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Original Paper

Optimal Aspect-Ratio for Various Types of Braced Domes under Gravity Loads

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Abstract

Latticed structures are one of best structural systems used for roofing. Lightness, rigidity, strength, shape flexibility, speed of construction, and economy were the main reasons behind the use of such systems in the last five decades. Braced-domes were one of oldest types of latticed structures and were used to cover many structures all around the world.In this paper, two main geometrical parameters of domes were studied; topology of the dome and aspect-ratio. Four different types of domes were studied using five different aspect-ratios for each type. SAP2000 was used to analysis a total of 20 models. Models were mutually rigidly-connected while pin-supported at bottom ring and subjected to total gravity loads of 120 kg/m^2.It was concluded from that Ribbed-dome had the minimum weight, but it had the lowest structural performance. On the other hand, Schwedler-dome had the maximum weight with the best structural performance. The optimal value of dome aspect-ratio (H/D) for all types was 0.25 as it resulted in maximum linear-buckling load with minimum displacements and internal forces but with slight increase in total dome-weight.

Keywords: Braced-dome, Aspect-ratio, Linear-buckling, Deflection, Dome weight

1. Introduction

Latticed structures are one of best structural systems used for roofing. Lightness, rigidity, strength, shape flexibility, speed of construction and economy were the main reasons behind the use of such systems in the last five decades. Amazing space structures have been fabricated and installed all over the world for covering sport roofing, aircraft hangars, skylights, railway stations, canopies, curtain wall stadiums and many other structures. Domes are one of the oldest structural forms used since the earliest times. A latticed-dome is defined as: a structural system that consists of one or more layers of elements that are arched in all directions. The surface of a dome may be a part of a single surface such as a sphere or paraboloid. Frequently single layer domes used in practice are Ribbed, Schwedler, Kiewit three-way grid, Lamella and Geodesic domes [1]. At a preliminary design stage of a latticed-dome, structural design engineers face two main problems in the geometrical design, choosing among different topology types of latticed domes and finding the corresponding optimal aspect-ratio. The stiffness, strength and stability are the main criteria for the selection of any structural system, so the structural designer is always looking for the dome type and aspect-ratio that would give the best structural performance.

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This study investigates the effect of geometric design parameters on the structural performance of latticed metal braced dome structures subjected to static loads. SAP2000 FEM software is used for the analysis and design of the braced domes using twenty models.A detailed description of the main types of braced domes can be found in [1,2]. Investigation of static, elasto-plastic stability of domes and effect of member imperfections were investigated in [3-7]. Chacko, et al. (2014) [8] studied the behavior of Ribbed-dome and showed that aspect ratios between 0.3-0.35 improved the performance of such domes in general. Eldhose, et al. (2015) [9] studied the behavior of Schwedler latticed domes using various aspect-ratios for different design criteria.In the present paper the effect of aspect-ratio for four different types of latticed domes: Ribbed, Schwedler, Kiewitt-6 and Geodesic subjected to gravity surface loads of intensity 120 kg/m^2 will be determined. The corresponding optimal weights of all dome-types will be investigated according to minimum displacements, internal forces and linear-buckling strength.

2. Finite Element Modeling

2.1 Geometric Parameters of Domes

Among many different types of single layer latticed domes, this study focuses on four main types: Ribbed, Schwedler, Kiewitt-6, and Geodesic domes. In order to study the effect of aspect-ratio on domes of diameter 20 m with five different rises (1.5m, 3m, 5m, 8m and10m), which cover a wide range of dome aspect ratios, from shallow to deep domes as shown in Figure 1. The number of ribs (longitudinal) and rings (circumferential) were kept constant for each type while the aspect-ratio was changed.

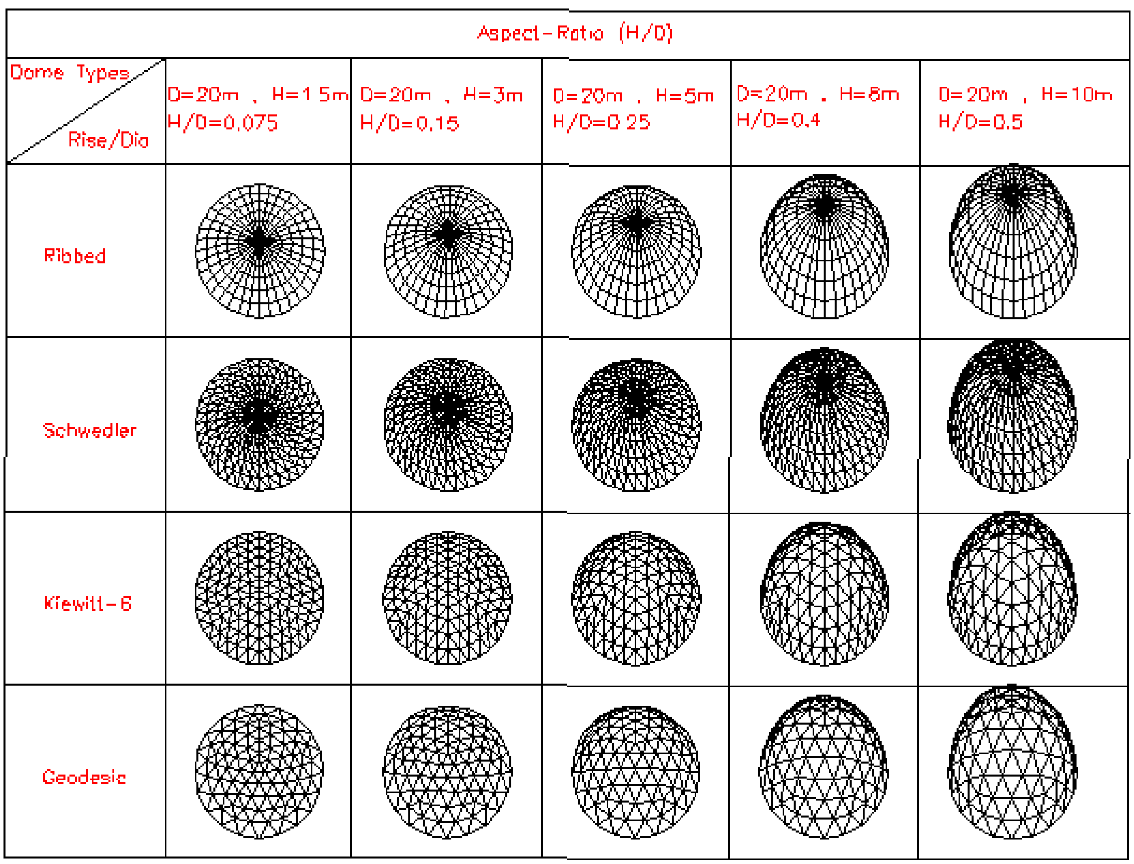

Figure 1. CAD-models showing the various aspect-ratios for the different dome types

2.2 Structural Parameters of Domes

All dome members are rigidly-connected using uniform pipe sections of size P50x4 made of steel grade ASTM A53-B, as shown in Table 1. All domes are subjected to surface gravity uniform loads of 120 kg/m^2, and pin-supported at all bottom ring nodes. Linear-buckling and linear-static analyses and design of dome members are carried out using SAP2000 computer package.

Table 1. Member properties

Pipe ID	Material	Outer Diameter (mm)	Thickness (mm)	Area (mm^2)	Moment of Inertia (mm^4)
P50X4	A53GrB	50	4	578.05	154051.14

3. Numerical Results and Discussion

The effect of aspect-ratio on design results such as: linear-buckling, deflections, internal forces and weight of the braced domes are obtained for each model (see Table 2) and discussed in the following sections.

3.1 Linear-Buckling

Linear-buckling analysis is performed to investigate the instability of a structure subjected to a specific load pattern. It involves the solution of the generalized Eigen-value problem $[K-\lambda G]\Phi=0$, where **K** is the total structure stiffness matrix of the system, **G** is the geometric stiffness matrix of the system , **λ** is the diagonal matrix of Eigen-value (buckling factor) , **Φ** is the mode-shape matrix corresponding to the Eigen-value. Buckling mode shapes and buckling factor depend on the applied load pattern. Buckling factor can be considered as a load safety factor.A representative Figure 2, shows the first mode of buckling-shape for the Ribbed-dome with (H/D=0.075) where the corresponding buckling factor is 0.29887. The effect of aspect-ratio (H/D) on buckling of various types of braced domes, the linear-buckling load ($\mathbf{P_{cr}}$) is found to be directly proportional to aspect-ratio (H/D) up to a value of 0.25 at which the buckling load is maximum. Ribbed domes have the lowest buckling strength, while Schwedler domes have the largest buckling strength. This is attributed to absence of panel bracing (diagonal) members in the Ribbed-dome.

3.2 Deflections

A representative Figure 4, which shows the deformed-shape of the Ribbed-dome (designated as: R-0.075) and is subjected to dead (D) and live (L) loads for the dome aspect-ratio (H/D=0.075). The absolute maximum displacement (deflection) in the Z-direction is inversely proportional to aspect-ratio (H/D) up to a value of 0.25 at which the displacement is minimum. After which, it becomes almost constant with slight increase. Geodesic domes have the maximum deflections while the other types are approximately the same as illustrated in Figure 5.

Table 2. Summary of SAP2000 models results

Description	Model Aspect Ratio (H/D)	0.075	0.15	0.25	0.4	0.5
1) Ribbed Dome	Number of Joints	217	217	217	217	217
	Number of Memebers	432	432	432	432	432
	1st- Mode Buckling Factor	0.30	1.04	1.96	1.72	1.17
	1st- Mode Buckling Load Pcr (kN)	112.69	419.63	906.05	1,041.97	866.11
	Maximum Absoulate Displacement in Z-Dir. (mm)	10.52	2.71	1.48	1.67	2.24
	Maximum Axial Compression Force (kN)	33.77	18.46	14.45	15.23	17.818
	Maximum Axial Tension Force (kN)	0	0	0	7.384	16.39
	Total Dome Weight (kg)	2,660.00	2,750.00	2,953.00	3,405.00	3,782.00
2) Schwedler dome	Number of Joints	217	217	217	217	217
	Number of Memebers	612	612	612	612	612
	1st- Mode Buckling Factor	4.38	12.33	14.33	10.09	6.88
	1st- Mode Buckling Load Pcr (kN)	1,655.11	4,969.43	6,622.04	6,118.98	5,088.69
	Maximum Absoulate Displacement in Z-Dir. (mm)	10.62	2.73	1.47	1.67	2.24
	Maximum Axial Compression Force (kN)	33.926	18.428	14.436	15.215	17.79
	Maximum Axial Tension Force (kN)	0	0	0	7.7329	16.317
	Total Dome Weight (kg)	4,296.00	4,445.00	4,783.00	5,538.00	6,170.00
3) Geodesic dome	Number of Joints	91	91	91	91	91
	Number of Memebers	250	250	250	250	250
	1st- Mode Buckling Factor	3.00	5.97	6.79	4.93	3.43
	1st- Mode Buckling Load Pcr (kN)	1,134.41	2,406.11	3,140.67	2,988.83	2,538.43
	Maximum Absoulate Displacement in Z-Dir. (mm)	13.68	4.67	3.06	3.44	4.50
	Maximum Axial Compression Force (kN)	39.708	22.447	17.378	17.921	20.632
	Maximum Axial Tension Force (kN)	0	0	5.38	14.951	24.817
	Total Dome Weight (kg)	2,494.00	2,565.00	2,727.00	3,089.00	3,390.00
4) Kiewitt-6 dome	Number of Joints	127	127	127	127	127
	Number of Memebers	342	342	342	342	342
	1st- Mode Buckling Factor	3.82	9.92	11.17	7.95	5.47
	1st- Mode Buckling Load Pcr (kN)	1,446.00	3,997.96	5,165.42	4,819.25	4,047.28
	Maximum Absoulate Displacement in Z-Dir. (mm)	9.19	2.66	1.71	2.06	2.86
	Maximum Axial Compression Force (kN)	30.425	16.803	12.674	12.947	14.97
	Maximum Axial Tension Force (kN)	0	0	1.388	11.848	21.096
	Total Dome Weight (kg)	2,911.00	3,001.00	3,206.00	3,665.00	4,048.00

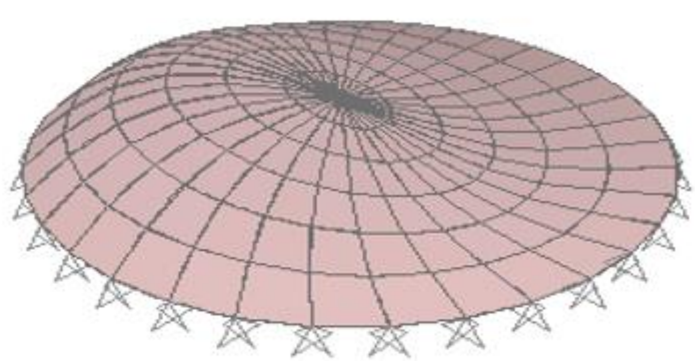

Figure 2. Dome type R-0.075-buckling mode shape (first mode)

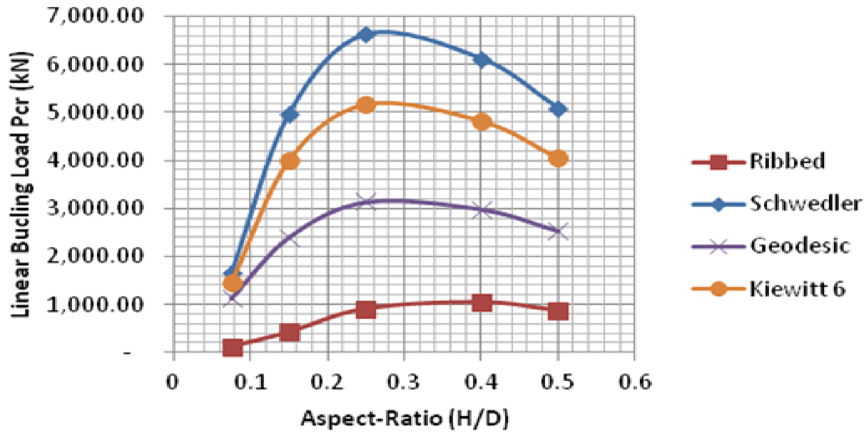

Figure 3. Linear-buckling load (P_{cr}) versus dome aspect-ratio (H/D)

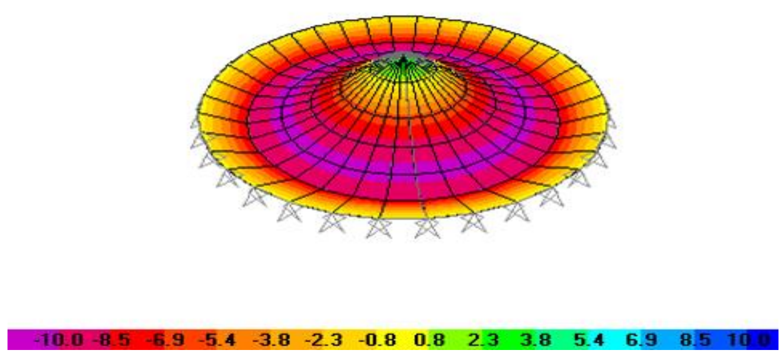

Figure 4. Dome type R-0.075 deformed-shape subject to gravity loads (D+L)

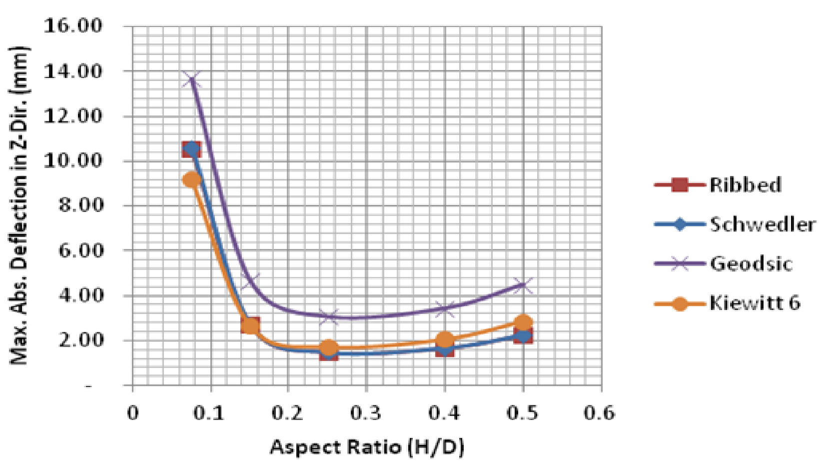

Figure 5. Maximum absolute deflection versus dome aspect-ratio (H/D)

3.3 Internal Forces

The maximum members' internal axial compression forces are inversely proportional to aspect-ratio (H/D) up to a value of 0.25 at which the corresponding compression force is minimum. Then, it becomes almost constant with slight increase in value. The geodesic dome has the maximum internal compression force while Kiewitt- 6 has the minimum force as shown in Figure 6. The maximum internal axial tension forces are negligible for shallow domes with aspect-ratio (H/D) up to a value of 0.15 for Kweitt-6 and Geodesic and up to 0.25 for Ribbed and Schwedler. After which, the relation starts to increase at a high-rate up to the aspect-ratio of 0.50. In general, the Geodesic-dome gives the largest tension force among all other types, as illustrated in Figure 7.

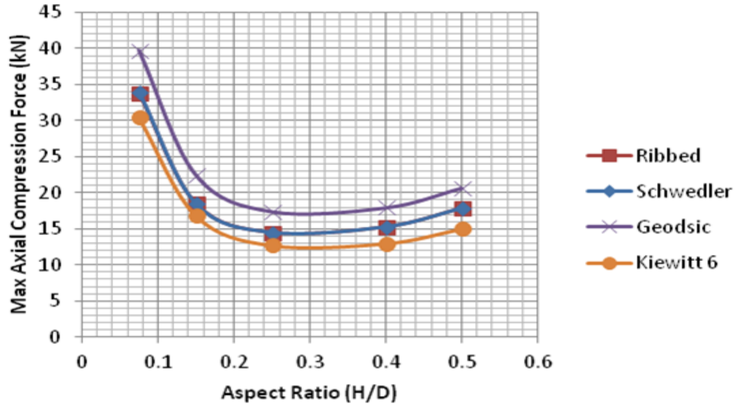

Figure 6. Maximum axial compression force versus dome aspect-ratio (H/D)

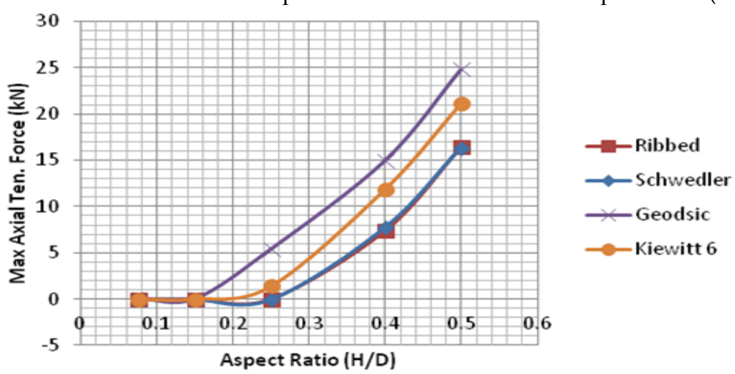

Figure 7. Maximum axial tension force versus dome aspect-ratio (H/D)

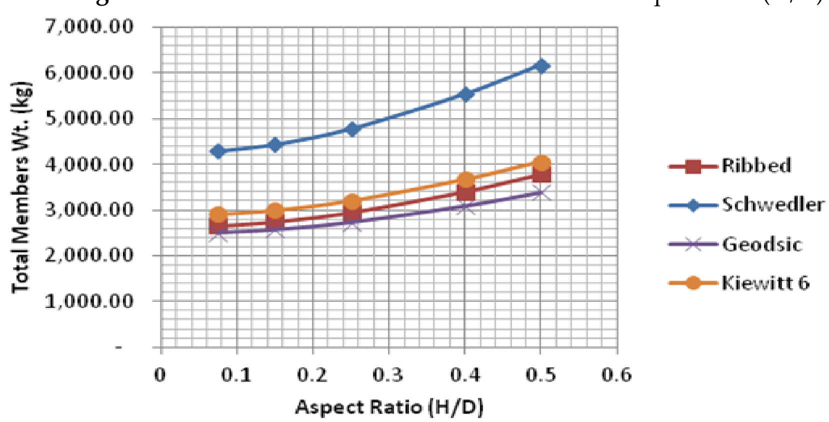

Figure 8. Total member weight versus dome aspect-ratio (H/D)

3.4 Dome Weight

The total dome weight is directly proportional to the aspect-ratio (H/D), such that the total dome weight increases as the aspect-ratio increases, as shown in Figure 8. The Schwedler-dome gives the maximum weight, while the Geodesic-dome gives the minimum weight.

4. Conclusions

In this paper, a parametric study was carried out in order to investigate the optimal aspect-ratio using four different types of braced-domes: Ribbed, Schwedler, Geodesic, and Kiewit-6. Applying linear-elastic and linear-buckling analyses of twenty dome models using SAP2000 software considering the following assumptions; rigidly-connected members, uniform cross-section, pin-supported bottom-ring of domes and uniform gravity loads, the following conclusions were drawn:

In general, the optimal dome aspect-ratio (H/D) for all types was 0.25, at which the linear-buckling load was maximum, and dome displacements and internal forces were minimum. In case of no pre-assigned architectural requirements for the domes, the structural design engineer should use an aspect-ratio of 0.25, although the resulting total dome weight at this ratio will be slightly higher than smaller ones.At all dome aspect-ratios and among all the four different types of domes considered in this study, the Ribbed-dome has the minimum total weight but with the lowest structural performance. On the other hand, the Schwedler-dome has the maximum weight but the best structural performance in terms of displacements, internal forces and linear-buckling strength.

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