# Parametric study of the factors affecting the structural performance of braced domes subjected to gravity loads

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**ABSTRACT**

Nowadays, single-layer braced domes are widely used by architects and engineers. The strength, economy, and fast installation were the main reasons for spreading this system around the world. The architectural design constraints of a dome impose structural challenges for the design engineer, especially when the span is large, with a small aspect-ratio or heavy design loads. Therefore, the structural engineer looks for different methods to strengthen the single-layer braced dome. This paper studied three different methods for improving the structural performance of the single-layer braced dome, including the grid-density, the member geometry (size), and the bracing systems with double-layer. A total of 96 finite element models were analyzed and designed using SAP2000 commercial software. Four main types of braced domes were studied, including Schwedler, Ribbed, Geodesic, and Kiewit-6. Two different types of joint connections were modeled (i.e., rigidly-connected and pin-connected). In addition, all models were pin-supported at the bottom ring and subjected to static gravity load only.

The results indicated that the joint rigidity had a significant impact on the linear buckling load and a minor effect on the maximum displacement and internal forces. Furthermore, it was found that the increase in grid-density, enlarging member size, or using bracing systems significantly improved the structural performance, but at the expense of increasing the of a single-layer brace dome 's weight.

**Keywords:** Braced-dome, Grid density, Linear-buckling, Structural Performance.

## INTRODUCTION

Single-layer braced domes are widely used by architects and engineers. Strength, economy, and fast installation were the main reasons for the spread of this roofing system around the world in the last half century. A braced-dome is defined as a structural system that consists of one or more layers of elements that are arched in all directions. The most popular types of braced domes used in practice are Ribbed, Schwedler, Kiewit three-way grid, Lamella, and Geodesic domes (Chen and Lui 2005). Braced domes are considered part of space frame (SF) structures. The SF is composed of an array of modular structures; each module is assembled of members connected at end nodes. Two basic types of node systems have been developed in practice, including pin and rigid connections, as shown in Figure 1.

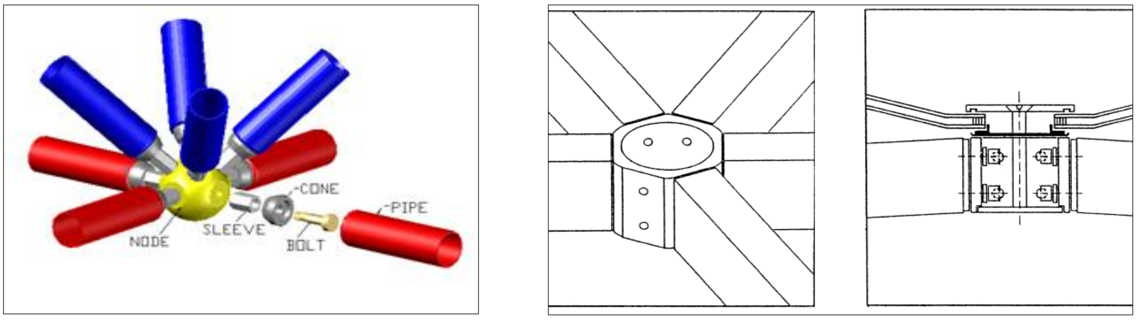


**Figure 1.** Space frame node systems: a) pin-connection (MERO system), b) rigid-connection (Type ZK system)

Double-layer SF domes were studied during the last two decades. For example, some researchers investigated the key parameters affecting the collapse behavior of diamatic domes, including aspect-ratio, gravity loads, and imperfection of nodes and members (Vazna and Zarrin 2020). While others studied the optimal geometric design (Babaei and Sheidaii 2013) for different aspect-ratios and supporting conditions (Jadhav et al. 2013). Furthermore, researchers found the stability of the dome improved as we changed the type from single to partial double-layer and full double-layer dome.

Furthermore, researchers studied many design aspects of SLBD including stability, effect of joint rigidity, capacity under gravity and lateral loads, and geometrical design parameters. The most critical design criterion investigated was the stability. Many researchers studied the buckling of braced dome structures either using approximate shell analogies or numerical finite element modeling (FEM). Many parameters that may affect the buckling of braced dome structure had been studied such as types of the dome, aspect-ratio, member's imperfection, joint-rigidity, and type of analysis (Gioncu 1995). Wu et al. (2013) investigated the linear elastic buckling of lattice domes and found that the Kiewit type had better structural stability than other types (Schwedler, and Lianfang). Fan et al. (2010) investigated the elasto-plastic stability of seven different types of domes considering the material non-linearity and different support conditions. Results showed that the support conditions did not affect the elasto-plastic buckling load. Zamanzadeh et al. (2009) developed a geometric parameter that represents the slenderness of a single-layer reticulated geodetic dome. Numerical results showed that linear and non-linear buckling loads are almost equal for slenderness factors above three. Guan et al. (2018) experimentally and numerically investigated the post-buckling behavior of Geodesic lattice dome. The results of the experimental test of the 3D printed scaled model were agreed with FEM.

Researchers found a significant impact of the joint rigidity on the buckling capacity, and post-buckling behavior including the snap-through existence in the SF domes (López et al. 2007; Shon et al. 2014). Gidófalvy (2012) concluded that the effect of joint-rigidity on the buckling load of single-layer steel grid shells was significant in large span dome compared to relatively small span. Similar results were obtained by Shon, S., et al. (2014), the buckling load was directly proportioned to joint-rigidity and rise- to-span ratio. Furthermore, Battista, R. et al. (2001) investigated the strengthening of a reticulated lattice dome against local instabilities. It was shown that in order to strengthen a large span double-layer reticulated dome, extensive safety, and stability analysis need to be performed. Although most of existing studies were done with either perfectly rigid, or pin connection, recently attempts were made to incorporate a semi-rigid joints in numerical modeling of SF domes (Ramalingam and Jayachandran, 2015; Zhao et al., 2016).

The behavior of single-layer dome under lateral loads were also investigated in the literature. Hosseini et al. (2012) conducted a numerical analysis, and found that seismic behaviors of the Ribbed domes and Schwedler were almost similar, and Ribbed dome had better seismic behavior than the Kiewit and Schwedler domes. Furthermore, Abdolpour et al. (2009) proposed analytical models for estimation of the equivalent total base shear force, and the distribution at different levels of the dome. Estimation was accurately estimating the seismic forces without a need to perform a complicated dynamic analysis. Fiouz et al. (2012) investigated the effect of wind load on different types of lattice dome, Ribbed and Schwedler with various rise-to-span ratios. The study showed that the type of dome does not significantly affect the deformation of the model. Chen et al. (2014) examined the wind induced response and equivalent wind static load on lattice dome structures with different aspect ratio. The results of the study showed that rise-to-span had an important role on the wind pressure distribution of the roof. Chacko et al. (2014) studied the behavior of Ribbed lattice dome with different aspect ratio. Findings showed that the failure of Ribbed dome was mainly due to buckling. It also showed that Ribbed dome is good in resisting the gravity load, but for resisting lateral load such wind diagonal bracing should be added to increase the lateral stiffness of dome. Eldhose et al. (2015) studied the behavior of Schwedler lattice domes. Findings showed that Schwedler dome showed good performance to resist lateral load. Author proposed different optimal aspect-ratios depending on the decision criteria that ranged between 0.15-0.40. The aspect ratio of 0.25 was optimal in-case of axial forces is the criteria, while 0.35 was the optimal in-case was the buckling load is the criteria of the selection.

In practice, the structural design engineer faced numerous challenges during the design process, including determining which type of braced dome has the best structural performance and minimum design weight for a given set of design requirements, such as a relatively heavy roofing load, a long design span, and an aspect-ratio architectural design constraint. In addition, architects always prefer the single-layer braced dome over the double-layer braced dome, which gives the maximum light and vision (Irisarri et al. 2010). Therefore, structural engineers look for different methods to strengthen and improve the structural performance of the braced dome.

## RESEARCH AIM AND SIGNIFICANCE

The mentioned literature showed that few researchers studied the structural performance of the steel-braced dome from a design perspective. In previous work by the present authors (Abu-Farsakh and Al-Huthaifi 2018), an optimal design aspect-ratio of 0.25 was proposed for the best structural performance of different types of braced dome. In this study, three methods are studied for improving the structural performance of single-layer braced domes while having architectural constraints on the dome aspect-ratio, including grid-density, member geometry (size), and bracing systems with double layer. The significance of this study is to help the practicing design engineer understand how different methods could affect the structural performance of the braced dome and at what cost for the additional material. Thus, based on the numerical results of this parametric study, the design of braced dome structures could be much easier, practical, and efficient.

## FINITE ELEMENT MODELING

### Geometric Parameters of Domes

In the present work, four main types of braced dome are studied; those include Ribbed (R), Schwedler (S), Geodesic (G), and Kiewit-6 (K) as shown in Figure 2. The aspect-ratio for all domes is constant with diameter of 20 m and rise of 3m. The number of ribs and rings were kept constant for each type of the studied braced domes.

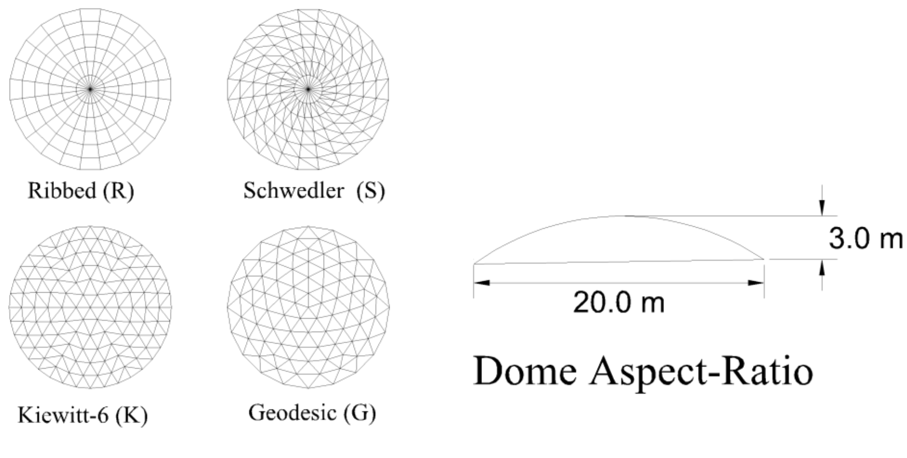


**Figure 2.** CAD-models showing the four different dome types

### Structural Parameters of Dome

The braced domes are modeled using truss line elements. All members have a tubular pipe section and are made of steel grade ASTM A53-B. Linear elastic behavior of steel material up to yield strength is used. All domes are pin-supported at the bottom ring and subjected to total gravity loads (i.e., dead and live) of 120 kg/m2. Both types of joints are modeled for each dome, including rigidly-connected (C) and pin-connected (P). The total number of FEM is 96, and the analysis and design are carried out using the SAP2000 computer package. Each model is designated using two letters: the first indicates the type of dome, and the second indicates the type of joint. For example, model R-C indicates a model for Ribbed dome with a rigid connection. The linear-buckling load, deflections, and internal forces are taken as structural performance indicators. The total weight of each model is also calculated in order to compare the effectiveness of each method.

## NUMERICAL RESULTS AND DISCUSSION

The effects of increasing the pipe size, grid density, and bracing on design results such as linear-buckling, deflections, internal forces, and weight of the braced domes were obtained for each model and discussed in the following sections.

### Effect of Member Geometry (Pipe Size)

The effect of increasing member geometry on improving the structural performance of the braced domes was studied here. Four different pipe diameters were included: 48.3, 60.3, 76.1, and 88.9. The thickness was constant and equal to 4mm for all pipes. The interaction of member geometry and joint-rigidity variables was studied through modeling two groups for each dome type; one with a pin-connected (P) member and the other with a rigid (C) joint. The design results of 28 different models were shown in Figure 3. Results showed the positive impact of increasing the member size (diameter) on the design performance indicators regardless of the dome types. Increasing the member size increased the buckling load capacity and reduced the maximum deflection. Moreover, the maximum compressive force was constant for different member sizes. In addition, the joint rigidity only affected the linear buckling capacity. Furthermore, the designer needs balance between required structural performance and the total weight of the dome. The increase in pipe size form 48.3 mm to 88.9 mm resulted in 100% enhancement and 50% decrease in buckling capacity and maximum displacement respectively. However, the weight of the dome was increased up to 2 times of its original weight.

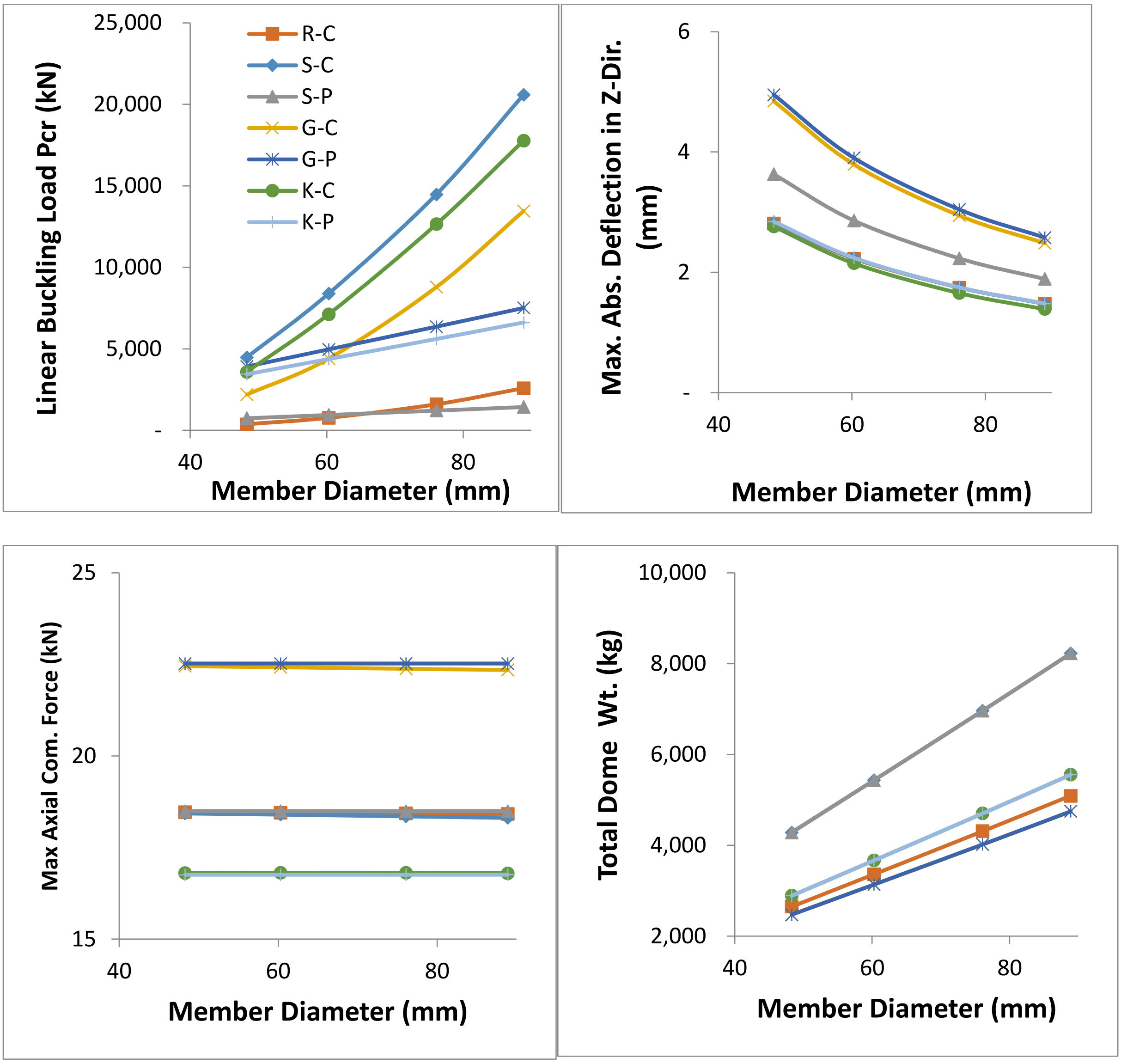


**Figure 3.** The effects of increasing the member size on design results a) linear-buckling, b) maximum deflections c) maximum compression forces d) total dome weight

## Effect of Grid-density

The effect of increasing dome grid-density on improving the structural performance of the braced domes was studied here. As shown in Figure 4, five different grid-density models were developed for each type of braced dome. The grid density was increased from a very low to a very dense grid topology. The interaction of grid-density and joint-rigidity variables is included through modeling in two groups for each dome type: one with a pin-connected and the other with a rigid (continuous) joint. As the surface area of the dome is constant for all models, the number of joints of each model is taken as an indirector of the grid-density. The design results of 35 models with different grid-densities are shown in Figure 5.

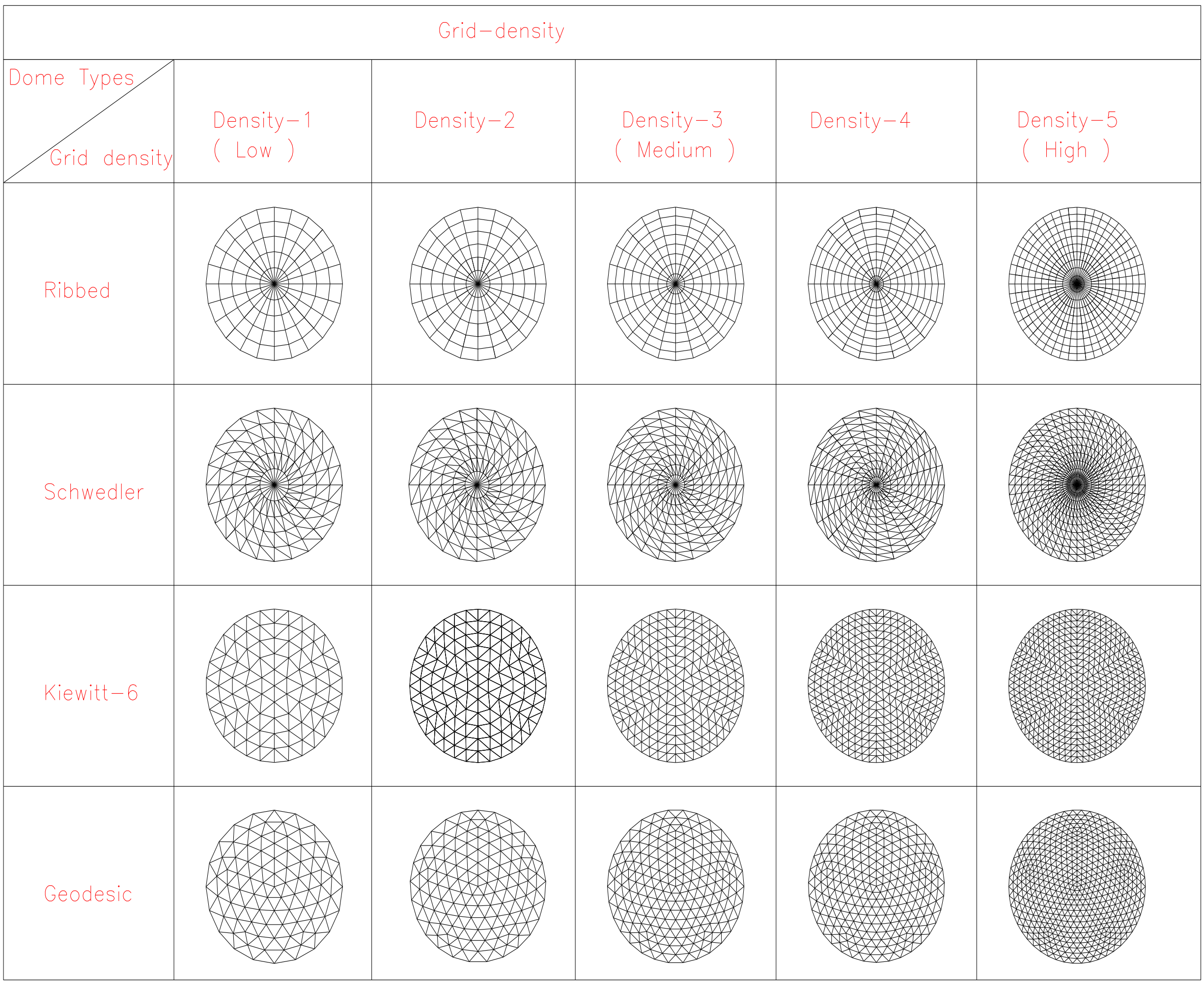


**Figure 4.** CAD-models showing the four different dome types with different grid-density

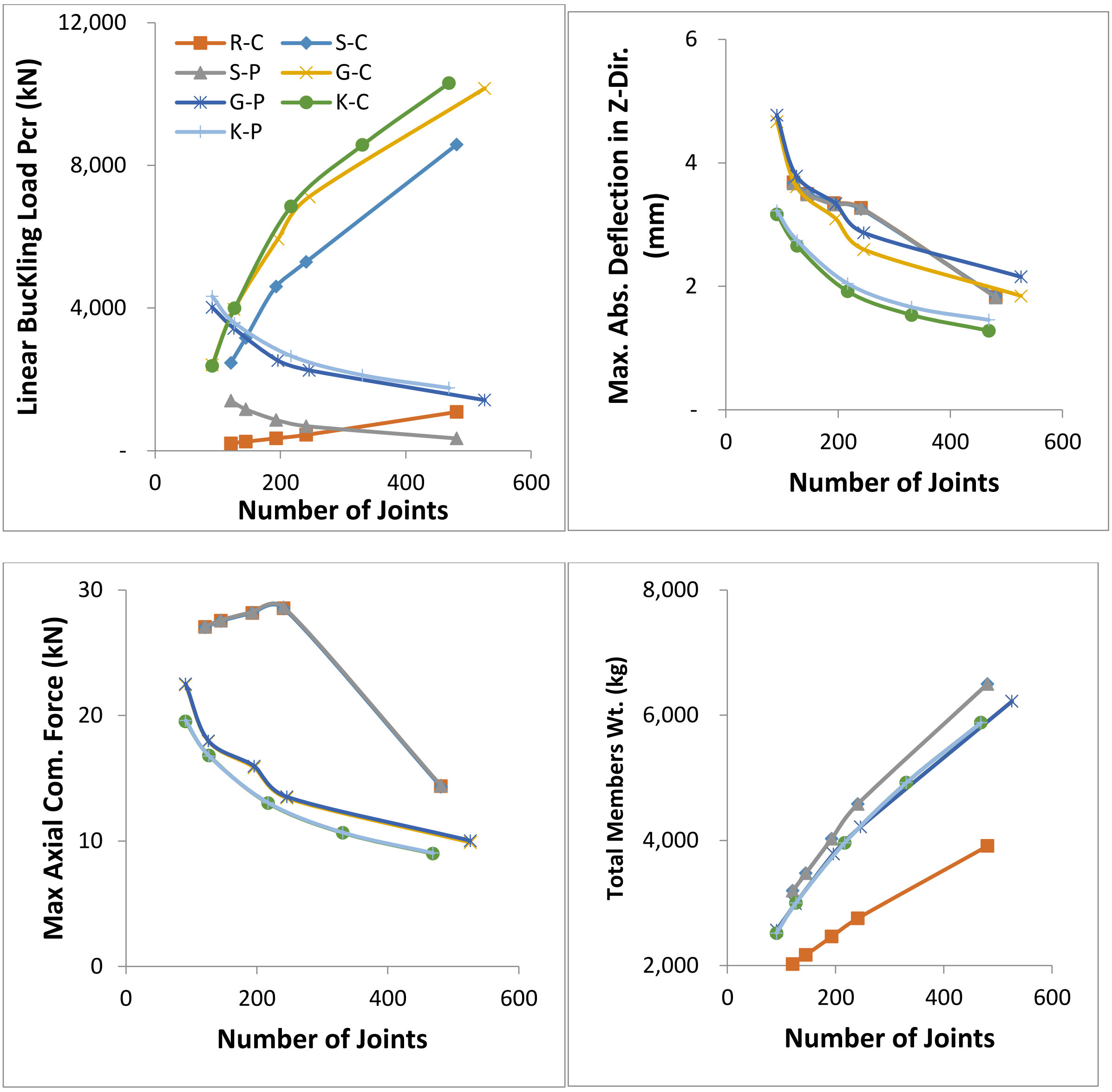


**Figure 5.** The effects of increasing the grid-density (number of joint per dome) on design results a) linear-buckling, b) maximum deflections c) maximum compression forces d) total dome weight

The results showed that increasing the grid density significantly improved the structural performance of the braced dome. It was found that the interaction of joint rigidity with grid-density affected buckling behavior. For rigidly-connected domes, the linear buckling load is directly proportional to the grid density as the braced dome approaches the solid shell buckling capacity. While the results of the pin-connected dome showed the opposite behavior, increasing the grid-density reduced the buckling load. This can be explained by comparing the different buckling modes of the same dome type with different joint systems, which showed that the buckling mode was changed from global to local as the grid-density was increased. The absolute maximum displacement in the Z-direction was inversely proportional to the grid-density of the dome. The stiffness of the braced dome was increased as the grid-density was increased, which therefore reduced the maximum displacement. In addition, the maximum internal axial compression force direction was inversely proportional to the grid density of the dome, indicating that more members mean a lower share of the total load.

To sum it up, results indicated that the grid-density has a great impact on the dome displacement and maximum internal forces regardless of the type of dome or jointing system. In addition, the stability was improved only for the rigidly-connected dome. However, the increase in grid-density was accompanied by an increase in the total weight of the dome, so the design engineer should use the minimum grid-density that satisfies the design requirement.

**Effect of Bracing Systems**

The effect of bracing of a single-layer braced dome with a double layer was studied using five patterns of each type of dome, as shown in Figure 5. The bracing pattern included the single layer dome (unbraced), circumferential bracing, 4 radial arch bracing, 6 radial arch bracing, and full double-layer bracing. Both types of joint-rigidity were studied with a total number of 33 models. In general, the results showed that bracing of a single-layer dome with an additional double layer relatively reduced the maximum deflection and member compression force regardless of joint rigidity or dome type. Moreover, it was noticed that linear buckling load was significantly increased with increasing the bracing density until it reaches its maximum value when it becomes a full double-layered braced dome. Similar results were reported in a different study (Jadhav et al. 2013). The buckling capacity of pin-connected domes was dramatically improved (Figure 7). The total weight of the dome is directly proportional to the bracing density of the pattern used. The weight of the full double-layer was approximately equal to 4-5 times the weight of the single-layer dome (Figure 7).

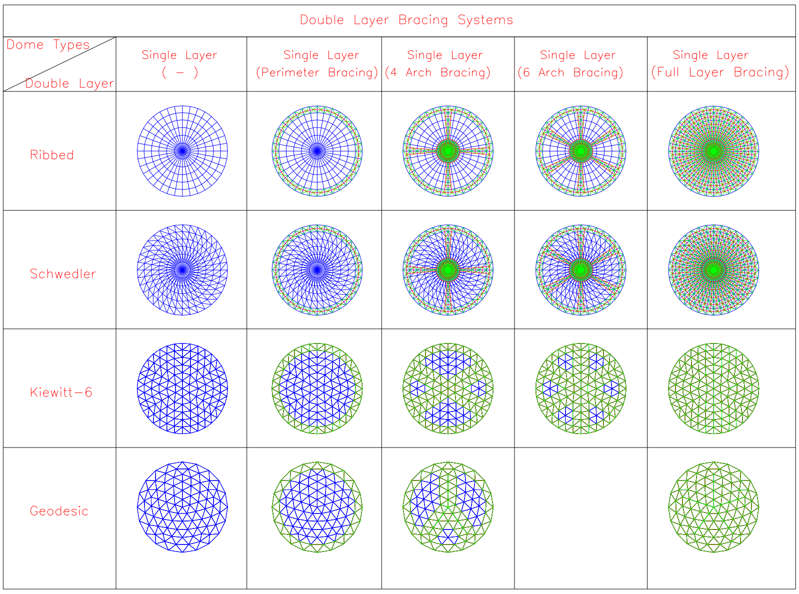


**Figure 6.** CAD-models showing the four different dome types with different bracing patterns (P1 to P5)

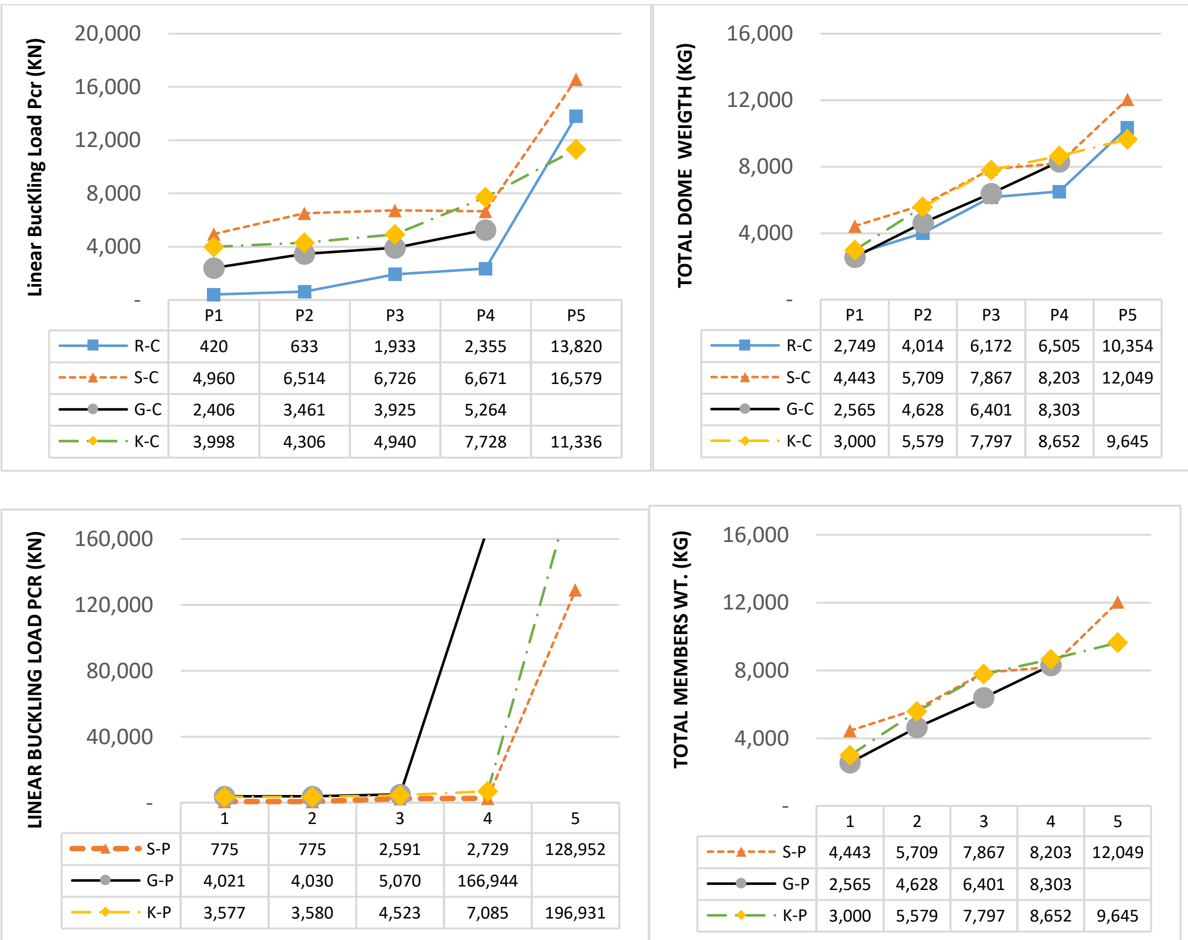


**Figure 7.** The effects of bracing patterns (double layer) on design results a) linear-buckling, b) maximum deflections c) maximum compression forces d) total dome weight

From the above observations, it was concluded that the designer could enhance the structural performance of the lattice dome by using the double layer bracing systems. The use of a radial arch pattern is better than a circumferential bracing pattern. But in general, a full double layer is the best pattern for bracing. It increases the buckling capacity and reduces the maximum displacement, but the total weight of the dome was increased by more than 4 times on average, and the total number of nodes and pipes was doubled, so again the structural designer needs to balance between structural requirements and cost.

## CONCLUSION

This paper investigated three different approaches to improve the structural performance of four different types of braced-domes (i.e., Schwedler, Ribbed, Geodesic, and Kiewit-6). Based on the numerical results of this study, the following conclusions were drawn:

1) The structural performance of the domes was improved by increasing grid-density, member size, or the use of bracing systems. However, this improvement was accompanied by an increase in the weight of the dome. Therefore, the design engineer should balance between structural requirements and cost.
2) The joint-rigidity had a significant impact on the buckling capacity of the braced dome.
3) As the diameter of the member (pipe) increased from 48.3 mm to 88.9 mm, linear buckling increased approximately five times in rigidly-connected domes and twice in pin-connected domes, with a 50% reduction in maximum deflection in both cases.
4) Doubling the grid number in the radial and circumferential directions of the rigidly-connected braced dome increased the buckling capacity by four times, resulting in a 50% reduction in maximum defection and an approximately 50% reduction in internal forces.
5) For pin-connected domes, the increase in grid-density had a negative impact on the linear buckling capacity where local buckling occurred at lower load. But it still enhanced the structural performance of the braced dome through reducing the maximum deflection and maximum internal forces.

6) The additional double-layer bracing in the radial direction was more structurally sound than the bracing in the circumferential direction.
7) In comparison with a single-layer braced dome, a full double-layered dome significantly improved structural performance with a linear buckling load of 4–100 times larger and 10–30% less in the maximum deflection.

## RECOMMENDATIONS FOR FUTURE WORK

Several additional areas of future research would improve the results and conclusions of this research, such as including other types of braced domes (i.e., trimmed schwedler, lamella, and three-way grid. The effect of material nonlinearity on the design results of the braced dome should also be studied with more advanced FEM software such as ANSYS or ABAQUS. The effects of wind and seismic loads should be investigated. The interaction between different variables of the study can be studied, such as the interaction between aspects ratio, grid-density, member geometry, and bracing systems. For a braced dome, the non-linear buckling capacity is more realistic than the linear one, so researchers can study it.

## ACKNOWLEDGEMENT

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