supports in order to undertake the reactions due to the seismic loads and sliding supports in order to allow a free movement of the double-layer grid.

The aim of the present paper is an approach to design a supporting system for double-layer grids, capable to undertake the horizontal seismic forces and simultaneously to allow a free movement of structure, in such a way, that a diaphragmatic function of the grid would be feasible.

II. RESEARCH METHODOLOGY

The supports must be able to undertake both perpendicular and lateral reactions; as a result the movement of the double-layer grid on both horizontal directions has to be prevented. On the other hand, due to changes of the ambient temperature, the prevention of a possible free movement on the restrained supports causes great reactions and self-strained axial forces in this region of the double-layer grid. In other words, two demands, opposing to each other, must be satisfied: a safe undertaking of the lateral reactions and simultaneously a possibility of the grid to expand and contract.

In this paper, a design of a specific supporting system to meet the aforementioned requirements has been approached. The proposed supports present **Resistance** in **Seismic** loads and simultaneously **Allow** the **Movement** of the grid due to changes of the ambient **Temperature** (SMART supports).

The SMART supports are not totally fixed on the horizontal directions. In particular, for the temperature load cases, the SMART supports function in such a way so as to allow the movement of the double-layer grid as much as it is necessary to cover the developed deformations. The above gap, necessary to accommodate the previous deformations, is estimated using the expression for the linear increase of temperature:

$$\Delta L = \alpha L_0 \Delta T$$

where ΔL is the member's increase of length, α is the coefficient of linear expansion or contraction, L_0 is the member's original length and ΔT is the change of temperature. In the relevant structural analysis, the above gap has been simulated by inserting an imposed displacement (Dl) on the supports' x or y direction.

For the seismic load cases, the diaphragmatic function of the grid is achieved by permitting a free movement of the double-layer grid until the appearance of horizontal forces. The gap determination (Dx/Dy) is based on the max displacement due to the earthquake's motion. As in the previous case for the structural analysis, an imposed displacement is applied on the supports in both horizontal directions.

The arrangement of the horizontal restrained supports was chosen in such a way that both the center of gravity and the center of the structure's rotation should coincide.

III. ANALYSIS AND IMPLEMENTATION OF "SMART" SUPPORTS

Flats and uniformly curved double-layer grids were studied in parallel, using: a) the existing type of the supporting system and b) the SMART supports. In both cases the arrangement of the supports was exactly the same. All double-layer grids had a module a=3.00m and a structural depth h=2.12m. The loads were acted on the nodes of the upper layer.

The structural analysis was carried out by SAP2000 [19]. The design loads (Table I) along with their combinations (Table II) were defined according to Eurocode 1 [20]. The seismic loads were evaluated according to Greek Seismic Code [21], while for the design of double-layer grid components, the Eurocode 3 were applied [22].

A. Flat double-layer grids

Four rectangular double-layer grids with dimensions 30.00x30.00m, 45.00x30.00m, 42.00x42.00m and 72.00x42.00m were studied. Certain nodes along the perimeter's bottom layer were supported on a rigid substructure.

In order to investigate and compare the results of as much as possible parameters, every flat double-layer grid was analyzed with four and eight restrained supports on both horizontal directions. Taking into account the aforementioned expression for the linear thermal increase along with the distance of each horizontally restrained node from the grid's centre of gravity, the gap for the corresponding thermal load case was estimated.

TABLE I. DESIGN LOADS

Load case	Value	
Self-weight of DLG	estimated automaticaly	
Dead load (G)	0.40	kN/m^2
Snow (S)	0.75	kN/m^2
Temperature changes (ΔT)	$\pm 40^{\circ}C$	
Seismic load ($E=m*\Phi d(T)$)		
zone II, $\gamma I = 1.15$, $\zeta = 4\%$, $\theta = 1.00$, $\beta 0 = 2.50$, $q = 1.50$	$\Phi_d(T) = 0.497g$	

TABLE II. COMBINATIONS OF LOADS

Combinations	Current	"SMART"
1	1.35G+1.50S	1.35G+1.50S
2	1.35G+1.50S+0.90T(con)	1.35G+1.50S+0.90T(con)-Dl
3	1.35G+1.50T(exp)	1.35G+1.50T(exp)+Dl
4	1.35G+0.90S+1.50T(con)	1.35G+0.90S+1.50T(con)-Dl
5	1.00G+0.30S+1.00E(+x)	1.00G+0.30S+1.00E(+x)+D(+x)
6	1.00G+0.30S+1.00E(-x)	1.00G+0.30S+1.00E(-x)+D(-x)
7	1.00G+0.30S+1.00E(+y)	1.00G+0.30S+1.00E(+y)+D(+y)
8	1.00G+0.30S+1.00E(-y)	1.00G+0.30S+1.00E(-y)+D(-y)

Where: Dl is the gap due to thermal loads
Dx/Dy is the gap due to seismic loads

Figures 1 and 2 demonstrate the imposed displacement for thermal (green) and seismic (red) load cases of a 30.00x30.00m double-layer grid with 4 and 8 supports in each horizontal direction respectively. Due to the paper space limitation, figures with the other double-layer grids were omitted.

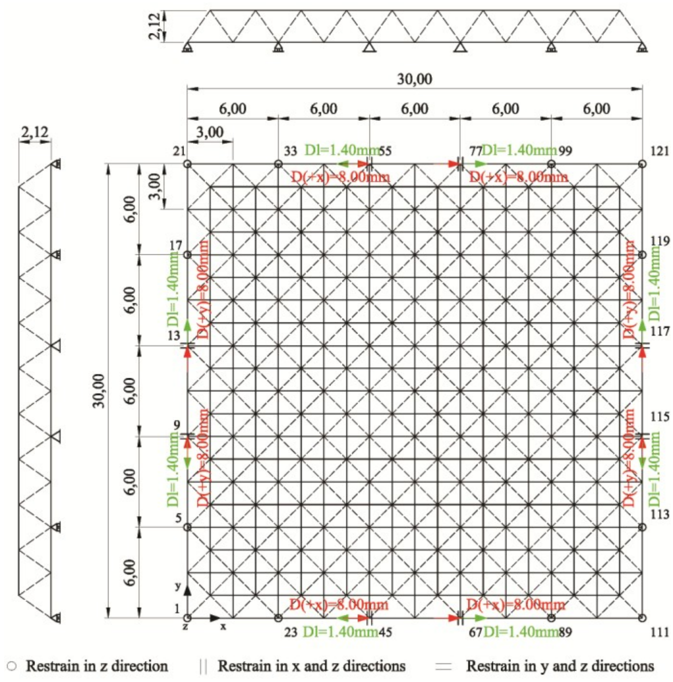

Figure 1. Imposed displacements for thermal and seismic load cases of a 30x30m DLG with 4 horizontal restrained supports

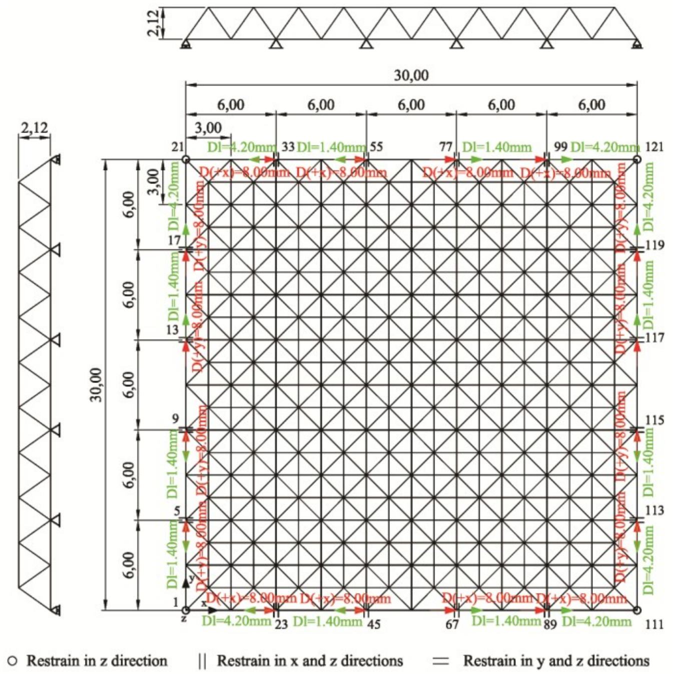

Figure 2. Imposed displacements for thermal and seismic load cases of a 30x30m DLG with 8 horizontal restrained supports

B. Uniformly curved double-layer grids

Two uniformly curved double-layer grids with dimensions 30.00x30.00m and 42.00x42.00m were analyzed.

Nodes of the bottom layer along the two opposite sides were supported every 6.00m on a rigid substructure. Four of them, shown in figure 3, were restrained in all directions to undertake the horizontal forces.

The vertical loads (dead, permanent and live), applied on the nodes of the upper curved layer, have obviously caused significant horizontal displacements in the x direction.

In the case of the SMART supports, a calculated gap (fig.3-fig.4) was introduced in them, to compensate for the local grid's deformation until the appearance of horizontal forces. The above gap was imposed in all load combinations. On the contrary, in the case of the current method, the supports were horizontally totally fixed.

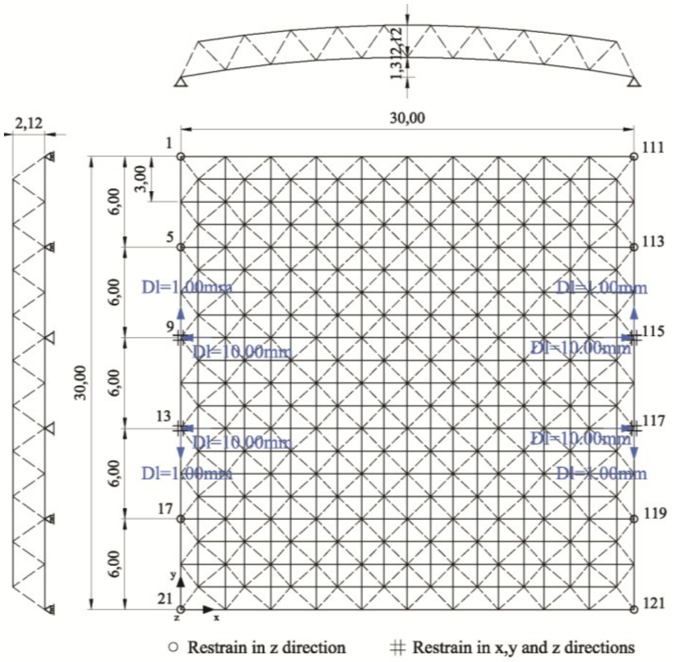

Figure 3. Imposed displacements of a 30x30m uniformly curved DLG

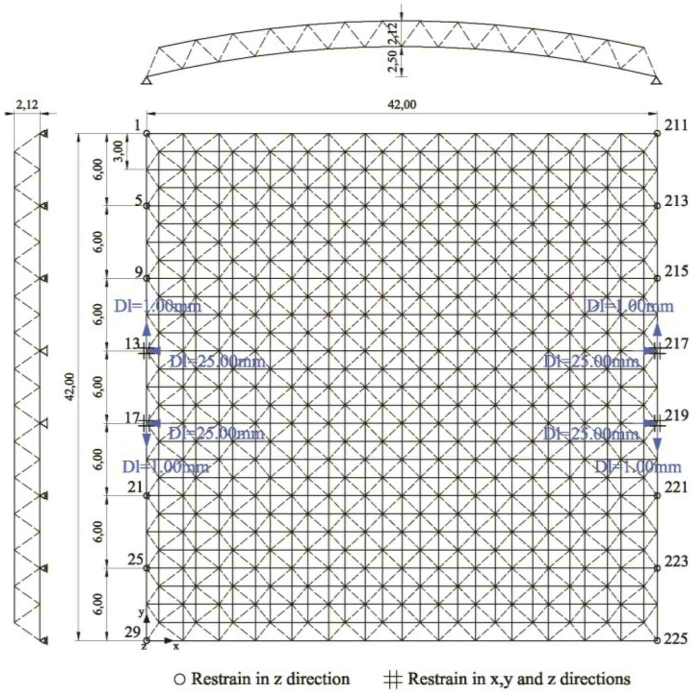

Figure 4. Imposed displacements of a 42x42m uniformly curved DLG

IV. DISCUSSION OF THE RESULTS

A. Flat double-layer grids

The lateral reactions, developed in both x and y directions were investigated. It has been observed that under any loading combination, in the presence of any temperature's changes, the magnitude of the reactions that yielded is significantly different between the two methods.

In tables III and IV, the developed lateral reactions, being smaller in the SMART case, are shown in both x and y directions, where the dead loads are combined with the corresponded thermal.

On the contrary, in the absence of any temperature's changes, the developed reactions due to the seismic combinations are almost the same. However, the overall lateral reactions carried by the double-layer grid to the substructure are about 20% smaller with the SMART method compared to the current one.

Tables V and VI summarize the overall reactions that present respectively 4 and 8 horizontally restrained supports, for both the current and the SMART methods. Furthermore, the self weight of the double-layer grid, when the SMART method is applied, is slightly less than the corresponding through the current method.

The loading combinations, under which the members of the double-layer grid are dimensioned, have also been examined. Here it has to be noted that a remarkable result has been revealed. In the SMART method, the percentage of the designed members, based on the loading combinations in the presence of temperature changes, is significantly smaller, about 10%, compared to the corresponding percentage where the current method is used. Actually, this is a totally desired condition, as the uncertainties, raised from the double-layer grid's structural behaviour under the uncontrolled self-strained situations, are substantially minimized.

TABLE III. REACTIONS IN x DIRECTION DUE TO THE COMBINATION 1.35G+1.50T(exp)

Double-layer grid (m x m)	**Reactions (kN)**					
	4 supports			*8 supports*		
	Current	SMART	Diferrence (%)	Current	SMART	Difference (%)
30.00 x 30.00	454.60	70.20	**84.56**	596.47	97.59	**83.64**
45.00 x 30.00	500.67	89.64	**82.10**	617.46	111.48	**81.95**
42.00 x 42.00	428.24	66.18	**84.55**	593.22	114.32	**80.73**
72.00 x 42.00	539.70	104.99	**80.55**	641.32	128.46	**79.97**

TABLE IV. REACTIONS IN y DIRECTION DUE TO THE COMBINATION 1.35G+1.50T(exp)

Double-layer grid (m x m)	**Reactions (kN)**					
	4 supports			*8 supports*		
	Current	SMART	Diferrence (%)	Current	SMART	Difference (%)
30.00 x 30.00	454.60	70.20	**84.56**	596.47	97.59	**83.64**
45.00 x 30.00	412.28	69.35	**83.18**	557.09	92.27	**83.44**
42.00 x 42.00	428.23	66.18	**84.55**	593.22	114.41	**80.71**
72.00 x 42.00	436.18	82.11	**81.18**	570.21	113.00	**80.18**

TABLE V. OVERALL REACTIONS WITH 4 SUPPORTS IN EACH HORIZONTAL DIRECTION

Double-layer grid (m x m)	Reactions (kN)					
	Current			*SMART*		
	x-x	y-y	z-z	x-x	y-y	z-z
30.00 x 30.00	454.60	454.60	98.80	114.81	114.71	92.10
45.00 x 30.00	500.67	412.28	251.50	175.99	162.50	242.92
42.00 x 42.00	428.24	428.24	206.72	214.69	214.69	200.67
72.00 x 42.00	539.73	436.18	281.26	333.37	346.37	279.81

TABLE VI. OVERALL REACTIONS WITH 8 SUPPORTS IN EACH HORIZONTAL DIRECTION

Double-layer grid (m x m)	Reactions (kN)					
	Current			*SMART*		
	x-x	y-y	z-z	x-x	y-y	z-z
30.00 x 30.00	596.47	596.47	107.93	97.59	97.59	90.13
45.00 x 30.00	617.46	557.09	268.19	111.30	92.37	242.92
42.00 x 42.00	593.22	593.22	216.74	141.56	141.59	244.74
72.00 x 42.00	641.47	570.35	302.20	221.30	216.71	280.75

B. Uniformly curved double-layer grids

Here the structural analysis in all directions demonstrates again a considerable reduction of the reactions' magnitude, when the SMART method is applied. Tables VII, VIII and IX show the reactions due to the combination of the permanent and live load.

TABLE VII. REACTIONS IN x DIRECTION DUE TO THE COMBINATION 1.35G+1.50T(exp)

Double-layer grid (m x m)	Reactions (kN) - x direction		
	Current	*SMART*	*Diferrence (%)*
30.00 x 30.00	595.20	234.51	**60.60**
42.00 x 42.00	1332.52	505.63	**62.05**

TABLE VIII. REACTIONS IN y DIRECTION DUE TO THE COMBINATION 1.35G+1.50T(exp)

Double-layer grid (m x m)	Reactions (kN) - y direction		
	Current	*SMART*	*Diferrence (%)*
30.00 x 30.00	84.27	29.00	**65.59**
42.00 x 42.00	217.17	24.86	**88.55**

TABLE IX. REACTIONS IN z DIRECTION DUE TO THE COMBINATION 1.35G+1.50T(exp)

Double-layer grid (m x m)	Reactions (kN) - z direction		
	Current	*SMART*	*Diferrence (%)*
30.00 x 30.00	291.82	230.79	**20.91**
42.00 x 42.00	542.91	359.79	**33.73**

The self-weight of the double-layer grids were also investigated. The SMART method has resulted in about 10% heavier structure. This result, along with the reduction of the lateral reactions due to the seismic combinations, indicates that a redistribution of the seismic loads is taking place. This means that a percentage of the seismic loads has been undertaken by the double-layer grid due to its high level of stiffness.

Figures 5 and 6 show that the percentage of members designed due to the seismic combinations through the SMART method is greater than that of the current.

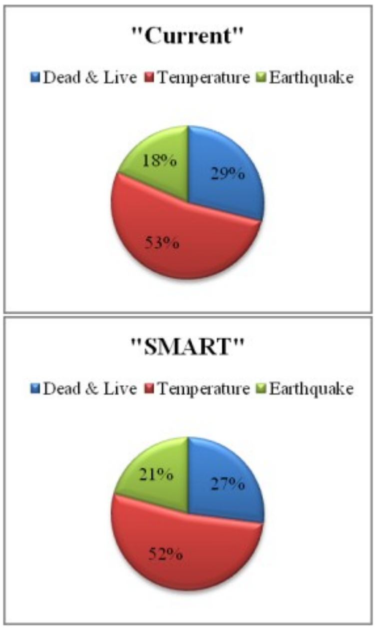

Figure 5. Diagrams of members' pieces due to load type of a 30x30m uniformly curved DLG

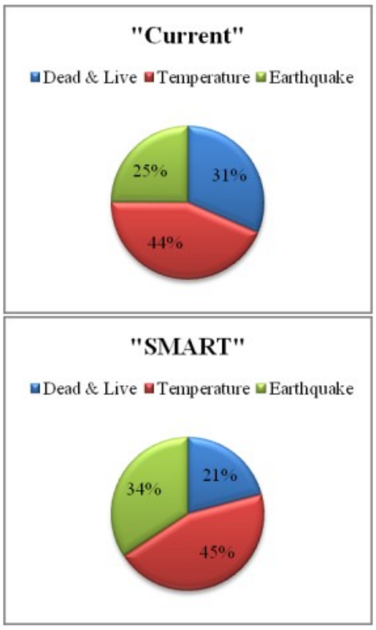

Figure 6. Diagrams of members' pieces due to load type of a 42x42m uniformly curved DLG

V. CONCLUSIONS

The key issue of the double-layer grids' supporting system has been researched in detail. Two types of double-layer grids (flat and uniformly curved) were studied using the SAP2000 software.

In order to obtain comparable results, the same arrangement of supporting points was applied, differing only in the implementation of the horizontally restrained supports.

In the case of the current method the horizontally restrained supports were laterally totally fixed, in contrast to the case of the SMART method, where a calculated gap was employed, to permit the movement of the grid during its thermal deformation, i.e. before any appearance of horizontal forces.

Based on the results obtained through the SAP200 software, the following conclusions were derived:

- The overall lateral reactions were decreased by 20% and 60% for flat and uniformly curved double-layer grids respectively, when the SMART method was applied.
- For the flat DLGs, the SMART method results to about 2% lighter grids. On the contrary, for the uniformly curved double-layer grids, the SMART method leads to about 10% heavier structure.
- Finally, in both types of double-layer grids, the percentage of members, designed due to the loading combinations in the presence of temperature changes is reduced in the SMART method.

The aforementioned results confirm that the SMART method combines the advantage coming from the current design methodology – where the centre of gravity coincide with the centre of elastic rotation - with the reduced reactions and the optimum design of the double-layer grid's components.

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