Analytical study on the Collapse Mechanisms of Single Layered Cylindrical Shell with the effect of Curvature

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Abstract*- With the rapid development of the large-span space structure, shell structures have been widely used in the public buildings such as gymnasiums, exhibition hall, airplane terminal, etc. recently. The essential geometrical property of all the shell structures that distinguishes one from other structural forms is the possession of both "surface" and "curvature" providing strength and stiffness. Therefore, many shell structures have been constructed with the purpose of providing roofing for temples, cathedrals, monuments or other buildings. Shell structures are very attractive light weight structures which are especially suited to building as well as industrial applications. The seismic performance of the single layered cylindrical shell is evaluated and the collapse modes are obtained. A detailed parametric study is conducted to find out the most prominent parameter affecting the performance of the single layered cylindrical shell and the parameters are ranked based on their influence on shell behavior. The parameters used in the analysis are rise to span ratio, roof weight, cross sectional size and earthquake records. The shape of a shell structure is important so that it performs optimally under gravity loads, carrying the loads to the foundations mainly through membrane action over the shell surface. Finally, the effect of curvature on the collapse of shell is examined by comparing singly curved shell and doubly curved shell.

***Keywords*- Single layered cylindrical shell, Collapse modes, Curvature.**

I. INTRODUCTION

Roof shells seem to be increasingly used to span large spaces. Shell structures are very attractive light weight structures which are especially suited to building as well as industrial applications. The curved form may lead to different failure modes and often unexpected behavior occurs. The analytical formulas are very complex and complicated in comparison with all the other structural forms. The spatial shell structure, which has been developed rapidly over the past three decades, is one of the main forms of large span space structure, and it has been widely used in large-scale public buildings such as gymnasiums, exhibition hall, airplane terminal, etc.

The shape of the shell is of great importance as the load-bearing efficiency derives from it. If the shape deviates from its stable geometry the structural advantages can be challenged. Deformation due to actions on the structure can in worst-case lead to collapse of the building. The aim thus becomes to pursue a design robust enough to withstand all plausible load combinations. The shape of the shell requires careful consideration and the design should be continuously modified until the solution is satisfactory. Parametric modelling provides this type of flexible workflow and is hence an efficient method to adopt for the design of shell structures.

II. OBJECTIVES

- To obtain the collapse mechanisms of single layered cylindrical shell by conducting analytical study.
- To find the effect of curvature on the collapse of shells by comparing singly curved shell and doubly curved shell through parametric study.

III. METHODOLOGY

- Literature review.
- Validation of single layered cylindrical shell using ANSYS workbench software.
- Obtaining the collapse mechanisms of single layered cylindrical shell based on the modal analysis in ANSYS.
- Modelling of the singly curved shell and doubly curved shell by varying different parameters. The parameters used in the study are rise to span ratio, roof weight and cross-sectional size of elements.
- Finding the effect of curvature on the collapse of shells by comparing singly curved shell, doubly curved shell and cylindrical shell.

IV LITERATURE REVIEW

Gui-bo Nie, Chen-xiao Zhang et al (2019) conducted the study on the seismic behavior and collapse mechanism of the single layered cylinder shell. The displacement responses, dynamic strain responses and acceleration responses are measured under two sets of seismic motions with different input principal directions, and the dynamic characteristics are obtained. And then, the effect of the input principal direction on the dynamic characteristics of the model will be investigated.

F. Cedron, A.Y. Elghazouli (2019) conducted a study to find the key parameters that define the geometry of the shells which are the span, B, the rise, H, and the length, L. The rise and the span define three points that form a circular arc on which the nodes of the edge arches are located at equal distances. two important ratios derived from these key parameters are the rise-to-span ratio, H/B, and the length-to-span ratio, L/B. The longitudinal edges of the cylindrical shell are pinned, with all translational movements restrained, but free to rotate in any direction. The edge arches are unrestrained, free to move and rotate.

Jun Xu, Rui Sun (2020) conducted a study on the seismic stability of single-layer dome structures which is closely related to both the external seismic ground motions and structural properties. Parametric analyses are implemented to investigate the impacts of different structural parameters on seismic stability and characteristic responses of single-layer dome structures.

Matteo Guidi, Annalisa Fregolent et al (2017) conducted a study on the curvature and dynamical properties of shells which depends on the ratio c/R, and their linear dynamics is investigated by standard modal analysis, adopting a commercial code, and accounting for curvature. Natural frequencies for a given mode are linear with c/R, decrease for membrane modes, and increase for transverse modes. Thus, membrane and transverse modes may shift as curvature grows; graphical and numerical results are reported.

Ashild Huseby, Marie Eliassen (2018) conducted a study to illustrate how the shape is crucial for the efficiency and structural behavior of the shell, and how double curvature gives a more robust structure which is less prone to deflect. Initially the shape showed substantially larger displacements for the Drifted (asymmetric) snow load case from Eurocode compared to the Undrifted (symmetric) case, and the optimized shape displayed an increase in the initial double curvature. The optimization approach led to an improved structural performance and a smaller gap between the structural response for the Undrifted and Drifted load cases.

Shadi Ostovari Dailamani (2010) conducted a study of the numbers of modes required for accurate prediction of displacement, acceleration, and stress response for a specific geometry of shell showed that unlike ordinary buildings, in roof shells there is a need to include substantial number of modes for a converged result. comparing the frequencies and linear responses of a doubly curved shell with a cylindrical shell, the results showed that the frequencies of a doubly curved shell are higher than a cylindrical shell. The increase in the natural frequencies resulted in much lower displacements and stress resultant responses in the doubly curved shell.

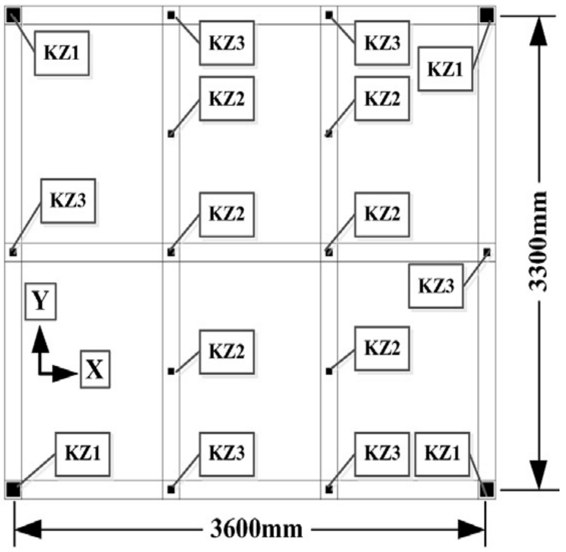
Tim Michiels, Sigrid Adriaenssens (2017) conducted a study for shallow shells and observed that the vertical components of the earthquake vibrations, can induce larger stresses in the shell than the horizontal components. It is further demonstrated that by increasing the rise and curvature of larger shells, their fundamental frequencies are increased and the damaging effect of the vertical earthquake vibration components mitigated.

V SINGLE LAYERED CYLINDRICAL SHELL

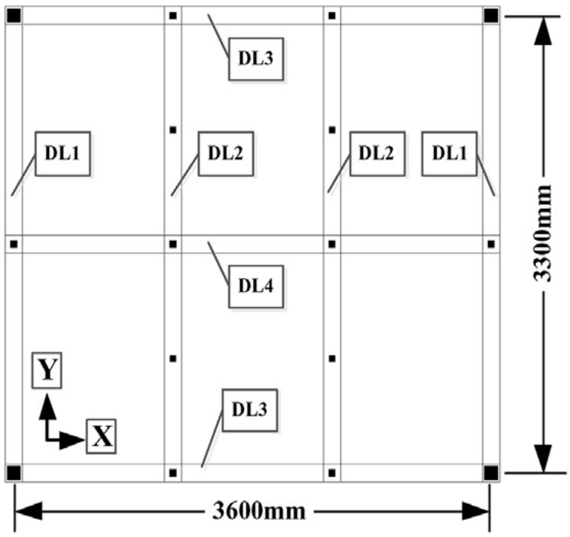
The vibration characteristics of a single layered cylindrical shell is determined through a modal analysis of the model created as shown in fig 1. And thereby, the validation of the model is performed.[3] ANSYS Workbench 2020 R2 is used to model the single layered cylindrical shell. It is the basis for delivering a comprehensive and integrated simulation. The entire simulation process is tied together by a project schematic, from which you can interact with applications that are native to ANSYS Workbench or launch applications that are data-integrated with ANSYS Workbench. It includes CAD connectivity, automated meshing, a project-level update mechanism, and optimization tools.

A Modelling of shell

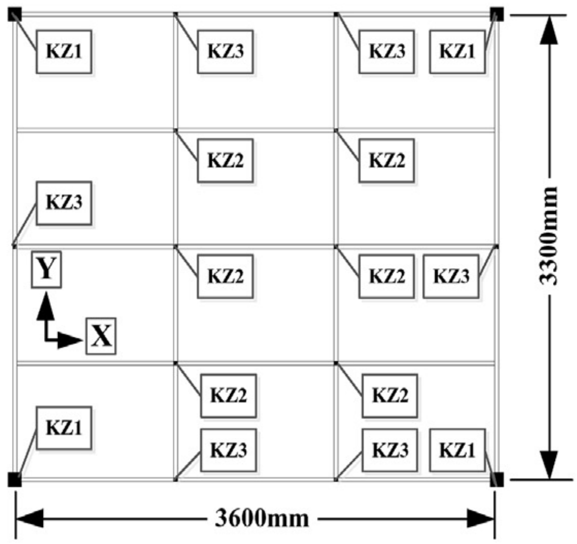
There are two stories with the total height of 3600 mm. The storey height of the first floor is 600 mm. The storey height of the second floor is 750 mm, and the single layered cylinder shell, which has the depth-span ratio of 1/3, height of 1100 mm is designed as the ceiling. It is 3600 mm with 3 spans in X-direction and 3300 mm with 2 spans in Y-direction to get more utilizable space, and the plan layouts are shown in Fig. 1 and the detailed information of all the members is listed in Table 1.



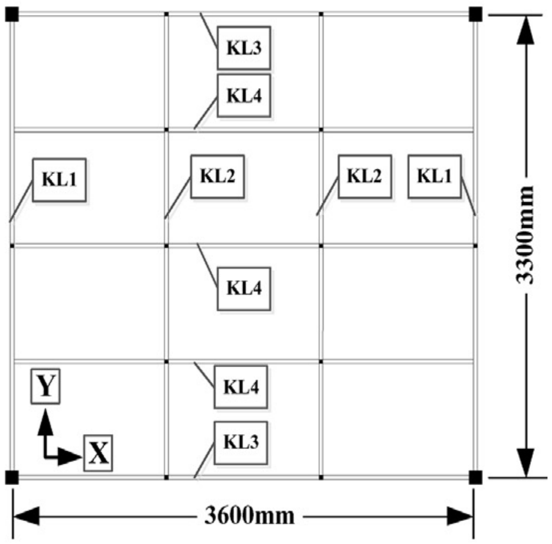
(1a) Column layout plan for the first floor of the model



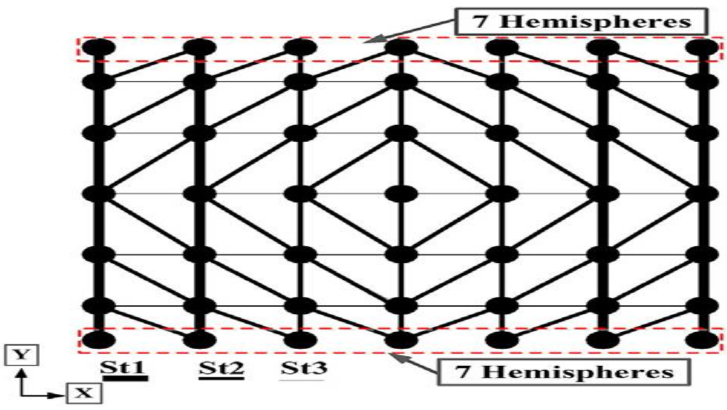
(1b) Beam layout plan for the first floor of the model



(1c) Column layout plan for the second floor of the model



(1d) Beam layout plan for the second floor of the model



(1e) Configuration of top chords
Fig 1. Details of model

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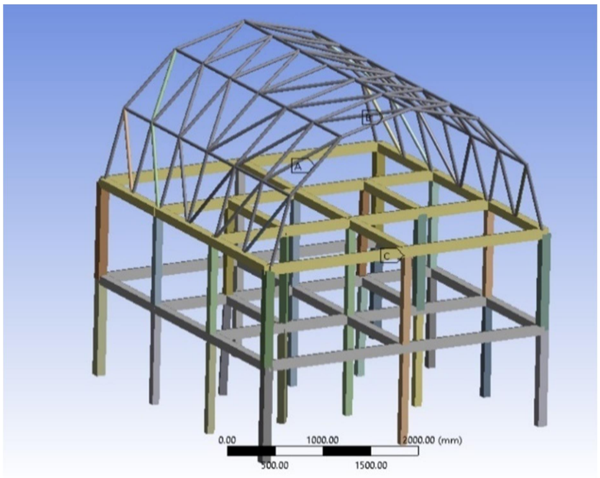
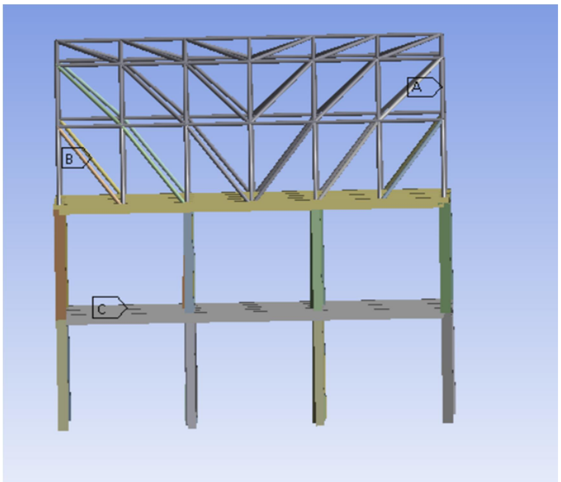
Table I. Section properties

No	Section type	Section size(mm)
KZ1	Square	100x100x5
KZ2	Square	30x30x2.5
KZ3	Square	30x30x2.5
KL1	Rectangular	50x30x2.5
KL2	Rectangular	50x50x3
KL3	Rectangular	50x50x2.5
KL4	Rectangular	50x30x2.5
DL1	Square	140x140x6
DL2	Square	140x140x6
DL3	Square	140x140x6
DL4	Square	140x140x6
St1	Circular	20x1.5
St2	Circular	16x1
St3	Circular	15x1

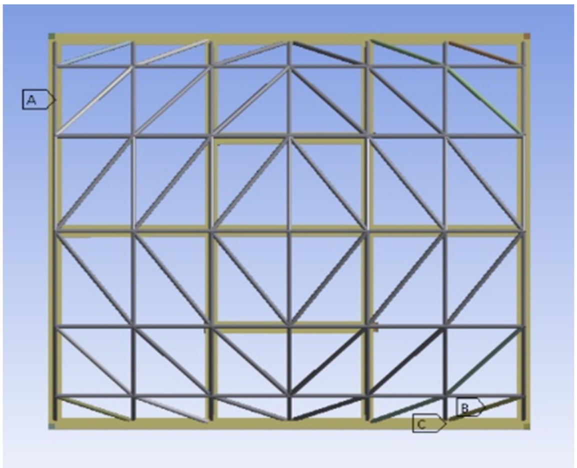
Beam 188 element is used to model the single layered cylindrical shell in FEA package ANSYS Workbench 2020 R2 as shown in fig 2. Structural steel with Youngs modulus 206 GPa and tensile yield strength of 254 MPa was adopted to model the figure 2 shown below.



(2a) Lateral layout of the model



(2b) side elevation of the model



(2c) Plan of top chords
Fig 2. FEA model

B Mode shapes

A mesh size of 50mm was adopted to get the convergent results. A modal analysis is done in ANSYS Workbench 2020 R2 to obtain the first 6 natural frequencies of the model created and the mode shapes obtained were evaluated to study the failure modes of model created. The natural frequencies obtained is given in table 2. The deformed shape obtained after modal analysis is shown in fig 3.

Table II. Natural frequencies obtained after modal analysis

Order	Natural Frequency (Hz)
1st	4.7845
2nd	7.361
3rd	11.228
4th	15.336
5th	16.334
6th	20.712

Modal analysis was performed to obtain the vibration characteristics of the structure under consideration. From fig 3, maximum value of deformation occurs along the linear chord and its adjoining diagonal chords.

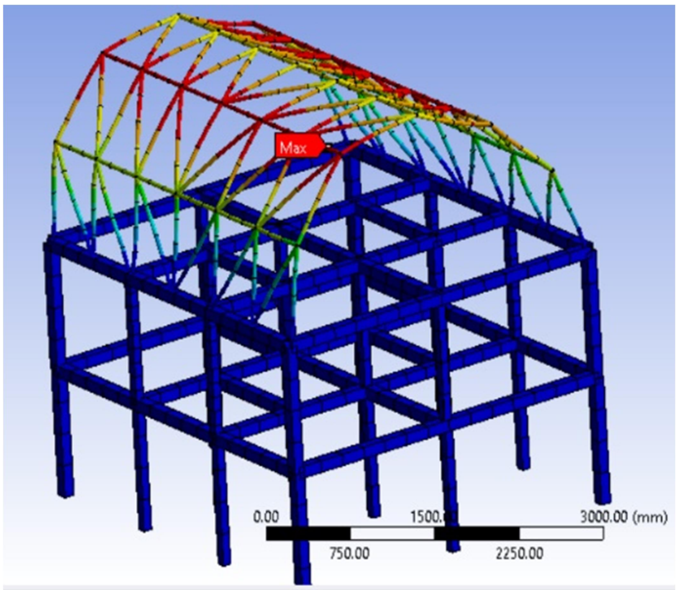
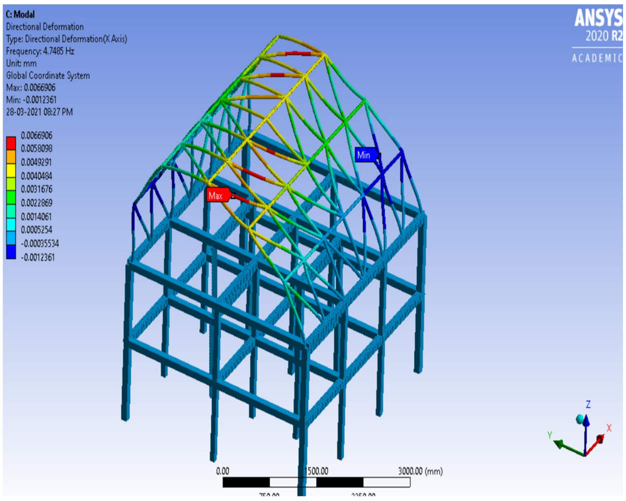
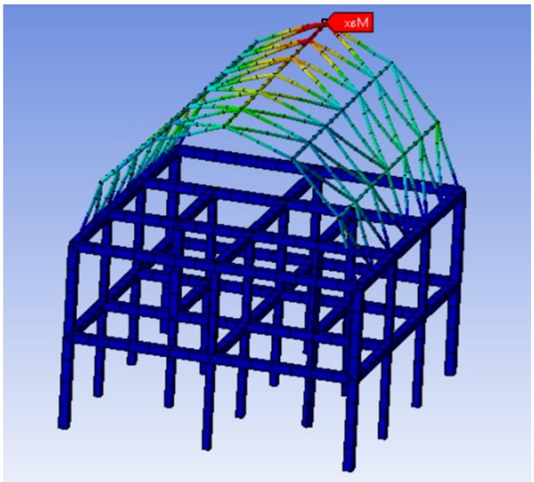


Fig 3. Deformed shape of the model

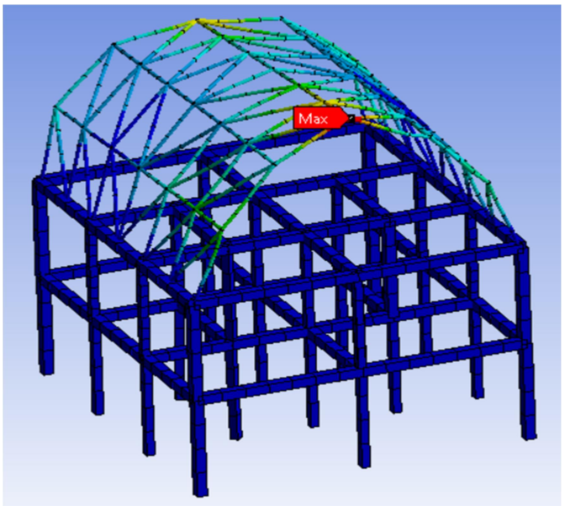
The shape taken by the structure during vibration is the mode shape of structure. By analyzing the mode shape, it is easier to know the failure modes of the structure under consideration. The mode shape curvature is used for the localization of damage of the structure and hence the damage identification. The mode shapes of the model created are shown in Fig 4.



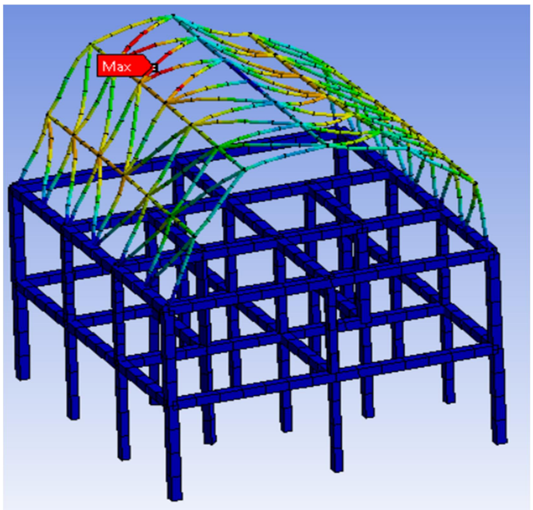
Mode shape 1



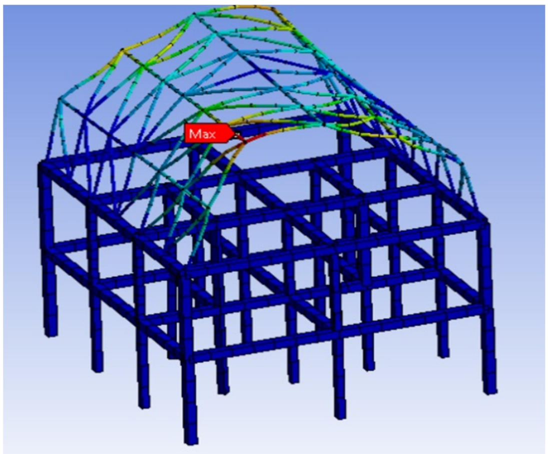
Mode shape 2



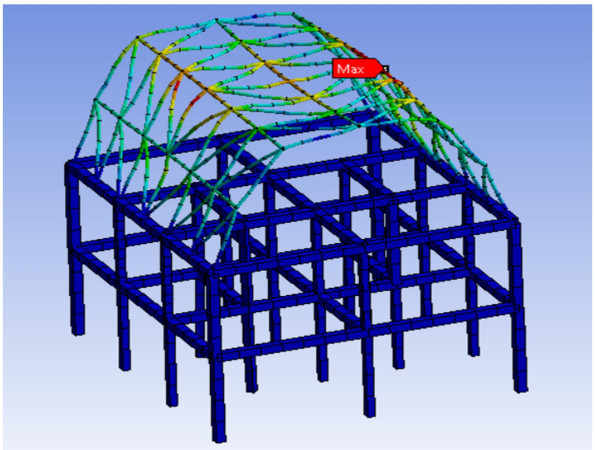
Mode shape 4



Mode shape 5



Mode shape 5



Mode shape 6

Fig 4. First 6 mode shapes of the model

It can be observed from the mode shapes that there are obvious damages including bending of chord members and displacement of nodes. By analyzing the failure modes, suitable measures can be adopted to arrest the energy transferred during collapse.

VI CURVATURE

It is possible to find the effect of curvature on the collapse of shells by comparing a singly curved and doubly curved shell. For this comparison, a single layered cylindrical shell and a single layered reticulated dome is adopted. A cylindrical shell is a singly curved shell which is curved along one linear axis and a dome is a doubly curved shell which is curved along two linear axes. A K8 dome is adopted to study the doubly curved shell.

A Parametric study

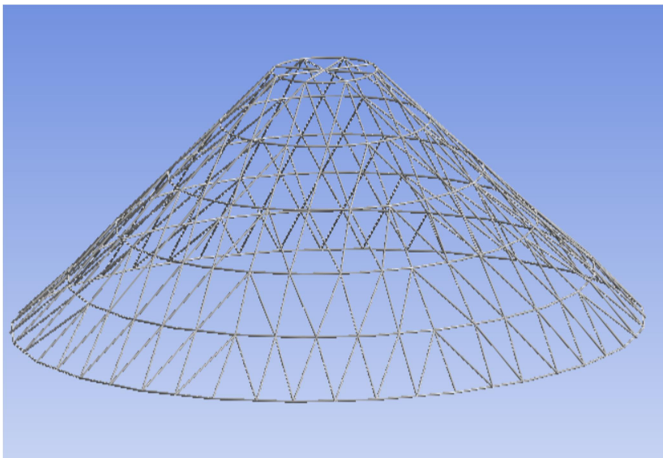
In order to comprehensively investigate the influences of different parameters on the seismic performance of cylinder and dome structures, a series of dynamic time-history response analyses are carried out with different parametric settings accounted, such as the rise-span ratio, roof weight, earthquake record and member cross-section size. The key factors affecting seismic stability of single-layer dome and cylinder structures are discussed. In this paper, the scheme of parametric analysis is shown in Table 3.

Table III. Parametric analysis scheme

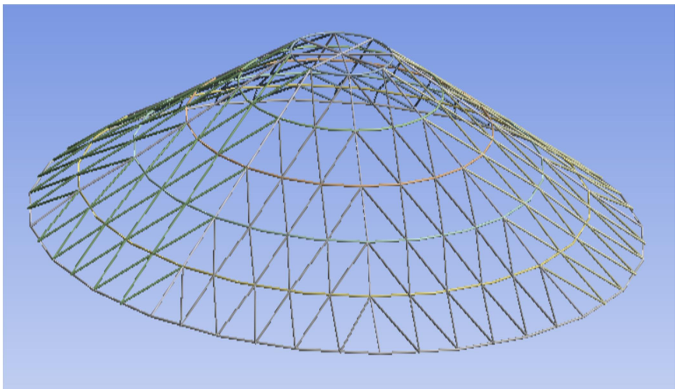
Structural Parameter	**Values**		
Span L	40m		
Earthquake record	EL Centro		
Rise to span ratio	1/3	1/5	1/7
Roof weight in N/m^2	1600	1800	2000
Cross sectional dimension in mm	$\emptyset 114x3$	$\emptyset 133x4$	$\emptyset 140x4$

A1 Effect of different rise to span ratios:

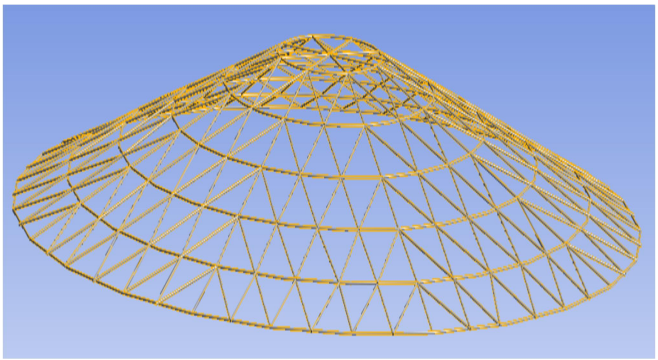
The rise-span ratio is an important parameter that affects the seismic performance of both single layered cylindrical shell and single layered reticulated dome. Fig 5 and 6 shows the dome and cylinder model created in ANSYS Workbench with different rise to span ratios.



(5a) Rise to span ratio:1/3

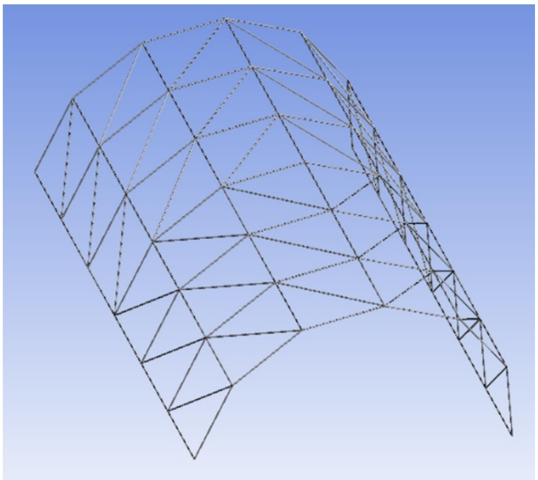


(5b) Rise to span ratio: 1/5

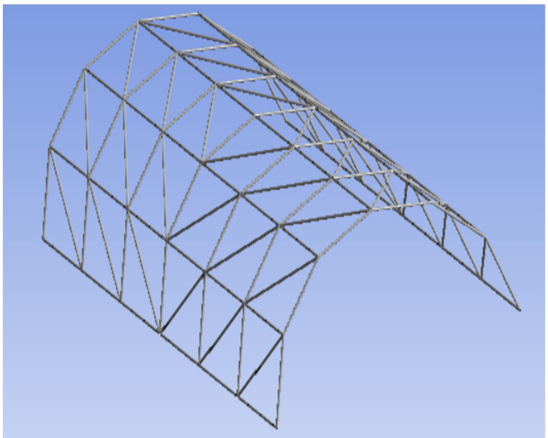


(5c) Rise to span ratio 1/7

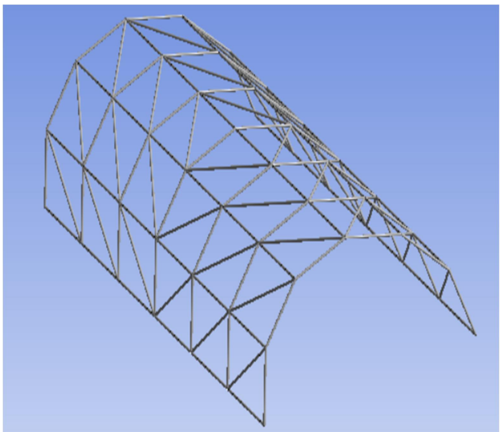
Fig 5: Dome model with different rise to span ratios



(6a) Rise to span ratio:1/3



(6b) Rise to span ratio:1/5

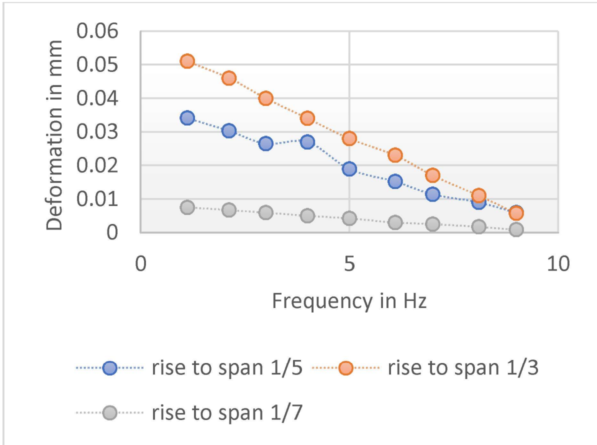


(6c) Rise to span ratio:1/7

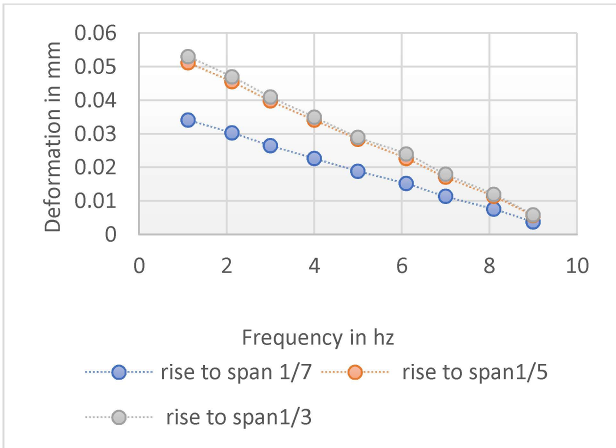
Fig 6. Cylindrical shell model with different rise to span ratios

BEAM188 element is used to model the cylindrical and dome structure. Seismic analysis in ANSYS workbench is done on 3 stages. Initially, static structural analysis was done with support conditions fixed and load of 1600N/m^2 which was applied as nodal loads. In the second stage, a modal analysis was performed to obtain the first 6 natural frequencies to know about the vibration characteristics of the model. Finally, a response spectrum analysis was done with the RS acceleration data of EL Centro earthquake to get the deformation of the model with the respective rise to span ratios. Fig 7 shows the deformation vs frequency for varying rise to span ratios.

It can be inferred from the graph that with the increase in rise to span ratio, the deformation of the structure increases. Consequently, the seismic performance of structures with low rise-span ratio could be much more superior. It could be concluded that it is more advantageous to utilize the curved structure with lower rise-span ratio for the better seismic performance [4]. For the same rise to span ratios, deformation is large for single reticulated dome structures. Hence, a singly curved shell like cylindrical shell can resist collapse due to seismic force with low rise to span ratios.



(7a) Cylindrical shell

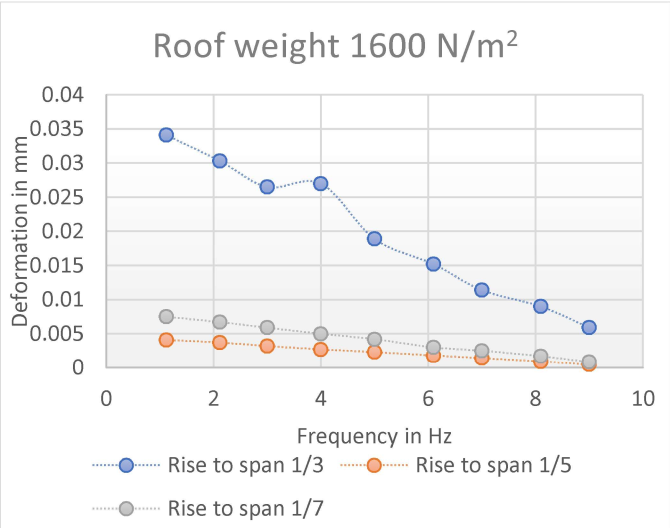


(7b) Dome

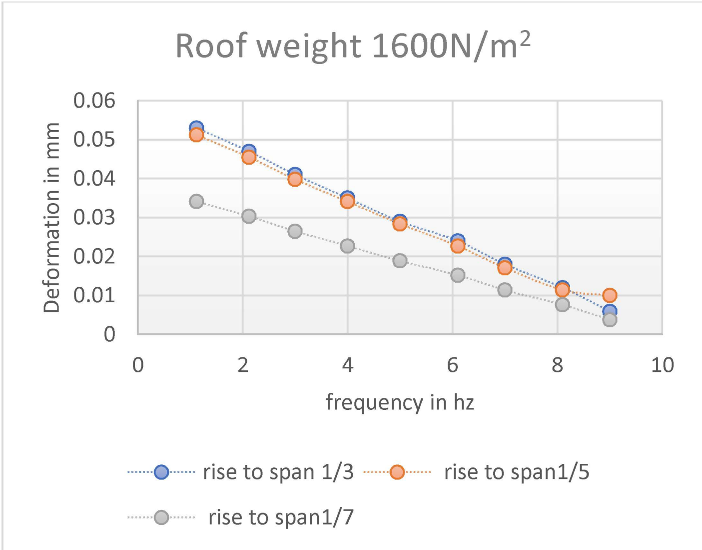
Fig 7. Deformation vs frequency graph for varying rise to span ratios

A2 Effect of different roof weights

The roof weight is an important factor in seismic response analysis of the single-layer reticulated dome structure although it does not change the geometry of the dome structure [4], which may still have a great influence on the dynamic response. It can be seen from the fig 8 that there is an increase in deformation of the structure when rise to span ratio is 1/3 when compared to the other two. For the rise to span ratios 1/5 and 1/7, moreover a similar behavior is observed with smaller deformations. This is because, the variation of roof weight does not change the geometry of the structure. The dynamic responses of structures under seismic ground motions do not greatly vary due to the change of roof weight [4]. Here also, a similar trend observed as seen in varied rise to span ratios. When comparing both cylindrical shell and dome, the cylindrical shell behaves with less deformation towards collapse state.

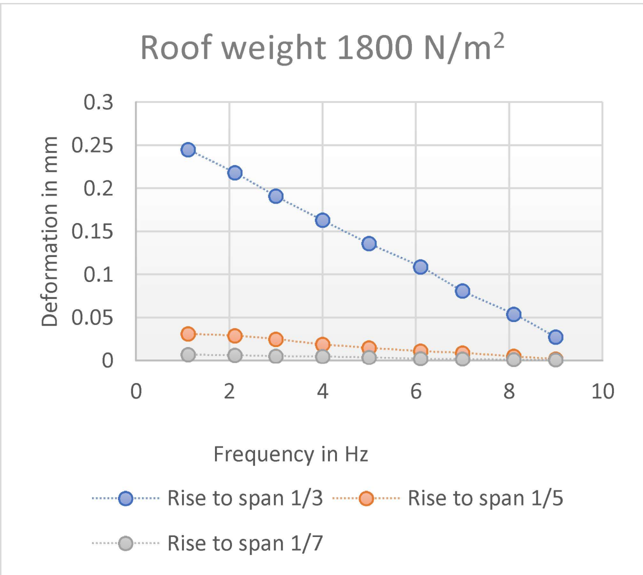


Cylindrical shell

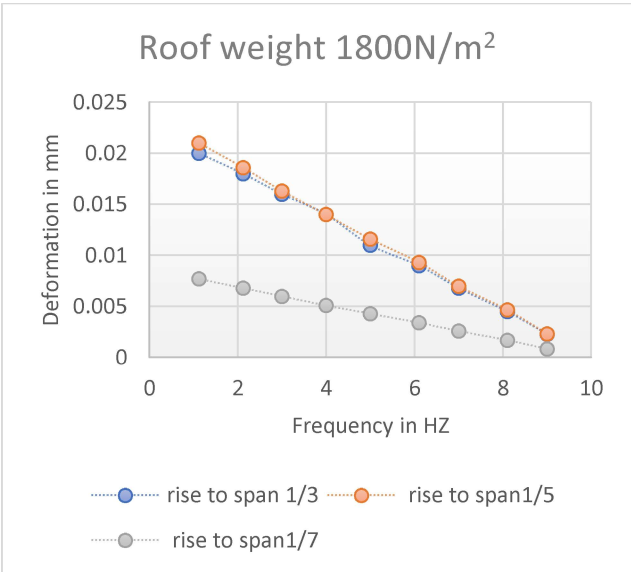


dome

(8a) Deformation vs frequency with roof weight 1600N/m^2

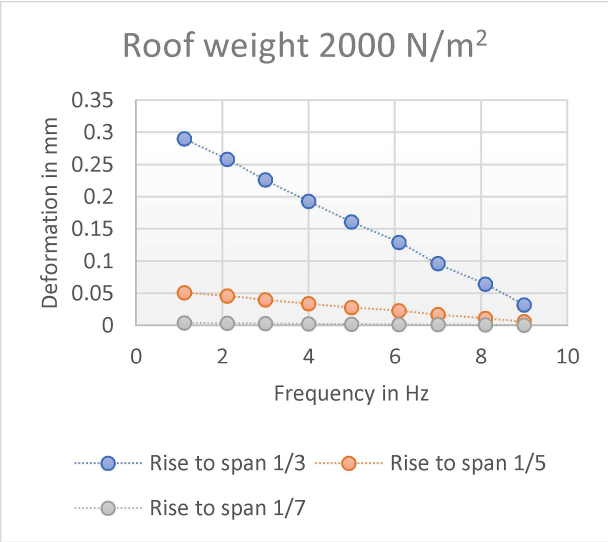


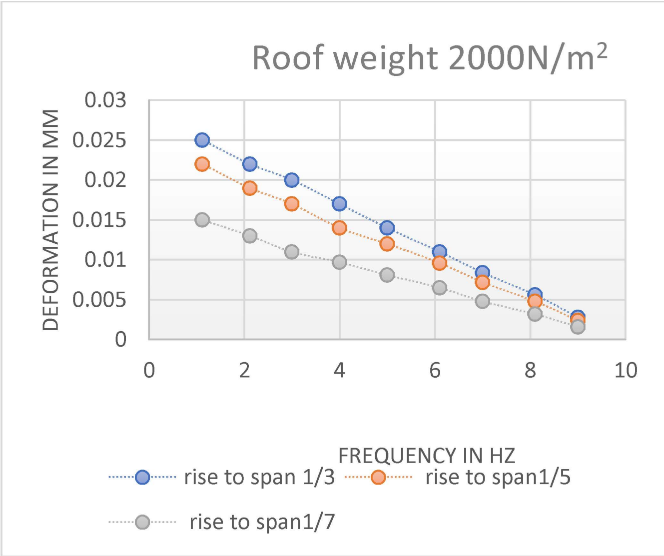
Cylindrical shell



dome

(8b) Deformation vs frequency with roof weight 1800N/m^2





Cylindrical shell

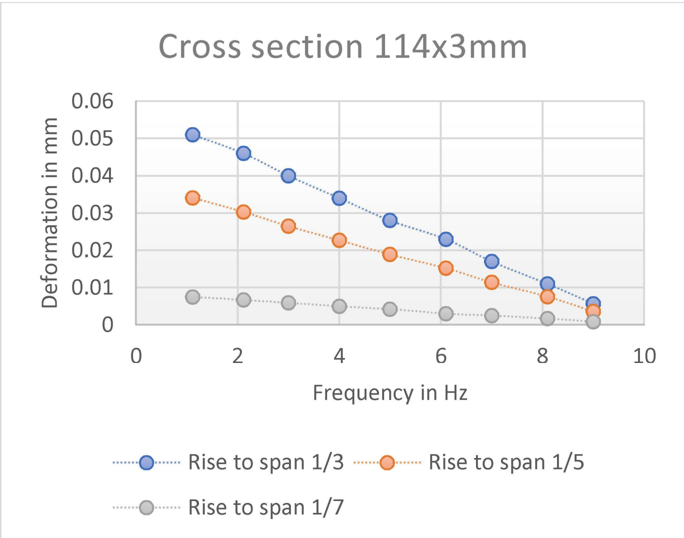
Dome

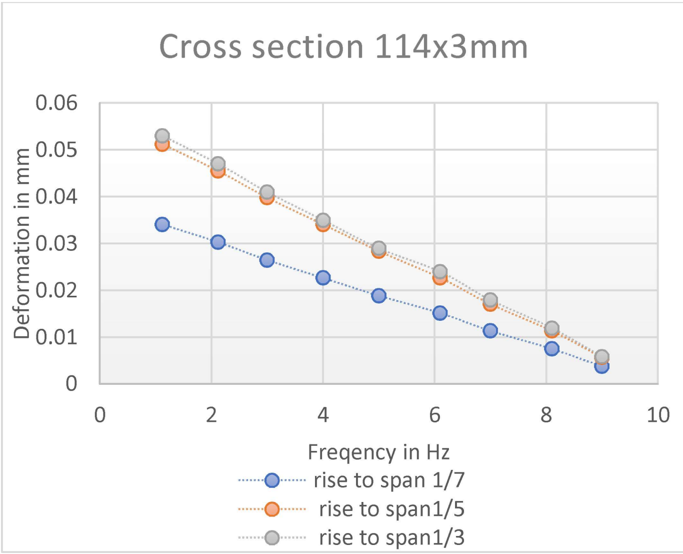
(8c) Deformation vs frequency with roof weight 2000N/m^2

Fig 8. Cylindrical shell with varying roof weights

A3 Effect of different cross-sectional size:

It could be anticipated that different member cross-sections have a very prominent impact on the seismic performance of single-layer dome and cylindrical structures, especially when the structure enters into the elasto-plastic working stage.[4] When the rise to span ratio increases, deformation also increases with respect to the cross-sectional dimension as shown in fig 9. For the same cross section, deformation varies largely between the rise to span ratios 1/3 and 1/7. But, between the ratios 1/5 and 1/7, this effect is relatively small. When the member size increases from 114mm to 140mm, a large difference in deformation is observed but between 133mm and 144mm dimensions, relatively small amount of deformation is seen. And also, if the member cross sections are reduced, the seismic performance of the cylindrical and dome structures are increased. A similar trend as seen in other parameters can be observed in this parameter. That is, A cylindrical shell with low rise to span ratio with reduced dimensions of members can resist collapse due to earthquake when compared to dome structures.

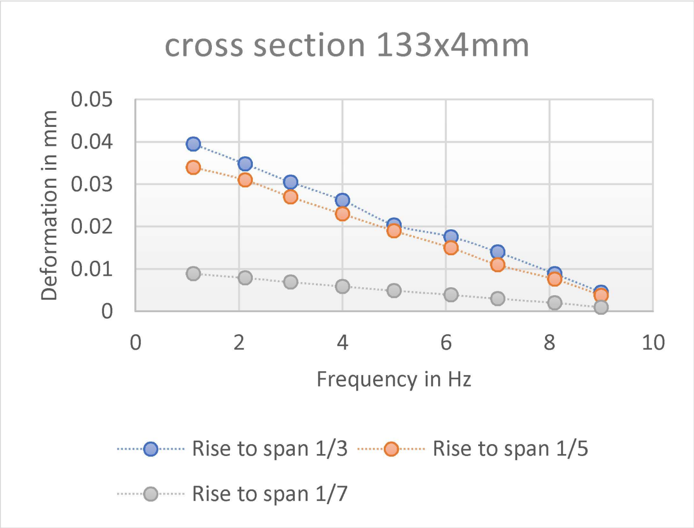


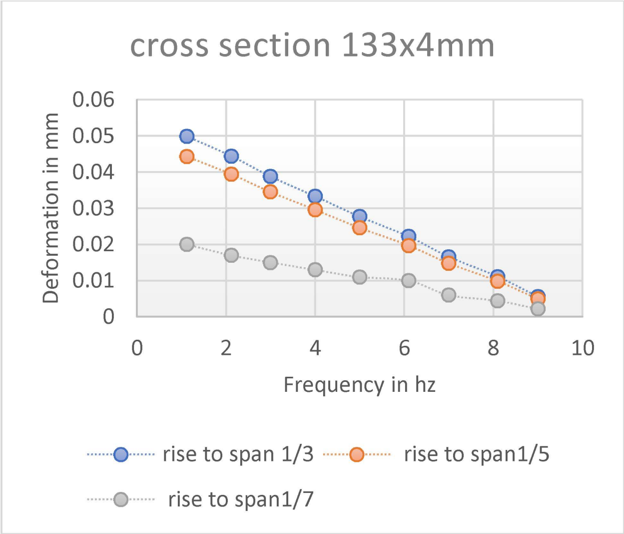


Cylindrical shell

dome

(9a) Deformation vs frequency with size 114x3mm

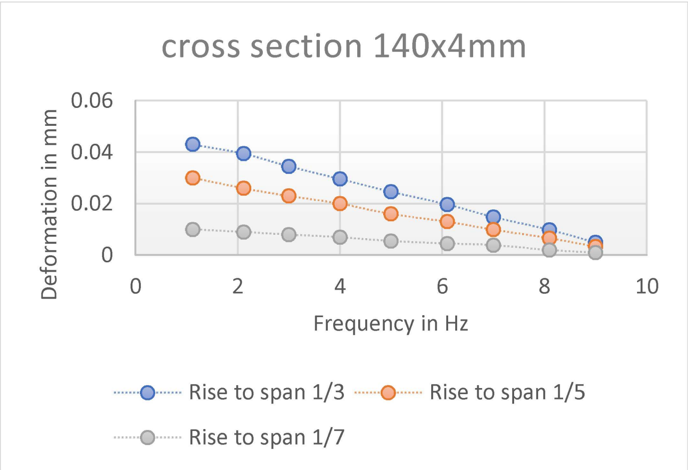


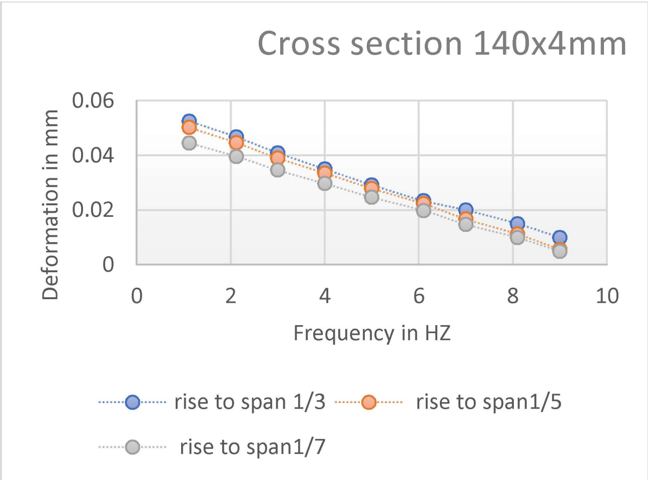


Cylindrical shell

dome

(9b) Deformation vs frequency with size 133x4mm





Cylindrical shell

dome

(9c) Deformation vs frequency with size 140x4mm

Fig 9. Cylindrical shell with varying cross-sectional dimensions

VII CONCLUSIONS

- The collapse modes of a single layered cylindrical shell are obtained. These mode shapes are useful to know the vibration characteristics which is utilized in damage identification.
- The parametric study conducted is helpful in determining the important factors affecting the collapse of shells.
- Rise to span ratio is an important parameter which significantly influences the seismic performance of shell structures. A rise to span ratio between 0.14 and 2 is optimum for shells to have good seismic performance.
- Secondly, cross sectional size of members selected plays another great role in determining the seismic performance of shell structures.
- Finally, the roof weight is an important factor in seismic response analysis but its affect is relatively small on collapse of shell structures when compared to rise to span ratio and cross-sectional dimension of the members.
- The ultimate motive was to find the effect of curvature on the collapse of shell structures. Two shell models were compared to find its curvature effect. A singly curved shell like single layered cylindrical shell and a doubly curved shell like

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single layered reticulated dome was compared by a parametric study.

- On comparison, a singly curved shell like cylindrical shell can be more resistant to collapse against seismic excitation due to comparatively less deformation values compared to doubly curved shell.

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