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A Numerical Investigation of the Structural Performance of Double-layered Grid Domes Using Software Packages

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ABSTRACT

In the 21th-century, large exhibitions halls covered by domes were constructed. Development of domes promoted by using metal structures, which has opened a new era for civil engineers in connection with the decision of maintenance problems of high strength and weight reduction of structures. Grid domes are a preferred structural form of roofs coverage. The paper aims to study the structural performance of double-layered grid domes using SAP2000 (v.14) and ETABS18. Four different types of double-layered grid domes considered in this work were the Schwedler dome (Type 1), three-way grid dome (Type 2), grid dome with different layers (Type 3), and grid dome with hexagonal patterns (Type 4). The configurations of grid domes were generated by Formian program software. The static linear analysis and design of mentioned grid domes were done and different load cases and their combinations were applied according to ASCE 7-10. It was observed that a double-layered grid dome with different layers (Type 3) was the most efficient in structural performance because the density of members per joint gave a very good distribution of axial forces distribution of the whole dome and then minimized the axial force in members and vertical deflections. The present study indicates that further detailed studies of the subject may lead to a more precise understanding of the performance of grid domes subjected to different load cases and this may bring about increased structural safety and serviceability and the economy in cost constructions.

Keywords: Structural performance, Schwedler, Grid, Dome, Load combination, Software Packages, and Type.

INTRODUCTION:

Various comparative studies of linear and non-linear structural behavior and performance of various configureations of domes were done using different numericalmethods and experimental investigation. Many previous studies of domed structures are viewed in this work. The first work aims to obtain which type of reticulated dome is superior in terms of material efficiency by comparing the minimized weight of different dome types, taking into account stress and buckling constraints. The results explain that the Schwedler dome gave minimum weight and has uniform axial forces distribution compared with the other types of domes (Gythiel *et al.,* 2020). In this work, single-layered two-way and three-way lattice isolated systems were studied under the effect of near-field and far-field ground motions. It was observed the two-way isolated system has a good dynamic response and near-field ground motion had a clear effect compared with far-field once (Zhang *et al.,* 2021).

In this work, the analysis of the metal dome was examined utilizingthe structural analysis program STAAD.Pro for the ana-lysis of various diameters of the tubular steel sections (Chandiwala and Technology, 2014). Another work introduces the results of a numerical, experimental investigation into the static stability of externally pre-ssurized hemispherical, and torispherical domes. Val-ues of experimental buckling pressures varied from 1.7 to 10 MPa (Błachut, 2009). In this research, three load cases and two support conditions were taken to study the failure of a double-layered grid dome utilizing non-linear static analysis. It was found that the load-carr-ying ability of the domewasreduced to 39% by remo-ving members of the bottom layers and web. (Rezania and Torkzadeh, 2019). In this work, the non-linear structural performance for inflation, symmetric and asymmetric loadings is carried out experimentally and numerically to show the efficiency of the proposed structure. This work deduces the structural principle of the considered system and illustrates its feasibility in the field of construction engineering (Wan *et al.,* 2021).

In this work, it wasexecuted an analysis of different typologies from which ancient domes are solved, paying attention simultaneously to the constructive technology and the construction efficiency (Escrig and Valcarcei, 1970). Five modes were studied with natural frequencies between 0.279 and 0.457Hz and damping rates of 1.5%. Modal forms are present mai-nly with normal and transverse directions. Besides, the observations illustrate that the internal pressure of the sports hall fluctuates slightly with the structural shape difference caused by the external wind. It was also observed that the cables in the areas of the roof ridges have more strain than those on the edges of the roof (Yin *et al.,* 2021). This study investigates the structural response and architectural options of the Kara Mustafa authority mosque. To find out specific mechanical properties, various tests were carried out on materials of the same age and showed similar properties of the examined mosque. In addition, finite element analyses were carried out to investigate static and dynamic responses.It found that the compressive and tensile stresses from the obtained analyses are less than the strength of the materials.However, tensile stresses from dynamic responsemay result cause structural problems (Seker *et al.,* 2014). In this work, a new technique was conferred by introducing uncertainties into the nonlinear dynamic analysis for single-layered lattice domes. The obtained results reveal the variations between typical analysis with deterministic parameters utilized in previous applications and the uncertain analysis methodology. Finally, a study was done, and the effects of sample size on the applied dynamic requirements, uncertainty about structural collapse, and uncertainty about damping coefficients were reported (Zhang *et al.,* 2020). The research presents the structural behavior of two geodesic metal domes having the same number of elements under earthquake loadings. The static analysis was done using the finite element program. The work will help to design domes in earthquake areas and in estimating the durability of various dome structures under earthquake loadings (Pilarska and Maleska, 2021). The structural instability of domes is revealed from an entirely new perspective, and an optimized model against instability has been formulated. The optimization was done on two large-scale realistic models. The stability and seismic performance of the optimized domes were carefully examined and compared (Ye *et al.,* 2018).

The modeled dome is calculated by using software ANSYS. Axial stress variation, maximum moment, and buckling load were obtained for the various sizes of the dome. It noted that comparative study is themethodto select optimum configuration. This will practically help to construct the domes with and without openings (Nayak *et al.,* 2020). In this work, to the comprehensive assessment of the behavior of a double-layer latticed dome, quite varioussuspicionparameters such as the mechanical properties of the steel material, mass, applied gravitational load, and geometric imperfectionsare taken into considerationnonlinear pushover analysis. Two completely different methods are used for Tornado Diagram Analysis (TDA) and First-Order-Second-Moment (FOSM). The obtained results show that there is a detailed agreement between TDA and FOSM that ends up with the order of random variables as stated by importance (Vazna and Zarrin, 2020).

The effect of initial geometrical imperfections on the stability of the metal dome was examined, and a prediction equation for the stability carrying- capability was introduced. The results present that the transition space of the dome when changing the radius of curvature is the weak space within the first key construction section. The impact of initial geometrical imperfections on the maximum carrying- capability is not vital. The purposeful failure is cracking within the ring beam throughout the second key construction section (Yan *et al.,* 2019). In this study, unsuspicious related to the dynamic requirements of a large-volume latticed structure with various variables were determined using the stochastic finite element method (SFEM) with the development of nonlinear time history analysis, and this method takes into account the detailed randomization of structure variables. This work presents an efficient solution to the structural dynamic problems of hyper large scale structures in SFEM (Zhang *et al.,* 2021). In this work, the structural dynamic response of single-layer latticed domes under blast load casewas done experimentally and nume-rically. A simulated model based on ANYSY/AUTO-DYN was established to emulate the experimental models, and animproved equivalent method was app-lied to facilitate the system of loads. Best convergence of values between experimental and numerical (Qi *et al.,* 2020).

Other research fixes to assess the structural and seismic safety of the seven Esfahan Shah Mosques in Iran by numerically investigating the nonlinear performance of the eight mosques for different scenarios and identifying if there is a correlation between cracks patterns nine resulting from numerical analysis, inspection, and historical evidence (Dinani *et al.,* 2021).

The response of metal domes subject to severe earthquake loading has been investigated and reportable. Many dome configurations are presented, both perfect and imperfect, besides varied rise-span ratios. Finite element analysis of those structures was examinedto work out the rate of spread of plasticity and the increase in nodal displacement under seismic loading. It noted that the dynamic strength failure acceleration diminished systematically with a corresponding increase within the rise to span ratio values. (Fan *et al.,* 2005). The final study has been engaged in theoretical and experimental works to study the structural performance of space truss systems, including modifications to improve structural response and establishing analytical models consistent with experimental behavior. The finite element analysis was done using the ANSYS and LUSAS programs (Souza *et al.,* 2003).

Objectives

The paper is aimed to study the structural performance of four types of double-layered grid domes under load cases and their combinations utilizing two structural programs SAP 2000 and ETABS 18 taking into account the variations axial forces distributions and vertical deflections on-grid domes.

MATERIALS AND METHODS:

All different configurations are assumedto be pin-jointed. There have been attempts to generate configurations using the programming language Formian. Formian calculates the coordinates of the configurations and uses AUTOCAD-DXF to transform them into software programs SAP2000 and ETABS18. SAP-2000 is a general-purpose finite element program that performs the static or dynamic, linear or nonlinear analysis of structural systems. It is also a powerful design tool to design structures following different codes of practice. These features and much more make SAP2000 the state-of-the-art in structural analysis program. ETABS 18 is engineering software for the analysis and design of different types of structures. Basic or advanced systems for static or dynamic conditions could also be evaluated by the program. For comparison purposes, four types of double-layered grid spherical domes were chosen. Each dome has a span of 20m and a height of 6m and the distance between layers is 0.5m. Types of grid domes considered are as follows:

Type 1 - double-layered Schwedler dome;

Type 2 - double-layered grid three-way dome;

Type 3 - double-layered grid dome with different layers in which external layer with triangular grids and internal layer with hexagonal grids;

Type 4 - double-layered grid dome with hexagonal.

The layout of double-layered grid domes listed above types was presented as illustrated in **Fig. 1-4**. The loads were calculated partially manually and the rest were generated using SAP2000 and ETABS18 load generator. The load cases were categorized as self-weight, dead load from covering material and fire protection, live load, wind load. SAP2000 and ETABS18 themselves with self-weight command generated the self-weight of grid domes. The dead load (covering material and fire protection) and Live loadare assumed to be 0.45 and 0.96 kN/m^2 respectively.

Dead (D) and live (L) loads converted to equivalent concentrated for-ces applied at top-layer joints. The wind load values (W)were generated using SAP2000 and ETABS18 according to ASCE 7-10 with the defined load com-mand section. The most suitable cross-section used for all members of grid dome types is steel pipe P2 which has a diameter of 60.3 mm and thickness of 3.91 mm, the cross-sectional area is 6.903 cm^2, the modulus of elasticity for steel E=200GPa and Poisson's ratio μ=0.3. Three load combinations were considered as follows:

Combo 1: 1.2 D + 1.6 L

Combo 2: 1.2 D + 0.5 L + 1.3 W

Combo 3: 0.9 D + 1.3 W

For analysis of double-layered grid domes, the use of modern structural analysis programs is expedient. Programs SAP2000, and ETABS18 related to such structural analysis complexes, which applied, in the present work. The geometry of grid domeswasgenerated by Program FORMIAN but the analysis of domeswasdone using SAP2000 and ETABS18 which are based on the finite element method.

The program ETABS18 was used to verify the results obtained by SAP2000. The program SAP2000 was taken as a basic reference for the comparison of axial forces and defle-ctions. To study the structural performance of the men-tioned double-layered grid domes, the check of buck-ling load for elements of the grid domewas examined.

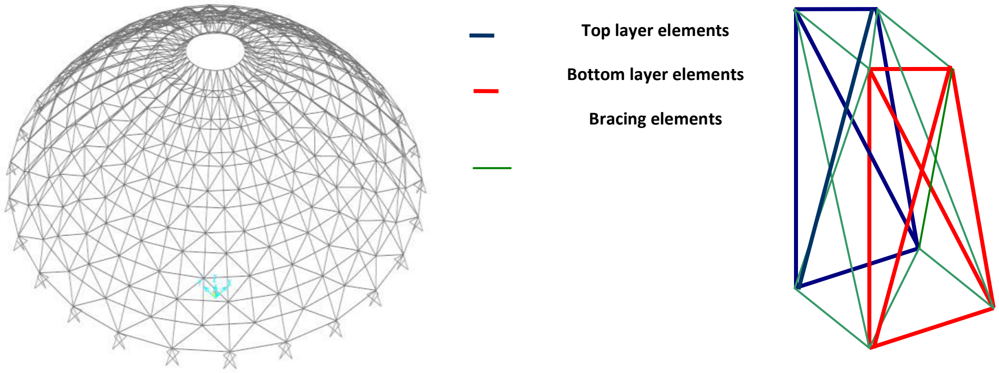


Fig. 1: Double-layered Schwedler dome (Type 1).

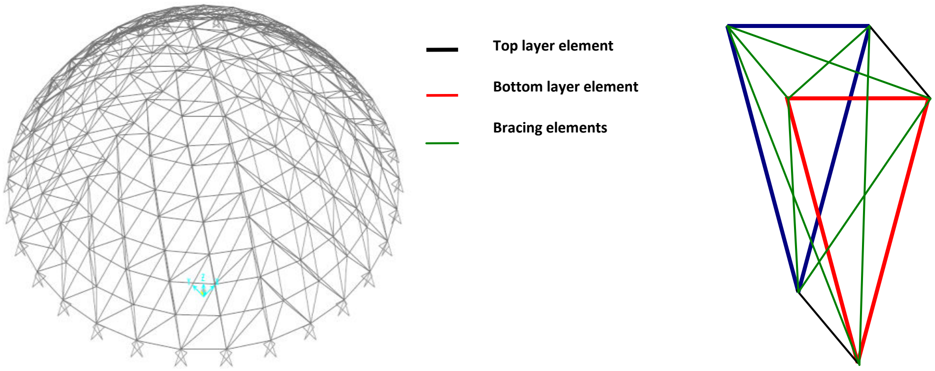


Fig. 2: Double-layered grid three-way dome (Type 2).

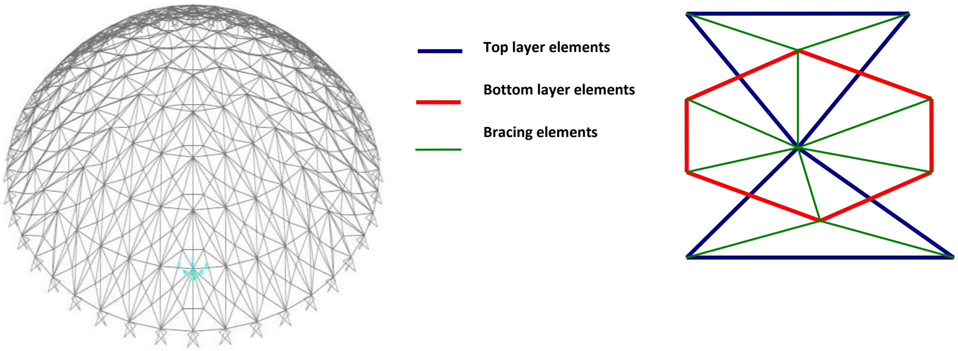


Fig. 3: Double-layered grid dome with different layers (Type 3).

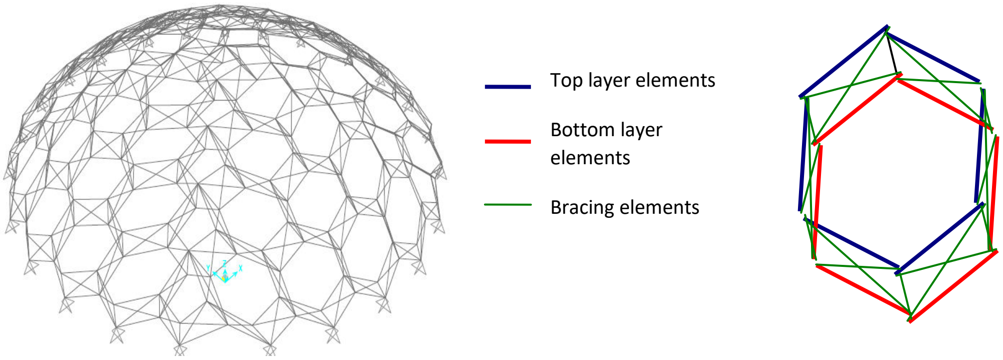


Fig. 4: Double-layered grid dome with hexagonal patterns (Type 4).

RESULTS:

The dome resists external loads with the system of internal forces acting in a grid shell. As a rule, axial forces acting in the domes along meridians are compression, and acting in-ring direction is tension. The distribution of axial forces on elements depends on the geometrical grid of elements. Double-layered grid domes have high flexural rigidity on all tangents in directions to the surface of the dome including in the case of space truss systems. The comparison of results on maximum axial compression forces in elements and maximum deflections presented for the mentioned types of grid domes as illustrated in **Table 1**, which were obtained using SAP2000 and ETABS18. Along with the ring directions, the axial tension forces have small magnitudes compared with the meridian direction, so the axial compression forces control the structural design of elements.

The design of all elements of double-layered grid domes was carriedout using design command in SAP 2000 program as illustrated in **Table 2**. To study the structural response, the variation of axial compression forces on the meridian section for all load combinations was presented only for the Sch-wedler domes as illustrated in **Fig. 5**. The comparison of axial forces distribution on the meridian direction was made for all double-layered grid domes for the maximum load combination (Combo 1) as illustrated in **Fig. 6**. Since the geometry of grid domes affects the distribution of axial forces, it is vital to tabulate the number of joints and members for each grid dome as illustrated in **Fig. 7**.

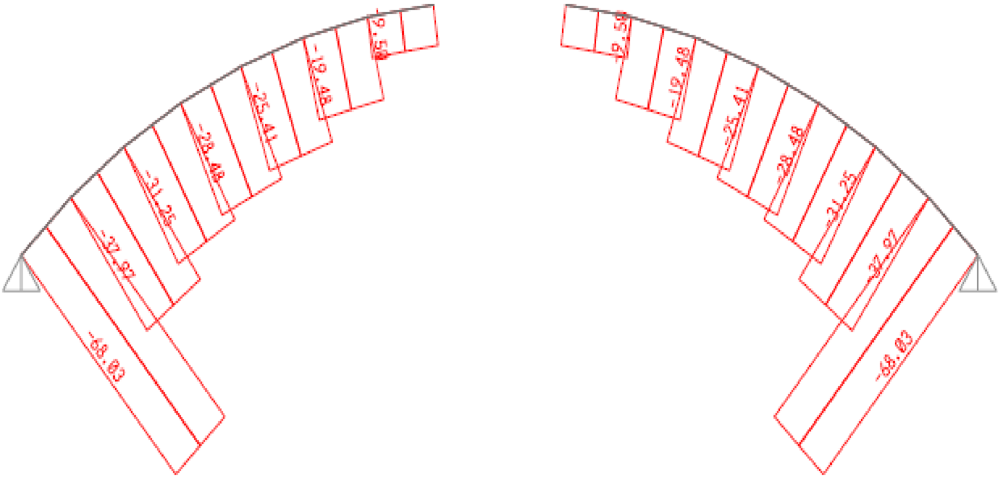
The total weight of double-layered grid domes was also calculated to select the more effi-cient and economical grid as illustrated in **Fig. 8**. To check the stabilityagainst buckling of double-layered grid domes after the design, the buckling of members was examined to determine the minimum safetyfactor against the buckling. The first safety factor against buckling for mentioned grid domes was taken presented in **Fig. 9**.

Table 1: Results of maximum axial compression forces and maximum vertical deflections in elements of double-layered grid domes using software programs SAP2000 and ETABS18.

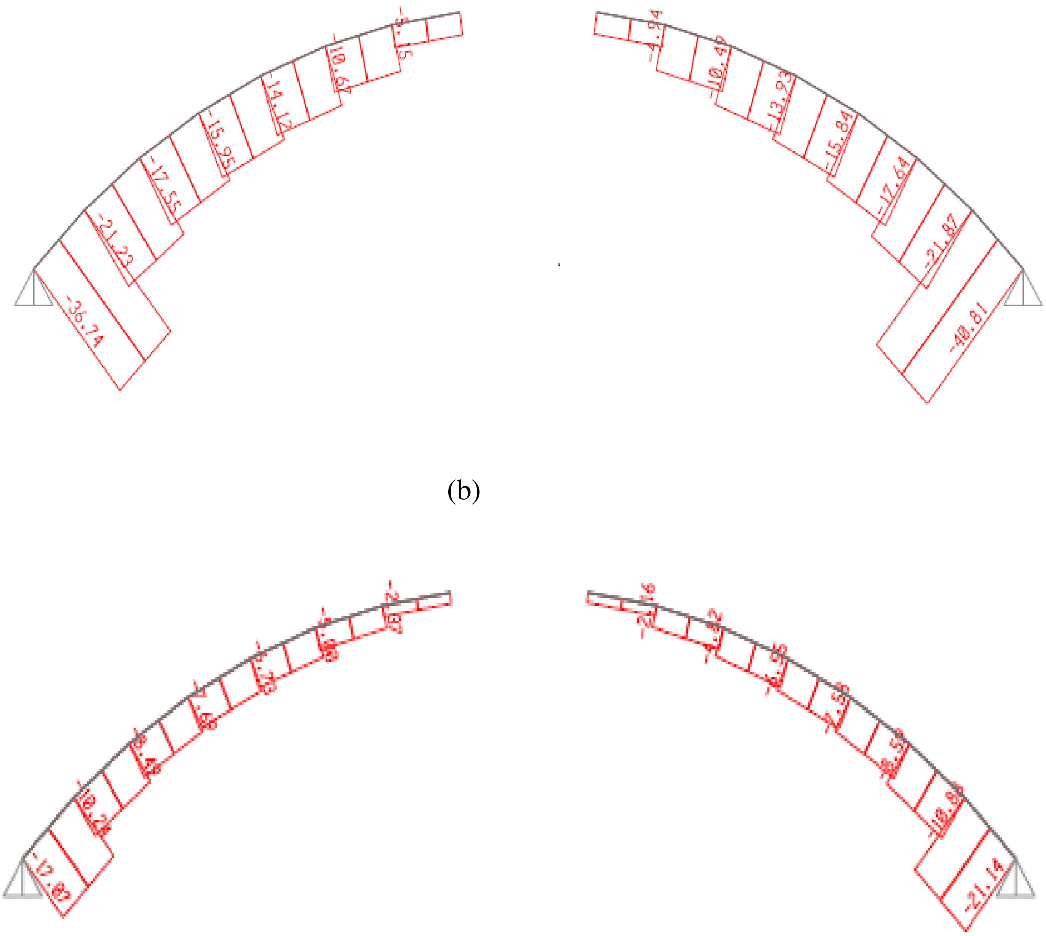
Type of double-layered grid dome	Load combination	Maximum axial force, kN		Difference %	Maximum vertical deflections, mm		Difference %
		SAP 2000	ETABS 18		SAP 2000	ETABS 18	
Schwedler Dome (Type 1)	Combo 1	68.0	68.4	-0.6	5.3	4.9	7.5
	Combo 2	40.8	44.4	-8.8	3.0	3.1	-3.3
	Combo 3	21.1	24.6	-16.6	1.5	1.3	6.7
Three-way grid dome (Type 2)	Combo 1	31.2	31.9	-2.2	5.2	5.2	0
	Combo 2	18.1	19.3	-6.6	2.9	2.8	3.4
	Combo 3	9.1	10.0	-9.9	1.4	1.3	7.1
Dome with different layers(Type 3)	Combo 1	32.0	33.2	-3.8	1.4	1.2	14.3
	Combo 2	20.3	22.6	-11.3	0.9	0.8	11.1
	Combo 3	11.3	12.4	-9.7	0.5	0.5	0
Dome with hexagonal patterns(Type 4)	Combo 1	50.5	52	-3.0	9.2	9.5	-3.3
	Combo 2	35.0	37.0	-5.7	5.4	5.6	-3.7
	Combo 3	21.0	22.0	-4.8	2.8	2.9	-3.5

Table 2: Structural design of members for various types of double-layered grid domes.

Dome Type	Pipe section properties					Maximum compressive Force kN	Compression Resistance kN	Tension Resistance kN	Remarks
	Pipe section	D (mm)	t (mm)	A (cm^2)	Radius of Gyration (cm)				
Type 1	P2	60.3	3.91	6.903	2	68	100	214	Satisfactory
Type 2	P2	60.3	3.91	6.903	2	31	59	214	Satisfactory
Type 3	P2	60.3	3.91	6.903	2	32	59	214	Satisfactory
Type 4	P4	114.3	6	20.45	3.8	50.5	459	635	Satisfactory



(a)



(b)

(c)

Fig. 5: Variation of axial forces in elements of double-layered grid Schwedler dome on the meridian section from all load combinations: (a) Load combinations 1; (b)Load combinations 2; (c) Load combinations 3.

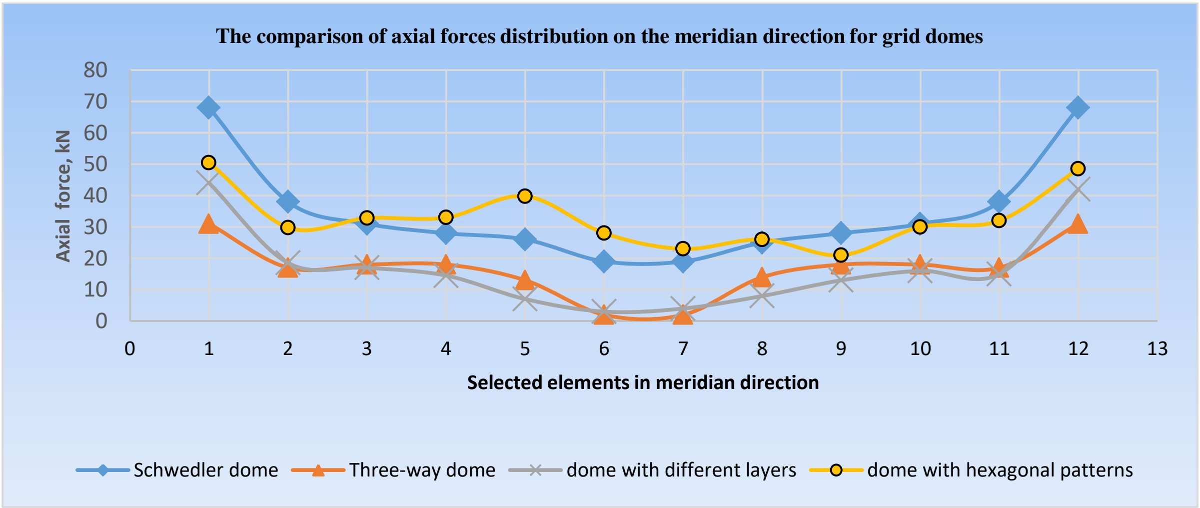
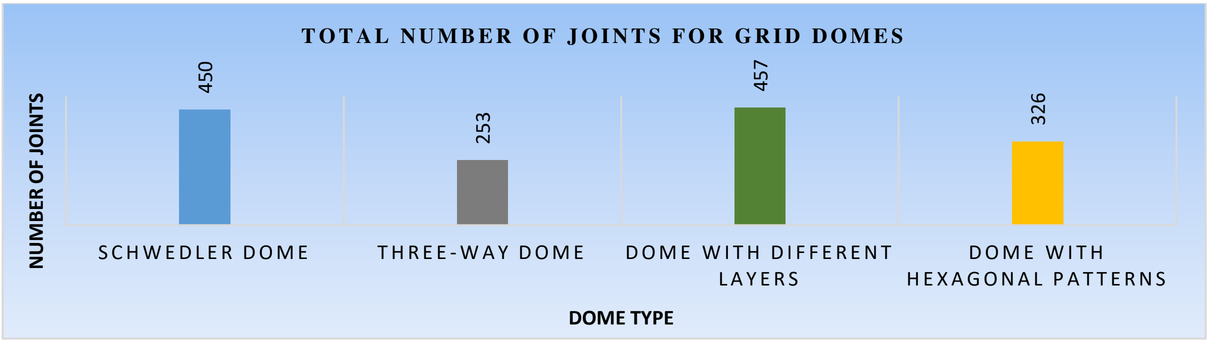
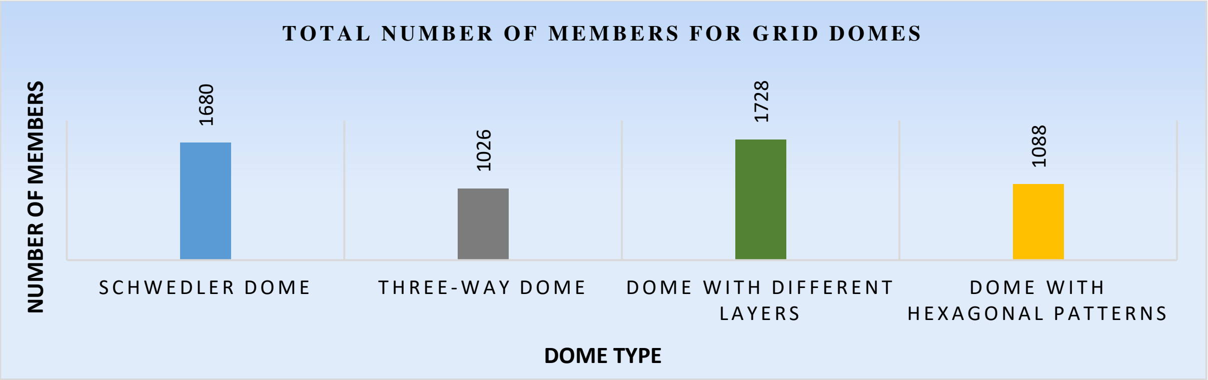


Fig. 6: The comparison of axial forces distribution on the meridian direction for all double-layered grid domesfor the ultimate load combination (Combo 1).



(a)



(b)

Fig. 7: Total number of joints and members of double-layered grid domes: (a) joints; (b) members.

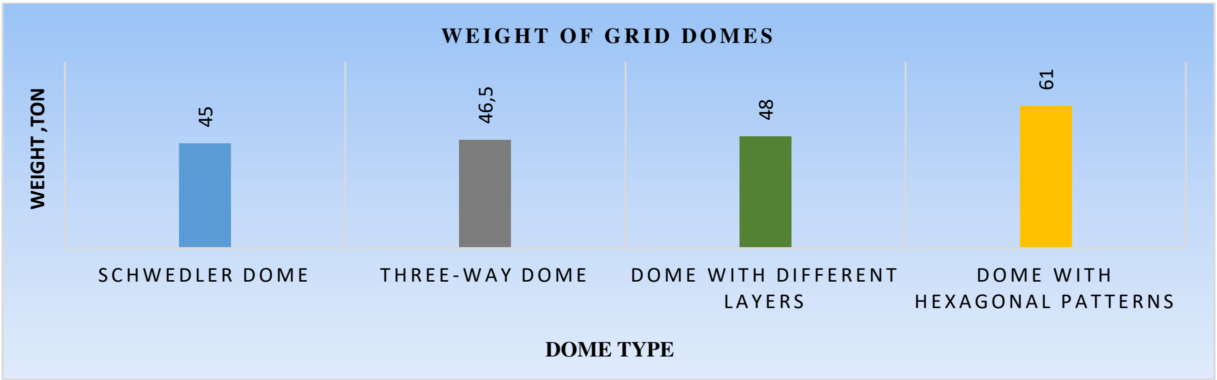


Fig. 8: Total number of joints and members of double-layered grid domes.

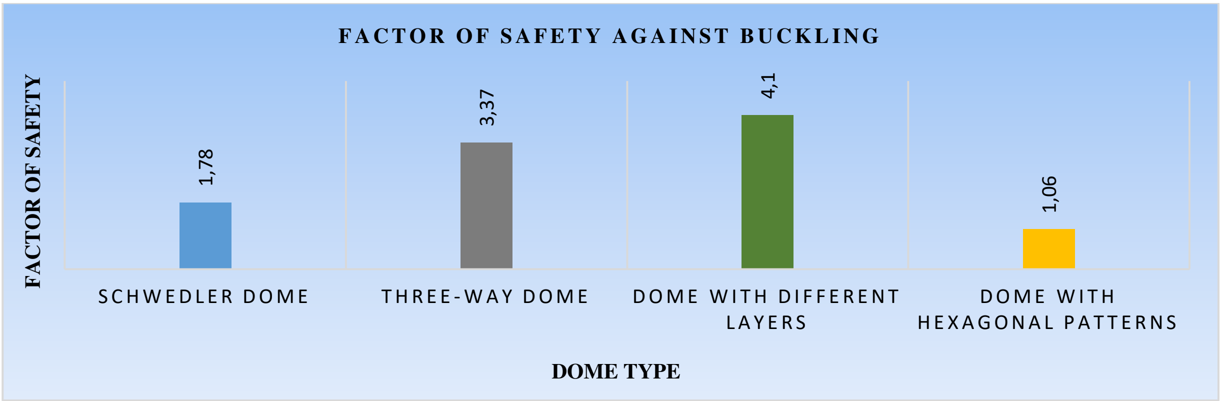


Fig. 9: The first factor of safety against buckling for double-layered grid domes.

DISCUSSION:

From the results, load combination 1 (Combo 1) gave the maximum values of axial forces and vertical deflections compared with the other load combinations. From the comparison ofthe two programs, it was noticed that SAP 2000 underestimates the values of axial forces and vertical deflections compared with ETABS 18 and the differences in axial forces obtained were about 0.6 -16.6% and 0- 14.3% in vertical deflections as illustrated in **Table 1**. As a whole, within limits of engineering accuracy, quantitative and quailtative conformity of received results under two independent software programs that give a conclusion about the correctness of the executed analysis. It noted that the axial forces distribution is approximately regular for Type 1, Type 2, and Type 3 but Type 4 gave irregular distribution because of geometry and intensity of members per joint. It was noticed that types 1, 2, and 3 of grid dome have the same pipe section (P2) when the optimized design was done by SAP 2000, but Type 4 has pipe section (P4) as shown in **Table 2**. It was found that Type 1 gave the minimum total weight compared with 3 types as illustrated in **Fig. 8**. It also noticed that Type 3 is more stable compared with the other types, which gave the biggest value of safety factor against buckling as shown in **Fig. 9**.

CONCLUSION AND RECOMMENDATIONS:

The conclusion of the study was summarized in the following points. Variations of loading cases and their combinations gave differences in the axial forces distribution and deformation patterns of double-layered grid domes. The design of members wasprovided according to AISC (LRFD method) with design strength 345 MPa using SAP2000 and section capacity in compression and tension were determined. All sections were satisfactory, the increase in cross-sectional area of members may increase the dome's weight, and then fabricated pipe may be increased. It was noticed that Types 1, 2, and 3 were nearly the same total weight.It was observed that a double-layered grid dome with different layers (Type 3) was the most efficient in structural performance because the members'density gave an excellent distribution of axial forces distribution and vertical deflections of the whole dome and then minimized the axial force in members and vertical deflections. It is suggested to use much more work on the effect on the structural performance of domes' various sizes and the boundary support condition of different members' cross-sectional area of each layer and bracing and other types of configuration may be of interest to the designer. The present study of the structural performance of double-layered grid domes is limited to static linear analysis, it was suggested to use the non-linear analysis, however, also requires further studies about structural performance.

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CONFLICTS OF INTEREST:

The authors declare that they have no competing interests in the research.

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