

DYNAMIC CHARACTERISTICS OF LARGE REINFORCED CONCRETE ELLIPSOIDAL DOMES

Tijo K Robinson¹, A.S. Nisha²

Abstract— According to the Indian seismic zone map, 59% of the Indian land area is under earthquake threat. Especially the North Eastern part adjoining the Himalayan belt. Over the last 15 years, 10 major earthquakes occurred in these regions, resulting in over 20 000 deaths. Several scientific publications warns the likeliness of the occurrence of severe earthquakes in these regions. Large span reinforced concrete domes with different shapes (spherical, ellipsoidal and paraboloidal) are commonly used as roof structures, especially in public buildings and places of worship. Behavior of reinforced concrete domes of large span under earthquake loads and the interaction between these domes and the adjoining structure is not well studied. This issue never received much attention by the research community due to the scarcity of such structures worldwide. To assess the seismic vulnerability of buildings with large domes, the dynamic characteristics and behavior of large reinforced concrete domes need to be studied and their susceptibility to damage need to be evaluated. This paper, specifically presents a study of reinforced concrete ellipsoidal domes and the effect of the variation of their thickness and height on their dynamic characteristics such as frequencies of vibration. The results obtained for ellipsoidal domes are compared with that available for spherical and paraboloidal domes from previous study.

Index Terms— *Dynamic Characteristics of Reinforced Concrete Domes Spherical domes, Paraboloidal domes, Ellipsoidal domes.*

1 Introduction

• Domes are superior to other structures in terms of strength to weight ratio and are provided when large uninterrupted space is the requirement. Domes are very strong and durable and in a realistic situation would probably still be standing when all conventional structures had failed (www.monolithic.com). Domes are among the most efficient structures available, especially as roof structures. However the complexity of their analysis, design, fabrication and some other reasons such as air-conditioning limit their use. The coupling among the bending and the axial behaviors of domes make them difficult to analyze (Leissa 1993). As a roof structure, the main force that a dome bears is its own weight. Thus its function is largely affected by its shape and geometry. Reinforced concrete shell structures (domes) undergo different load combinations with three-dimensional geometrical complexity, as well as three dimensional nonlinear behaviors of its material. These complex conditions make analyzing the structural behavior for predicting its response imprecise (Liessa 1980, Hejazi 2003). For investigating the dynamic response of domes to applied loads, the variables that affect their behavior are cut down to a limited number and are mainly dome shape, thickness, span length, and height. Domes may be located in seismic zones and therefore they will be subjected to dynamic loads. Although the dynamic forces on a concrete dome generally do not control the design, however, in earthquake prone areas the most disastrous force that can be applied on a dome is earthquake load. Several researchers have studied the free vibration characteristics of shells in general and formulated three dimensional analytical solutions (Leissa 1993, Tan 1998).

• **Fig. 1: Pantheon, Rome**

- Tijo K Robinson is currently pursuing masters degree program in structural engineering in University of Calicut, India, PH-8547363868. E-mail: tjokrobinson@gmail.com
- A.S. Nisha is currently working as Assistant Professor in N S S College of Engineering under Calicut University, India, PH-8943489501 E-mail: getmenisha@gmail.com

This paper presents a study of dynamic behavior of reinforced concrete Ellipsoidal domes and the effect of the variation of their thickness and height on their frequencies of vibration. The rationale for conducting this research and the reasons are that: (1) North Eastern part of India adjoining the Himalayan belt is under severe earthquake threat due to increase in population and unscientific construction of multistoried apartments and factory buildings. (2) All efficient structures, when fails, undergo a catastrophic failure. (3) The relative scarcity of comprehensive study of dynamic response of large span reinforced concrete domes with different geometry.

2 TYPES OF DOMES



Domes may be thin or thick shells in the form of surface of revolution, which are preferred as roof structures. A surface of revolution is generated by rotating a plane curve about an axis lying in the plane of the curve. Domes are classified based on material, thickness with respect to its radius of curvature and the shape of meridian curve. There are several types of domes that can be categorized based on their shapes. Spherical domes are in the shape of sphere and transfer the loads into uniform load over the dome surface. Roman architects studied the possibilities of a spherical dome.



Fig. 2: Church of Sant Elia, Sardinia

Some domes are in the shape of parabola and are called paraboloidal shells or domes. These domes were widely used in buildings belonging to gothic architecture.



Fig. 3: Dhyanalinga Dome, Coimbatore

Ellipsoidal domes are the result of revolution of ellipses and they have elliptic shapes. They are relatively few in numbers.

Fig. 4: Biosphere, Montreal

A more recent innovation in domes is the geodesic dome, referred to as a tension/compression structure. They are made up of triangular elements, whose vertices lie approximately on the surface of the dome.

The shape of domes holds the secret to their dynamic behavior, and requires a comprehensive study. Several researchers have studied in general, the free vibration response of spherical shells (Kang et al. 2000, Liew et al. 2002 and Lee et al. 2002), paraboloidal shells (Kang et al. 2005) and ellipsoidal shells (Shim et al. 2004).

3 DYNAMIC BEHAVIOUR AND PARAMETRIC STUDY

In this study 29 ellipsoidal domes were modeled using shell element in SAP2000. The four-node quadrilateral shell element was used to analyze the domes. Modal analysis was performed to determine the inherent dynamic characteristic of the dome such as natural frequencies and mode shapes using different dome thicknesses and different dome heights. In carrying out parametric studies, several parameters have been used. As a shell, the thickness plays an important role in the dynamic characteristics of the dome and its load carrying capacity. Thus one of the parameters taken into consideration is the thickness of the dome. Modal analysis has been carried out for several cases as follows using SAP2000 (SAP2000 2016). Two cases were presented in this investigation: (1) Ellipsoidal dome with fixed span, $L = 15\text{m}$, fixed height, $H = 4\text{m}$, and variable thickness (0.04 - 2.5 m); (2) Ellipsoidal dome with fixed thickness, $t = 0.2\text{ m}$, and variable height (1m - 15m).

3.1 Ellipsoidal Dome with Variable Thickness

Figure 5 shows the variation of frequency of vibration with dome thickness for a dome of height $H = 4\text{m}$ and span $L = 15\text{m}$. It is observed that the rapid increase in the frequency of vibration becomes a gradual increase when the thickness exceeds 0.2m for an ellipsoidal dome. However, their lower modes including fundamental mode tend to converge towards a certain frequency value specifically when the thickness is about 0.75m as shown in Figure 5.

3.2 Ellipsoidal Dome with Variable Height

Figure 6 shows the variation of frequency of vibration with dome height for a dome of thickness $t = 0.2\text{m}$ and a span $L = 15\text{m}$. The frequency of the ellipsoidal domes increases with the increase in the dome height to a certain limit and then decreases, as shown in Figure 6.

4 Comparison with spherical and paraboloidal domes

The results published by Adballa .J.A et al [1] on the dynamic characteristics of large reinforced concrete spherical and paraboloidal domes are borrowed to compare with the results of this investigation.

Fig. 8: Variation of frequency with thickness for paraboloidal dome

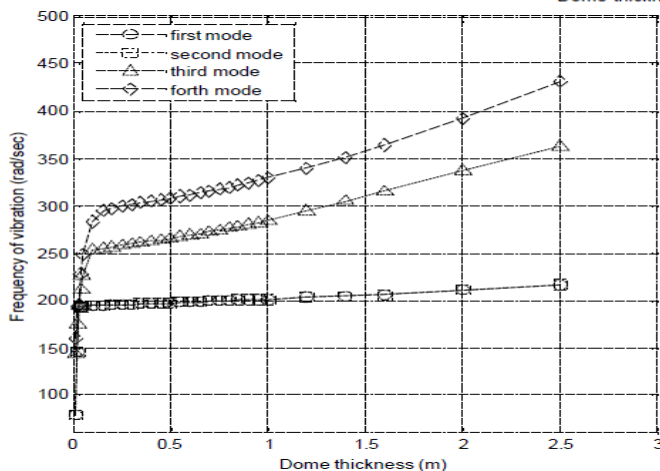
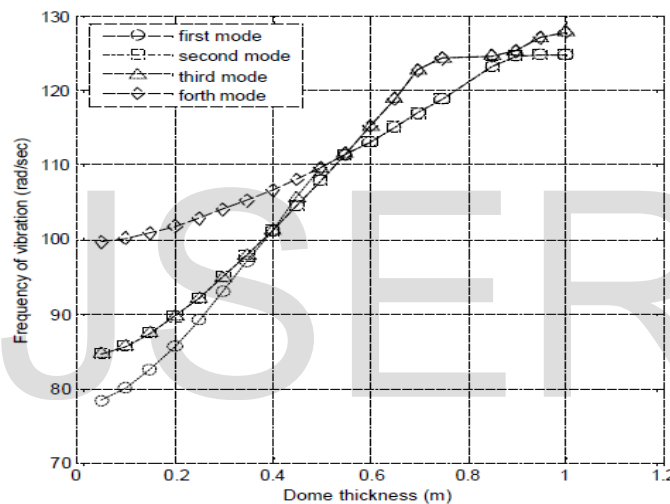


Fig. 6: Variation of frequency of vibration with height for ellipsoidal domes

Fig. 5: Variation of frequency of vibration with thickness for ellipsoidal domes

Figure 7 shows the variation of frequency of vibration of a spherical dome with thickness. As the weight of the dome increases by increasing the dome thickness the fundamental frequency of vibration of the spherical dome and that of the second mode of vibration show slight increase as compared to the frequency of vibration of higher modes, which shows, relatively more rate of increase.

Fig. 7: Variation of frequency with thickness for spherical dome

Figure 8 shows the variation in frequency of vibration of a paraboloidal dome. It is observed that the frequency of vibration increases gradually with the increase in the paraboloidal dome thickness for all modes but at different rates. However, all modes tend to converge toward certain values. They specifically have the same frequency value when the thickness is about 0.55m.

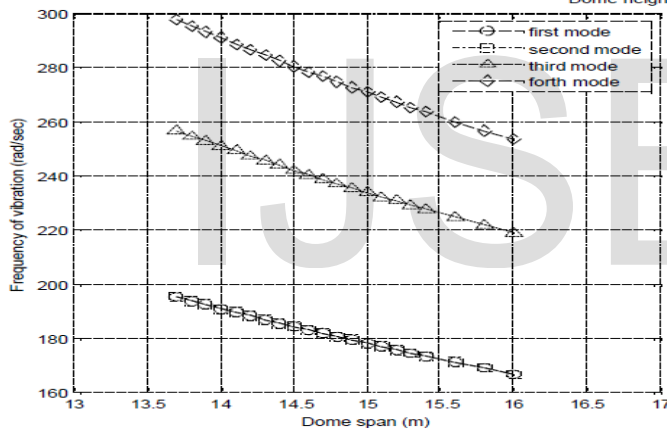
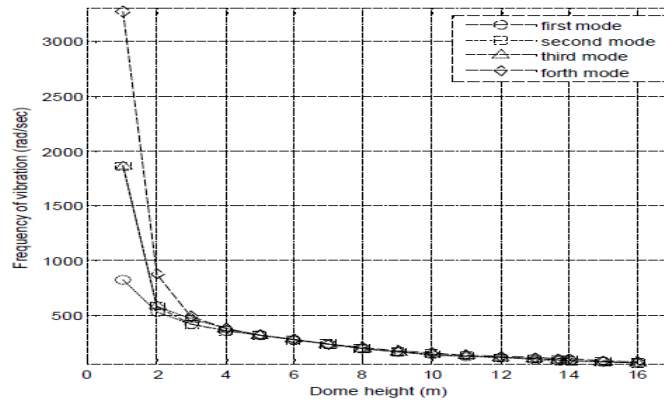


Fig. 9: Variation of frequency with height for spherical dome

Fig. 10: Variation of frequency with height for paraboloidal dome

Figure 9 shows the variation in the frequency of vibration of a spherical dome with height. It is observed that there is a decrease in the frequency of vibration of all the four modes as the dome height increases and the rate of decrease is the same and is linear.

Figure 10 shows the variation of frequency of vibration of a paraboloidal dome with height. There is a nonlinear decrease in the frequency of vibration of the domes with the increase in the dome height.

Fig. 11: Variation of radius of curvature with height for spherical dome

Fig. 12: Variation of radius of curvature with height for paraboloidal dome

Fig. 13: Variation of radius of curvature with height for ellipsoidal dome

The geometry of a dome is best defined by its radius of curvature. The variation in the frequency of vibration with height for domes are best explained by the corresponding variation in their radius of curvature. Figure 11 shows the variation of radius of curvature with height for a spherical dome. It can be observed that

the radius of curvature increase linearly with height for a spherical dome while the frequency of vibration decreases linearly. The variation of radius of curvature with height for a paraboloidal dome is shown in Figure 12. It can be seen that the radius of curvature increase non-linearly with height while the frequency of vibration decrease non-linearly. Figure 13 shows the variation of radius of curvature with height for a region on the surface of the ellipsoidal dome. The variation in the curvature is not unidirectional, the radius of curvature decreases with height to a certain limit and then increases while the frequency of vibration increases with height to certain limit and then decreases. It is this region in the elliptical curve which is responsible for its bidirectional behavior. Thus the radius of curvature and the frequency of vibration have inverse relationship.

5 CONCLUSION

This paper presented a parametric study of the relationship between thickness, height etc. of reinforced concrete ellipsoidal domes and their dynamic characteristics, specifically, frequency of vibration. It also compares the results for ellipsoidal domes with published results available for spherical and paraboloidal domes. From this study it can be concluded that:

- The frequency of vibration of reinforced concrete ellipsoidal dome increase with increase in the thickness. This behavior is similar to that shown by spherical and paraboloidal domes.
- As the height increase the frequency of vibration of ellipsoidal dome increases to a certain limit and then decreases. But for spherical and paraboloidal dome the frequency of vibration kept decreasing with increase in height linearly for the former one and non-linearly for the latter.
- The frequency of vibration of a dome depends highly on the inherent geometry which essentially is a function of the radius of curvature.
- For spherical and ellipsoidal domes, lower modes have more modal participation while the modal participation from higher modes is more in the case of paraboloidal domes.
- In order to assess the seismic vulnerability of reinforced concrete buildings with large domes , further studies need to be carried out that include: (1) investigation of the interaction between domes and buildings; (2) study of the dynamic response of different types of domes to different ground motion records; and (3) assessment of seismic vulnerability of reinforced concrete buildings with large domes to earthquake ground motion using nonlinear dynamic time-history and nonlinear static pushover analysis procedures.

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