A Seismic Performance of Reticulated Dome Structures

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Abstract: Reticulated dome structure are most preferred for a large spanned structure. The analysis and design of dome structure is quite different form that low rise dome structure because of lateral force due to wind and earthquake. Dome structure system is the connection between the members is rigid and the bearing is fixed hinge. In the study of the dome structure patterns namely Kiewitt-6, Kiewitt-8 and Kiewitt-10 under the seismic behavior & identify the structural efficient. The dome resist both gravity & lateral load by axial action of the member. A reticulated dome length of span 60m, 80m, 100m, 120m consider the study purpose structure and is design. Earthquake parameters are considered form IS 1893-2016. Here analysis of dome structure system will be conducted by using analysis & design software Sap2000. In this research, a set of structure using reticulated kiewitt dome structure having three various patterns of dome structure for different span and different rise to span ratio. Finally, the seismic behavior different reticulated Kiewitt dome models based on vertical rare earthquake load compared term of displacement, time period, base rection, pushover curve, plastic hinges patterns, failure mechanism of dome structure.

***Keywords* – Reticulated dome, Kiewitt dome structure, rise to span ratio, vertical rare earthquake, pushover analysis.**

I. INTRODUCTION

Over the past decades, spatial structures have been extensively used in the construction of many large span structures such as aircraft hangars, exhibition halls, stadia, airport terminals, gymnasia, bridge systems, railway platform shelters, shopping malls and atriums. Spatial structures represent the ultimate in aesthetics and engineering efficiency in structural systems, and behind their elegance and simplicity lays their structural capacity to cover very long spans. Reticulated dome's main structure can be very fast installed in just a few hours instead of months or years of and lightweight. There are no evidence proving that there was ever a problem with these structures nor damage created by wind and typhoons to the domes that are designed in a good way. Reticulated dome is a space type of structure that looks like a section of a sphere. This instrument is made of a grid of triangles that eventually form a spherical surface. The greater the number of triangles the better form of a sphere-shaped dome is approached. The pattern of a Kiewitt dome consists of a series of subdivided triangles along the circumferential direction, which have a common vertex at the crown of the dome. (I) Reticulated K6 dome structure (II) Reticulated K8 dome structure (III) reticulated K10 dome structure.

According reticulated dome the nonlinear dynamic response history analyses at each increased level of seismic records magnitude and permitted the calculation of collapse loads of domes Ming Zhang (2019). which different 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 Willem Gythiel (2019). The maximum lateral force acting in the structure under seismic loading are obtained through the analysis. Base shear is an estimate of the maximum expected lateral force that will occur due to seismic ground motion at the base of a structure Parvathy K.T (2020). Finite element analysis of these structures has been undertaken to determine the rate of spread of plasticity and the rate of increase in node displacement under seismic loading F. Fan (2018)

the failure mechanism of a single-layer reticulated dome under seismic load, parametric analyses through increment dynamic analysis (IDA) are conducted on the dome. The results of the analyses indicate that the limit load of the structure significantly increases together with the plastic development with the decreasing rise–span ratio, roof mass and initial defects prior to the failure to collapse Feng Fan (2014). the theory of Hamilton variation principle which is the current method for impact problem, central difference method which is efficient solution of finite element method for impact problem and adapts to solve non-linear dynamic problem FAN Feng (2008). single-layer Kiewit reticulated dome under impact loads, the following four failure modes are given according to the results of the vertical displacement, stress in main members, and the plastic deformation: (1) type 1: no failure; (2) type 2: moderate failure; (3) type 3: severe failure and (4) type 4: slight failure.

II. BUILDING CONFIGURATION

For the reticulated dome structural patterns modal Kiewitt 6, 8, 10 of consider for analysis. Total 48 model consider for analysis and design with rise to span ratio 0.20, 0.25, 0.30, 0.40 and different span 60m, 80m, 100m, 120m. First analysis and design all diagrid structure and then result compared for different dome pattern and different span of structure. The typical plan and elevation are shown in figure 3.8 & figure 3.9. Dead load, live load and earthquake load case are considered for analysis and design. Modelling analysis and design of all reticulated dome models are carried out using SAP2000 software. For linear static analysis and design beam elements and braces are modelled by truss elements. The support conditions are considered as hinged supports. All structural members are designed using IS 800:2007.

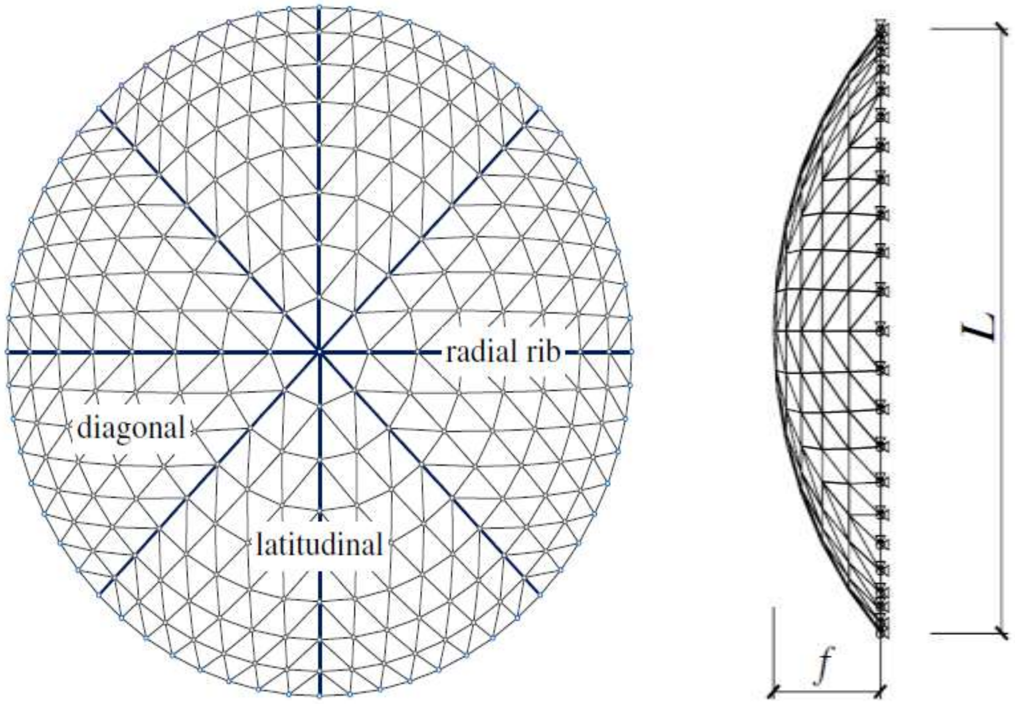


Figure 1: Typical Floor Plan and Elevation of reticulated dome

Table 1 – Building parameters

Dome span	60m, 80m, 100m, 120m
Rise to span ratio	0.20, 0.25, 0.30, 0.40
Dome patterns	K6, K8, K10
Young's modulus	210 GPa
Poisson's ratio	0.3
Yield strength	345 MPa

Table 2 – Loading condition

Dead load and live load	0.5 kN/m²
Zone factor (Z)	0.24
Importance factor (I)	1
Response reduction factor (R)	5
Soil type	Medium

Table 3 – Reticulated dome model

Model name	Span	Rise to span ratio	Dome patterns	Model name	Span	Rise to span ratio	Dome pattern
D_S60_R0.20_K6	60	0.20	K6	D_S100_R0.20_K6	100	0.20	K6
D_S60_R0.25_K6	60	0.25	K6	D_S100_R0.25_K6	100	0.25	K6
D_S60_R0.30_K6	60	0.30	K6	D_S100_R0.30_K6	100	0.30	K6
D_S60_R0.40_K6	60	0.40	K6	D_S100_R0.40_K6	100	0.40	K6
D_S60_R0.20_K8	60	0.20	K8	D_S100_R0.20_K8	100	0.20	K8
D_S60_R0.25_K8	60	0.25	K8	D_S100_R0.25_K8	100	0.25	K8
D_S60_R0.30_K8	60	0.30	K8	D_S100_R0.30_K8	100	0.30	K8
D_S60_R0.40_K8	60	0.40	K8	D_S100_R0.40_K8	100	0.40	K8
D_S60_R0.20_K10	60	0.20	K10	D_S100_R0.20_K10	100	0.20	K10
D_S60_R0.25_K10	60	0.25	K10	D_S100_R0.25_K10	100	0.25	K10
D_S60_R0.30_K10	60	0.30	K10	D_S100_R0.30_K10	100	0.30	K10
D_S60_R0.40_K10	60	0.40	K10	D_S100_R0.40_K10	100	0.40	K10
D_S80_R0.20_K6	80	0.20	K6	D_S120_R0.20_K6	120	0.20	K6
D_S80_R0.25_K6	80	0.25	K6	D_S120_R0.25_K6	120	0.25	K6

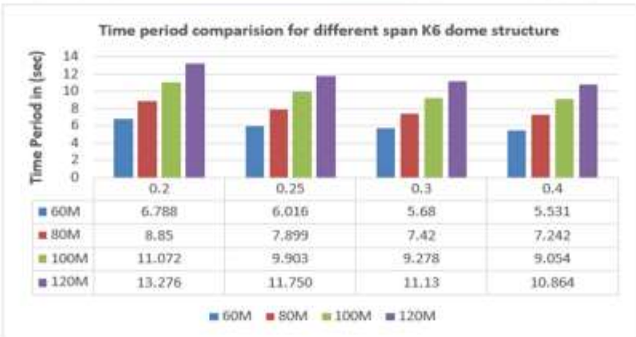
D_S80_R0.30_K6	80	0.30	K6	D_S120_R0.30_K6	120	0.30	K6
D_S80_R0.40_K6	80	0.40	K6	D_S120_R0.40_K6	120	0.40	K6
D_S80_R0.20_K8	80	0.20	K8	D_S120_R0.20_K8	120	0.20	K8
D_S80_R0.25_K8	80	0.25	K8	D_S120_R0.25_K8	120	0.25	K8
D_S80_R0.30_K8	80	0.30	K8	D_S120_R0.30_K8	120	0.30	K8
D_S80_R0.40_K8	80	0.40	K8	D_S120_R0.40_K8	120	0.40	K8
D_S80_R0.20_K10	80	0.20	K10	D_S120_R0.20_K10	120	0.20	K10
D_S80_R0.25_K10	80	0.25	K10	D_S120_R0.25_K10	120	0.25	K10
D_S80_R0.30_K10	80	0.30	K10	D_S120_R0.30_K10	120	0.30	K10
D_S80_R0.40_K10	80	0.40	K10	D_S120_R0.40_K10	120	0.40	K10

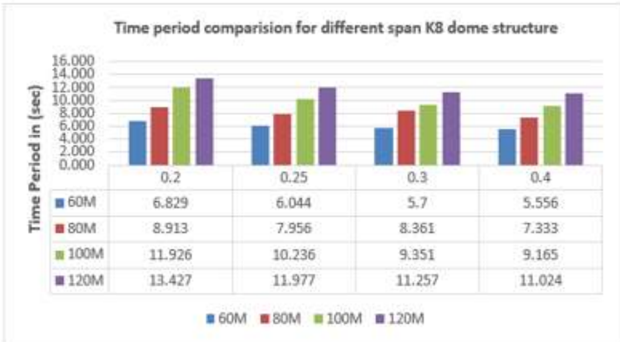
III. MODAL ANALYSIS

For the seismic analysis of reticulated dome structure first modal analysis is carried out in form of Fundamental Natural Time-Period. Time taken foe each complete cycle of oscillation is called Fundamental Natural Period of system. Time period is an inherent property of a system, when it allows to vibrate freely without any external force and it depends on the mass and stiffness of structure. Natural time period is inversely proportional to frequency of structure. It means structure consist higher natural time period is less rigid compare to structure having lower natural time period. The relation among frequency & time period is given by following expression.

$$T = \frac{2\pi}{\omega}$$

For the seismic behaviour of the reticulated K6 dome structure to result of time period of the comparison of the value. The reticulated K6 dome various span increase the time period is increase and rise to span ratio increase the time period as decrease value. Reticulated K6 dome structure the time period reduces effect of dome structure is increase in stiffness. The reticulated dome rises to span ratio 0.2 modal time period of 0.25 rise to span ratio 12.83% less than. The 0.25 ratio of dome modal time period to compare the 0.30 ratio of time period is a less than 5.91%. The 0.20 ratio of dome modal of time period compare to 0.40 ratio of dome modal time period less 22.72%.





For the comparison of the reticulated K8 dome structured of different span and rise to span ratio in result of time period. the dome span increases the time period value increase. The rise to span ratio of the reduced the value of time period increase. The K8 dome structure of the stiffness depended on time period. the span of 60m dome modal time period to compare 80m span dome modal time period 23.38% increase. The span 60m dome modal of time period to compare 120m span dome modal 49.13% of increase the time period.

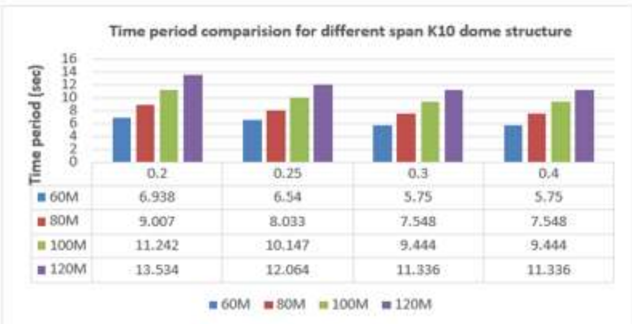


Figure 2: Time period comparison for different pattern of reticulated dome structure.

IV. PUSHOVER ANALYSIS

4.1 Procedure adopted in pushover analysis

A three-dimensional model that represents the overall structural behavior was created in SAP2000 software. Reticulated dome 60m span and 0.20 rise to span ratio for the reticulated patterns dome. Firstly, the model was applied DL and LL, then performed seismic analysis for Zone IV loads as per IS 1893:2016 and truss members were designed. The designed truss sectional properties take for the pushover analysis..

The type of analysis was performed for pushover curve in SAP2000 were:

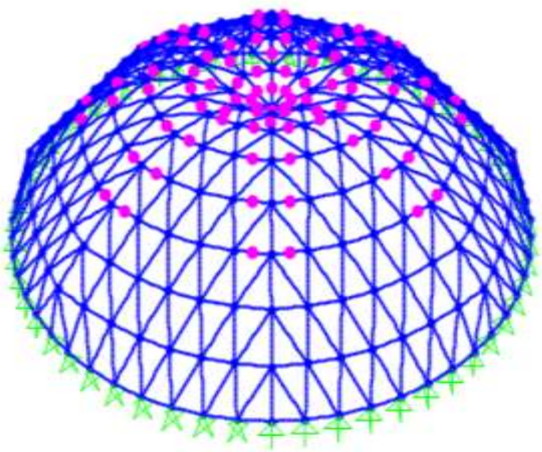
a) **Gravity pushes non-linear static analysis:** Load case **(**1.0DL+0.25LL) considered for calculation of mass at each joint as per IS 1893:2016. The same mass was used for gravity push nonlinear pushover analysis. A predefined lateral load pattern which was distributed along the height of building was applied. No load was applied at bottom and maximum load applied at top as triangle load. Instead of calculating and applying the load on each point of a frame in vertical direction, first modal values and shape calculated from modal analysis was considered as lateral load pattern, i.e., the value of mode was applied as vertical push load in displacement in Z direction (U3) was considered. Control node is used to monitor displacements of the structure. Its displacement versus the base-shear forms the pushover curve of the structure. Node at the roof top was considered as control node.

b) **Push Z nonlinear static analysis:** Nonlinear static load continues for gravity push use first mode in Z direction, Displacement control, monitored displacement, max 4% displacement, multiple states of min 20 and max 100 were considered and results were saved. Modal load 1 shall be considered. Node on the roof top was considered as monitored node. Lateral loads were increased until some members yield under the combined effects of gravity and lateral loads Before performing the Gravity push analysis, Assign M3 hinges to both ends of all beams, P-M2-M3 hinges to both ends for all column and P hinges to the centre of braces. Hinge overwrite command was used for updating hinge parameters.

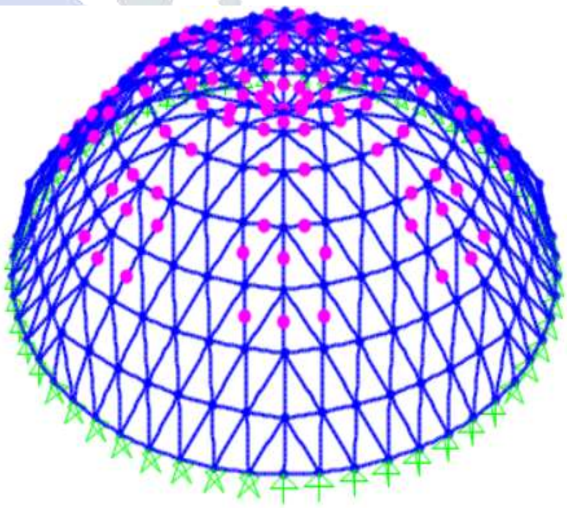
The program records base shear and roof displacement at first yielding from the analysis. Then the gravity loads were removed and a new lateral load increment was applied to the modified structural model such that additional members yield. A separate analysis was performed on modified structural model for zero initial condition under each incremental lateral load. So, member forces at the end of an incremental lateral load analysis were obtained by adding the forces from the current analysis to the sum of those from the previous increments. In other words, the results of each incremental lateral load analysis were superimposed. Similarly, the increment of lateral load and the roof displacement were added to the corresponding previous total values to obtain the cumulative values of the base shear and the roof displacement. The above steps were repeated until the roof displacement reaches a certain level of deformation or the structure becomes unstable as the hinge capacity reaches its collapse state. The roof displacement was plotted with the base shear to get the global pushover curve of the structure.

4.2 Outcome of Pushover Analysis

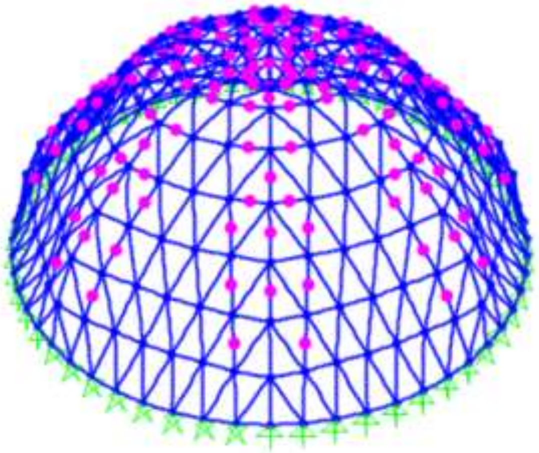
Typical hinge formation and displacement vs base reaction of pushover curve for reticulated dome structure shown in figure**.**



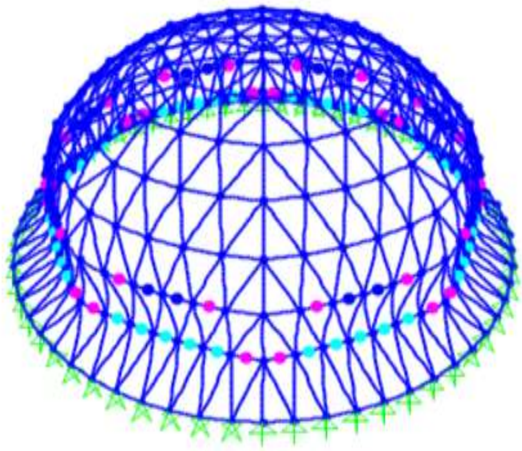
(a) D_S80_R0.20_K8



(b) D_S80_R0.25_K8

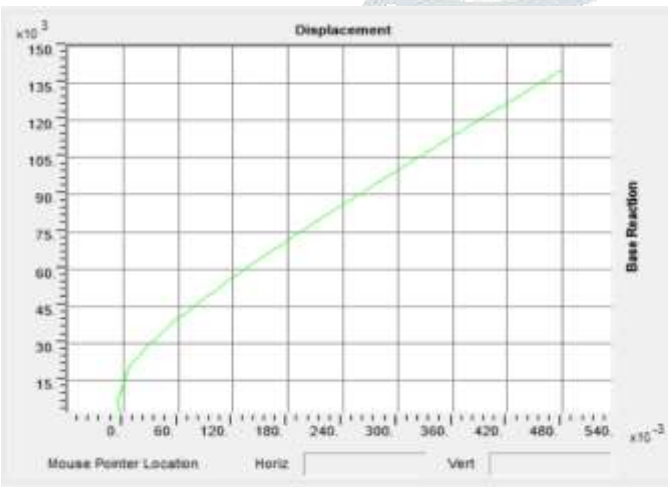


(c) D_S80_R0.30_K8

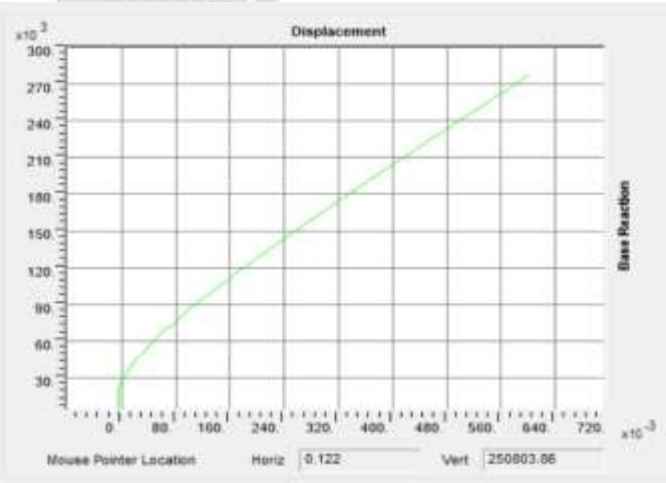


(d) D_S80_R0.40_K8

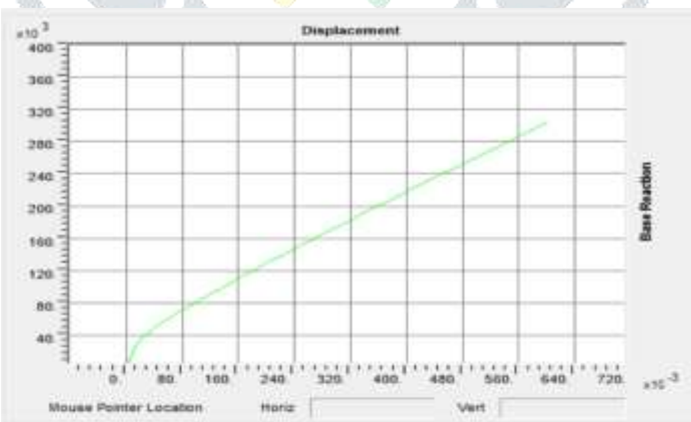
Figure 3: Typical hinge formation in reticulated dome structure.



(a) D_S80_R0.20_K6



(b) D_S80_R0.20_K8



(c) D_S80_R0.20_K10

Fig 4 : Pushover curve for reticulated dome structure

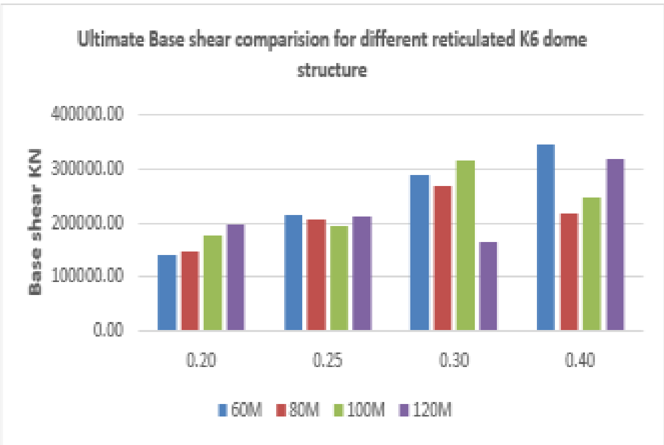
The lateral roof level displacement and base reaction values at ultimate point from pushover curves for different reticulated dome structure shown in Table .4

.

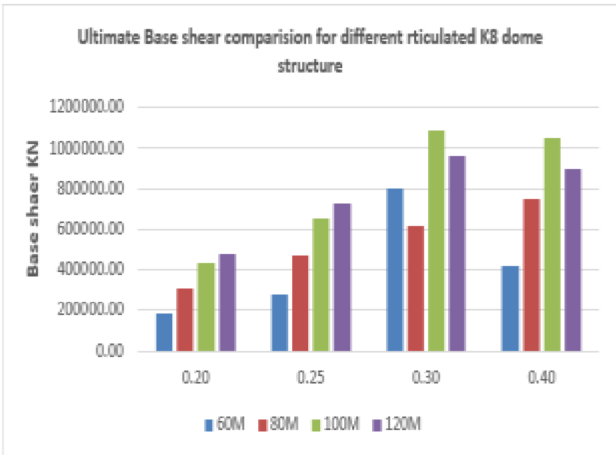
Table 4 – Displacement & Base shear at ultimate point

Displacement & Base shear at ultimate point			Displacement & Base shear at ultimate point		
Model name	Base share (KN)	Displacement(mm)	Model name	Base share (KN)	Displacement(mm)
D_S60_R0.20_K6	140342.18	478.69	D_S100_R0.20_K6	177340.93	227.965
D_S60_R0.25_K6	215205.26	543.199	D_S100_R0.25_K6	194191.11	269.855
D_S60_R0.30_K6	288102.82	719.599	D_S100_R0.30_K6	317312.67	350.532
D_S60_R0.40_K6	345330.85	844.269	D_S100_R0.40_K6	249313.06	278.706
D_S60_R0.20_K8	187093.2	470.021	D_S100_R0.20_K8	431416.91	801.753
D_S60_R0.25_K8	277137.1	599.812	D_S100_R0.25_K8	654616.67	1000.85
D_S60_R0.30_K8	798484.88	1290.82	D_S100_R0.30_K8	1085687.4	1559.2
D_S60_R0.40_K8	417163.08	854.403	D_S100_R0.40_K8	1051446.8	1468.86
D_S60_R0.20_K10	198093.7	480.011	D_S100_R0.20_K10	367355.78	799.649
D_S60_R0.25_K10	303621.09	599.747	D_S100_R0.25_K10	562837.68	999.363
D_S60_R0.30_K10	402548.62	719.656	D_S100_R0.30_K10	749594.11	1199.09
D_S60_R0.40_K10	542697.31	959.442	D_S100_R0.40_K10	1003298.5	1598.48
D_S80_R0.20_K6	146404.31	188.977	D_S120_R0.20_K6	197890.58	231.19
D_S80_R0.25_K6	207726.8	233.033	D_S120_R0.25_K6	210930.46	286.987
D_S80_R0.30_K6	267884.68	301.176	D_S120_R0.30_K6	165362.38	450.253
D_S80_R0.40_K6	217339.02	245.959	D_S120_R0.40_K6	318272.36	358.912
D_S80_R0.20_K8	307814.38	640.631	D_S120_R0.20_K8	481373.89	961.501
D_S80_R0.25_K8	468593.9	800.201	D_S120_R0.25_K8	731069.32	1200.62
D_S80_R0.30_K8	614060.92	959.889	D_S120_R0.30_K8	959272.68	1440.61
D_S80_R0.40_K8	753210.31	1189.15	D_S120_R0.40_K8	899505.19	1321.01
D_S80_R0.20_K10	320020.63	640.75	D_S120_R0.20_K10	466271.44	960.731
D_S80_R0.25_K10	486194.09	800.303	D_S120_R0.25_K10	710511.14	1199.98
D_S80_R0.30_K10	931119.32	1477.21	D_S120_R0.30_K10	933659.73	1439.4
D_S80_R0.40_K10	832958.81	1279.43	D_S120_R0.40_K10	883458.68	1326.96

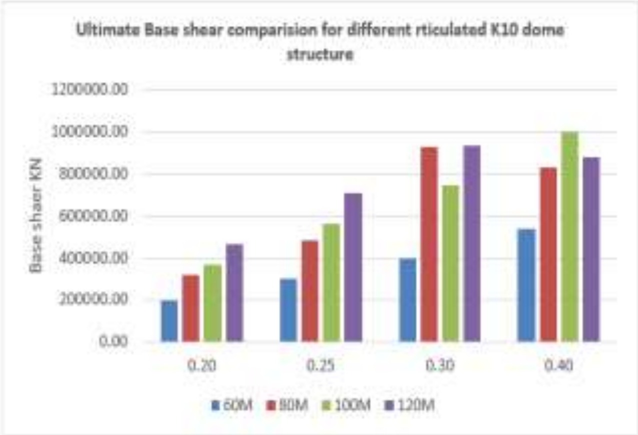
Comparison of lateral roof level displacement and base reaction values at ultimate point from pushover curves for different reticulated dome structure shown in figure 5.



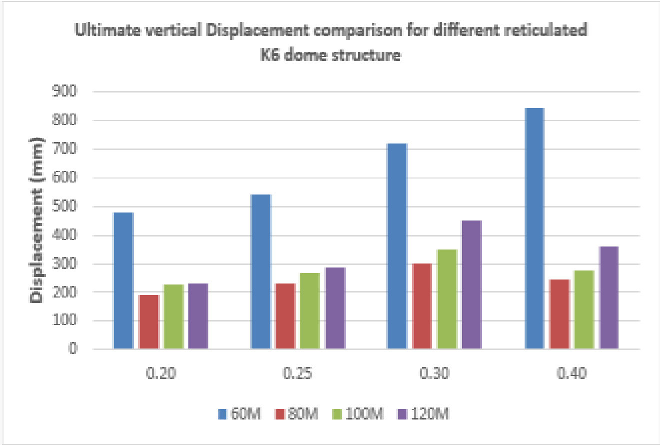
(a) reticulated K6 dome structure



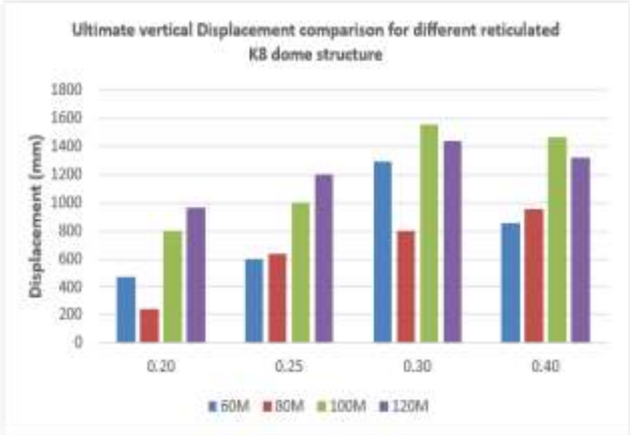
(b) reticulated K8 dome structure



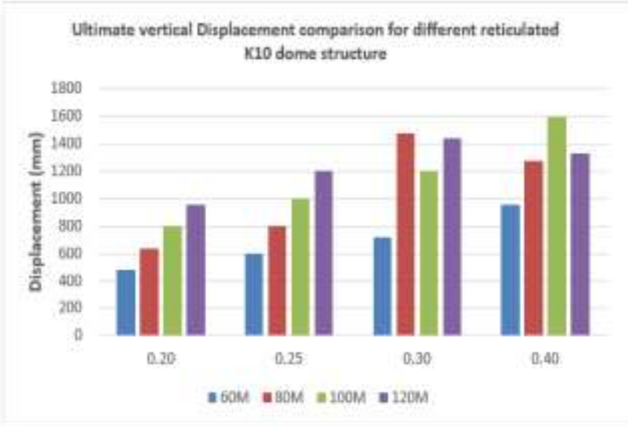
(c) reticulated K10 dome structure



(d) reticulated K6 dome structure



(e) reticulated K8 dome structure



(f) reticulated K10 dome structure

Figure 5: Ultimate base shear and ultimate displacement for different reticulated dome structure

V. COMPARISON OF DIFFERENT PATTERNS RETICULATED DOME STRUCTURE

For the reticulated dome modal 80M span consider for analysis. Three different models consider for analysis and with dome patterns K6, K8 and K10. Performed linear static and non-linear pushover analysis then result compared for different patterns. The plan and elevation are shown in figure. In all reticulated dome patterns model is kept uniform thought the height. Dead load, live load and earthquake load case are considered for analysis and design.

Table 5 – Reticulated dome model

Model name	Span	Rise to span ratio	Dome patterns
D_S80_R0.20_K6	80	0.20	K6
D_S80_R0.20_K8	80	0.20	K8
D_S80_R0.20_K10	80	0.20	K10

➢ Modal Analysis

For the seismic analysis of patterns of the reticulated dome structure first modal analysis is carried out in form of Fundamental Natural Time-Period. Here, time period comparison for first mode for a different pattern of the reticulated dome structure plotted in the graphical as shown in figure.

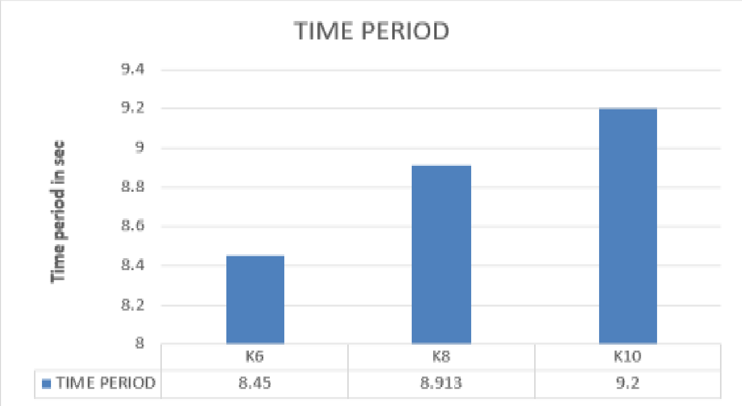


Figure 6 – Time period comparison for different pattern reticulated dome

- **NON-LINEAR PUSHOVER ANALYSIS OF RETICULATED DOME PATTERN STRUCTURE**

Pushover analysis was performed by assigning default-hinge properties of type PMM, P and M3 hinges to steel truss member in SAP2000 program based on the ASCE 41-17 guidelines. For truss elements the axial load effects were ignored and considering the rigid floor diaphragm effect. No shear hinge formation was considered in this analysis.

Table 6 – Displacement & Base shear at ultimate point

Displacement & Base shear at ultimate point		
Model name	**Base Shear (kN)**	**Displacement (mm)**
D_S80_R0.20_K6	146404.31	188.977
D_S80_R0.20_K8	307814.38	640.631
D_S80_R0.20_K10	320020.63	640.75

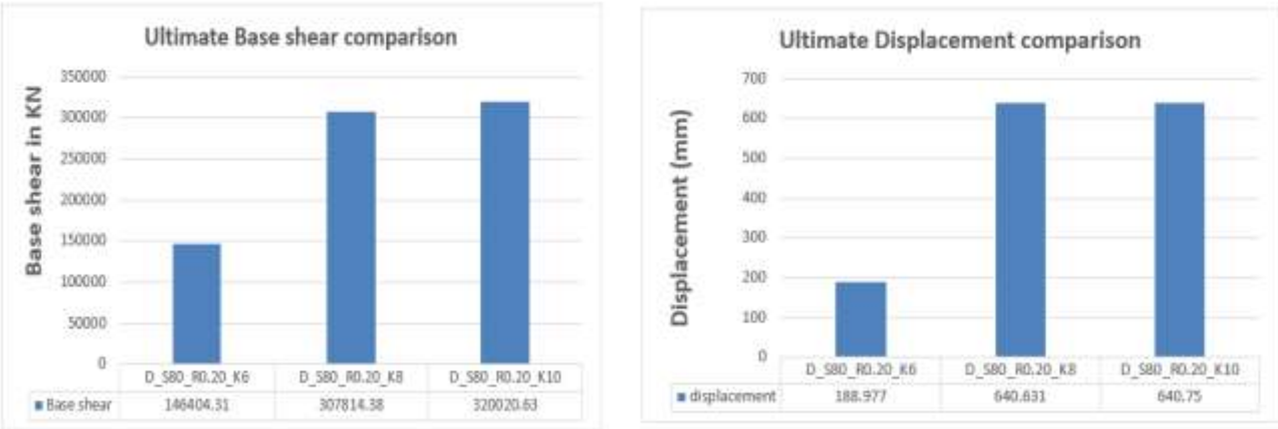


Figure 7 – Ultimate base shear and displacement of different pattern reticulated dome structure.

The D_S80_0.20_K6 dome modal of the ultimate base shear to compare the D_S80_0.20_K8 and D_S80_0.20_K10 respected to 52.43% and 54.23% the ultimate base shear the reticulated dome structure. The D_S80_0.20_K6 dome modal of the ultimate displacement to compare the D_S80_0.20_K8 and D_S80_0.20_K10 respected to 70.50% and 70.50% increase the ultimate displacement the reticulated dome structure.

VI. CONCLUSION

Behaviour of reticulated dome structure under gravity & lateral loading is presented & see the effect of various span and various rise to span ratio on the response of reticulated dome structure. For the analysis total 48 models were considered for 60m, 80m,100m, & 120m and 0.20, 0.25, 0.30, 0.40 rise to span ratio of reticulated dome. A first linear static analysis was carried out and designs the building element as per code IS 800:2007. Then nonlinear pushover analysis was performed vertical push for different reticulated dome structure and determine the base shear and displacement at ultimate point. Analysis result was compared in terms of Natural time period, displacement, distribution of EQ & gravity load, pushover curve and plastic hinge.

- The reticulated dome models show that amongst different geometrical particulars considered, only ‘rise-to-span-ratio’ and ‘relative stiffness of the supports’ strongly affect.
- The reticulated dome of the displacement of less than 1/400 of rise of the structure is safe (IS 1893 part 4).

- According to IS 1893 (part 4) for a large structure whose plan dimension is higher compared with height, it should be designed for vertical displacement of 1/400 of height. Compared with this research, different patterns of reticulated dome modal for a rise to span ratio 0.25 and 0.30 are only being satisfied required codal criteria.
- The D_S60_0.20_K6 dome modal to ultimate base shear to compare the D_S80_0.20_K6, D_S100_0.20_K6 and D_S120_0.20_K6 respected to 34.78%, 51.28% and 59.26% increase the ultimate base shear of the reticulated K6 dome structure.
- The D_S60_0.25_K8 dome modal the ultimate displacement to compare the D_S80_0.25_K8, D_S100_0.25_K8 and D_S120_0.25_K8 respected to 6.36%, 40% and 50% increase the ultimate displacement the reticulated K8 dome structure.
- The D_S80_0.20 dome modal the deformation of plastic hinge member to compare the D_S80_0.25, D_S80_0.30 and D_S80_0.40 respected to 19.04%, 30.76% and 70.58% decrease the deformation of the plastic hinge member the reticulated K8 dome structure.
- The reticulated dome structure various rise increases the dome stiffness is increase.
- The reticulated dome structure rise to span ratio is increased the time period and displacement increase.
- Reticulated dome structure is affected to the response modification factor and ductility factor.

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