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Nonlinear Seismic Analysis of Reinforced Concrete Multi-Bay Cylindrical Shell Structures

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Abstract: ***In spite of recent development in earthquake resistant engineering, earthquake still inflict widespread damage at various parts of the world. The importance of space structures to survive earthquake have been noticed from the experience of severe earthquakes. At present various measures against the earthquakes are applied to the space structure. Non-linear Static analysis has been widely used on earthquake response prediction of building structures under severe earthquakes. It needs to be studied whether it is applicable for reinforced concrete Cylindrical Shell structures or not. In this paper, Non-linear Static analysis of Multi-bay Cylindrical Shell structures is introduced. The first mode lateral loading pattern for the Multi-bay Cylindrical Shell structure with nine other cases is adopted to perform the pushover analysis. The Non-linear Static analyses results are compared with linear static, linear dynamic and non-linear time history analyses results. All the analyses were performed using SAP2000.***

Keywords: Multi-bay Cylindrical Shell structures, Non-linear analysis, Earthquake response

1. Introduction

This study deals with an application of shell structures called Multi-bay Cylindrical Shell structures in seismic areas. Shells and spatial structures are adopted for construction of large span structures in which a large space is realized without columns as the structural components. In those cases, the structures are expected to resist against various design loads mainly through their extremely strong capability which can be acquired through in-plane or membrane stress resultants and this is just the reason by which they themselves stand for external loads without columns as their structural components in the large span structures. In civil engineering construction, singly curved cylindrical are commonly used as roofing units. However, they are frequently subjected to dynamic loadings in their service life and hence, the knowledge of their dynamic behavior is important from the standpoint of analysis and design.

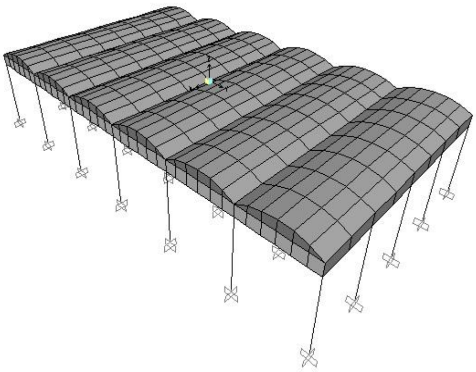
In the present scenario, because of the wide range of geometry possible with shells, the accumulated understanding is still limited, thus there is a need of an attempt to be proposed to lay down certain recommendations which will be used as general guidelines for the performance study of shell structures subjected to seismic loading. Therefore, on the basis of certain objectives, some methodology needs to be proposed for learning the behavior of shell structures under seismic type of loads. So, a three-dimensional finite element model for seismic analysis is then developed. A complete response spectrum analysis is performed using SAP 2000 finite element package software.

2. Methodology

Description of the Structure

In shell structures, the reinforcement bars that resist the in-plane stress resultants should be placed in two or more directions and should ideally be oriented in the general directions of the principal tensile stresses especially in regions of high tension. Even though moment reversal is not anticipated, reinforcement to resist stress couples should be placed near both faces, since the bending moments may vary rapidly along the surface. Under seismic loading, the two layers also include the membrane reinforcement. The provision of adequate clearance and cover may necessitate increasing the shell thickness. Special attention is required for edges members that must be proportioned to resist the forces imparted by the shell. Fig.1 shows the meshing view and first mode shape for Multi-bay Cylindrical Shell structure. Table 1 gives the details of parameters considered for Multi-bay Cylindrical Shell structure.

In practice, we can consider two regions in shell structures: (1) region where the stresses are primarily in-plane or membrane and, (2) regions with significant bending action. In the first case, direct tensile stresses should be resisted entirely by reinforcing steel in concrete shells. Regions with direct compressive stresses are generally controlled by stability requirements. In the second case, the moments or stress couples may be resisted by considering a concrete section with reinforcement near the surfaces to act as a wide flexural member. So, a suitable depth is required for facilitate the provision of ample reinforcing steel. The values of internal stress resultants and distribution are necessary to perform the design of reinforcement. Under lateral seismic loading with gravity loads, reinforcement design for RC shells is more complex than the case with only gravity loads.



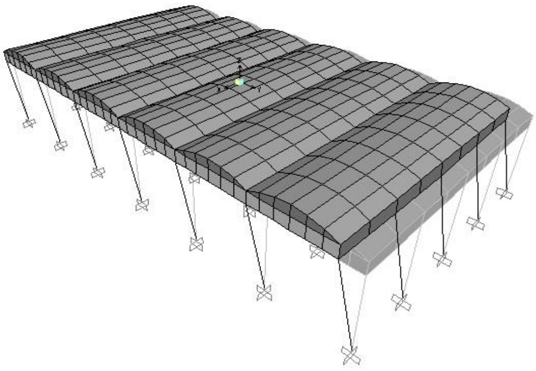


Figure 1: Meshing view and First Mode Shape of Multi-bay Cylindrical Shell Structure

Table 1: Selected parameters for Multi-bay Cylindrical Shell Structure

NO.	Description	Parameter
1.	Span in X direction	20 m
2.	Span in Y direction	36 m
3.	Live load	0.5 kN/m^2
4.	Grade of Concrete	M-25
5.	Type of Steel	HYSD bars
6.	Column Height	6.0 m
7.	Column Size	0.5 m x 0.5 m
8.	Column Support condition	Fixed
9.	Beam Size	0.5 m x 1.0 m
10.	Shell reinforcement	10d[at]200 c/c in both-faces & in both-ways.
11.	Diaphragm thickness	0.50 m
12.	Radius of Shell	6 m
13.	Thickness of Shell	0.25 m

Finite Element Model

The finite element model is a 3D shell element with both bending and membrane capabilities. Both in-plane and normal loads are permitted. The element has six degrees of freedom at each node: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z-axes.

The structure is idealized as an assemblage of thin constant thickness shell element with each element subdivided into three numbers of layers as shown in Fig.2. The layered shell allows any number of layers to be defined in the thickness direction, each with an independent location, thickness, behavior, and material. Material behavior is considered to be linear. The layered shell usually represents full-shell behavior, although we can control this on a layer-by-layer basis unless the layering is fully symmetrical in the thickness direction. Three-dimensional modeling of the Multi-bay Cylindrical Shell structure is performed using SAP2000 (Version 14) program. The finite element model is a 3D shell element with linear layered shell capabilities. Both in-plane and normal loads are permitted.

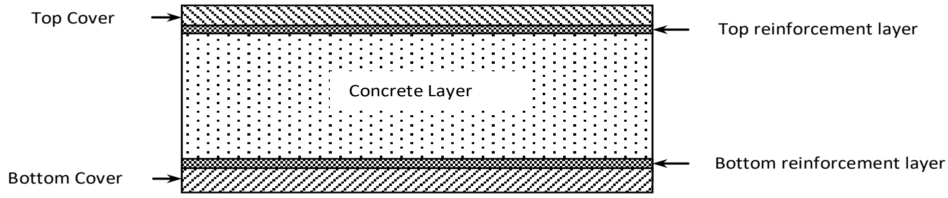


Figure 2: Layered Shell Model

Free Vibration Analysis

The first step in earthquake analysis must always be the solution of the free vibration problem. This is necessary to get a first important insight into structural dynamic properties. The modal characteristics of the Multi-bay Cylindrical Shell are presented in the X, Y and Z directions in Table 2.

Table 2: Modal Characteristics of Multi-bay Cylindrical Shell Structure

Mode	Period	Modal Participating Mass Ratio			Mass Participation Factor		
		X	Y	Z	X	Y	Z
1	0.8378	0	**0.999**	0	4.15E-10	**39.352**	8.23E-10
2	0.8263	**0.999**	0	0	**- 39.361**	4.05E-10	- 2.25E-09
3	0.7579	0	0	0	- 4.14E-11	- 1.70E-10	- 1.55E-09
4	0.1195	1.07E-18	2.41 E-05	1.05E-14	4.08E-08	0.1933	4.051E-06
5	0.1173	0	1.04E-17	0.034	2.61E-09	- 1.27E-07	- 7.312
6	0.106617	1.38E-18	1.81E-05	1.81E-14	4.629E-08	0.16789	5.30E-06
7	0.095643	5.52E-19	2.71E-16	**0.0593**	- 2.92E-08	6.48E-07	**9.587**
8	0.085007	0	1.02E-15	0.03443	1.358E-10	1.25E-06	7.305
9	0.081394	1.49E-18	0.000005	1.26E-14	- 4.81E-08	0.086202	4.42E-06
10	0.073297	1.88E-06	4.35E-15	7.55E-14	- 0.054068	- 2.59E-06	1.1E-06

Linear Static Procedure (LSP)

Under the Linear Static Procedure (LSP), design seismic forces, their distribution over the height of the building, and the corresponding internal forces and system displacements are determined using a linearly elastic, static analysis. In the LSP, the building is modeled with linearly-elastic stiffness and equivalent viscous damping that approximate values expected for loading to near the yield point. Design earthquake demands for the LSP are represented by static lateral forces whose sum is equal to the pseudo lateral load.

Response Spectrum Analysis

The response spectrum analysis is used for the prediction of displacements and element forces in structures. The method involves the calculation of only the maximum values of the displacements and members in each mode using smooth design spectra. The analysis consists of a three dimensional mode shapes and natural frequencies of vibration calculation. These are the undamped free vibration response of the structure. The structure has constant stiffness and mass effects. The mass is taken distributed along the structures by a density. Then, the structure is excited by a spectrum of known directions and frequency components. Modal analysis method did not require a set of master degrees of freedom, and it gives more accurate answers with the comparison with reduced method for eigen values calculation. But, it takes somewhat longer to solve. In this method a number of modes are considered for the structural response calculation. For each principal direction, the square-root-of-sum-of the-squares (SRSS) modes combination method is used for the purpose of structural design. This approach assumes that all the maximum modal values are statistically independent. As per IS: 1893-2002 (Part-1), the structure is considered in Zone-V and soil type-II.

Nonlinear Static Procedure (NSP)

A pushover analysis is performed by subjecting a structure to a monotonically increasing pattern of lateral loads, representing the inertial forces, which would be experienced by the structure when subjected to ground shaking.

Table 3: Loading direction and pattern for each pushover analysis case

Analysis Case	Loading Direction	Loading Pattern
1	X	The first mode shape
2	X	Acceleration load
3	Y	The first mode shape
4	Y	Acceleration load
5	Z	The first mode shape
6	Z	Acceleration load

Under incrementally increasing loads various structural elements may yield sequentially. Consequently, at each event, the structure experiences a loss in stiffness. Using a pushover analysis, a characteristic non-linear force displacement relationship can be determined.

A well-designed structure should be capable of equally resisting earthquake motions from all possible directions. Six pushover analysis cases, as listed in Table 3, are performed in three directions i. e. X, Y and Z directions. The general finite element package SAP 2000 (Linear and nonlinear static and dynamic analysis and design of three dimensional structures) is used as a tool for performing the pushover analysis. SAP 2000 (Version 14) static pushover analysis capabilities, which are fully integrated into the program, allow quick and easy implementation of the pushover procedures prescribed in ATC-40 and FEMA-356 for both 2 dimensional and 3 dimensional structures. It also provides default-hinge properties and recommends PMM hinges for columns and M3 hinges for beams as described in FEMA-356 [3]. Multi-bay Cylindrical Shells are supported on edge beams and columns. M3 auto hinges are provided in edge beams and PMM auto hinges are provided in columns.

Nonlinear Dynamic Procedure (NDP)

Under the Nonlinear Dynamic Procedure (NDP), design seismic forces, their distribution over the height of the building, and the corresponding internal forces and system displacements are determined using an inelastic response history dynamic analysis. The basis, modeling approaches, and acceptance criteria of the NDP are similar to those for the NSP. The main exception is that the response calculations are carried out using Time-History Analysis. With the NDP, the design displacements are not established using a target displacement, but instead are determined directly through dynamic analysis using ground motion histories.

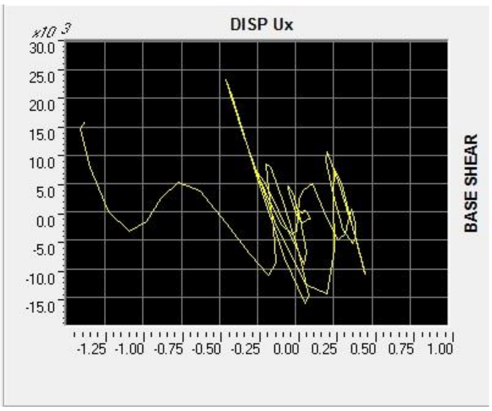
3. Results and Discussion

The bending and twisting moment are very low. This confirms the membrane resisting mechanism in shell structures. Absolute maximum bending moment M_x, M_y and M_{xy} per unit length and absolute maximum membrane forces T_x, T_y and T_{xy} per unit length are determined in Table 4.

Table 4: Max. Absolute Membrane Forces & Bending Moments for different Analysis Procedures

Maximum Absolute Values	Linear Static Analysis	Linear Dynamic Analysis	Nonlinear Static Analysis	Nonlinear Dynamic Analysis
Membrane force T_x	2950.56	75696.54	20262.7	196230.08
Membrane force T_y	5711.5	80175.26	18971.88	200759.29
In-plane shear force T_{xy}	1681.79	17704.65	5691.42	45898.13
Bending moment M_x	11.2773	309.704	116.008	774.99

Bending moment M_y	6.8122	925.94	156.268	534.881
Twisting moment M_{xy}	7.7601	524.7164	127.290	829.55



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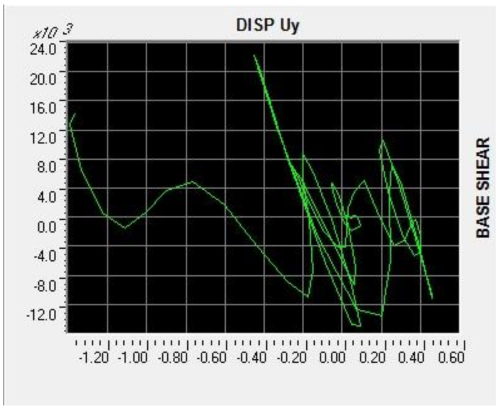

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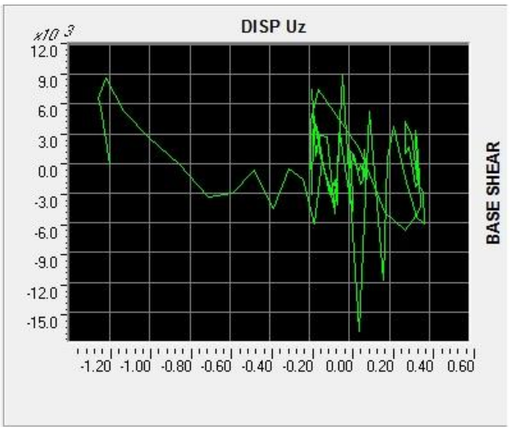

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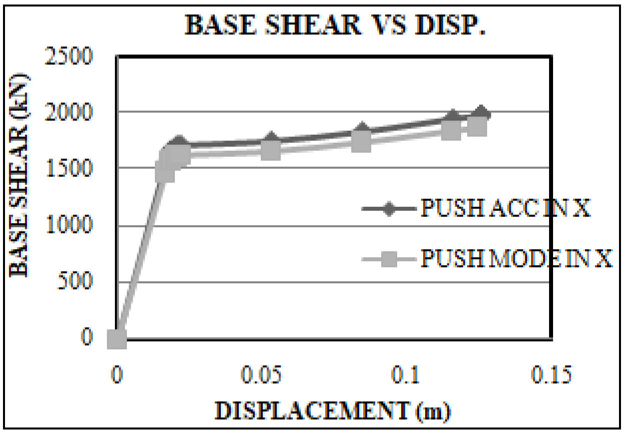
Figure 3: Base Shear Vs Displacement Plot for Time History Analysis in X, Y and Z direction

Table 5: Response of Structure for Nonlinear Static and Dynamic Analysis procedures

Direction	Performance Point		Lateral Displacement (M)		Base Shear Force (KN)	
	S_d/m	S_a/g	Push Over	Dynamic	Pushover	Dynamic
X	0.044	0.366	0.1394	0.191	4964.77	7292
Y	-	-	0.0455	0.0838	3232.57	9879
Z	0.055	1.00	0.1005	0.040684	15627	4448



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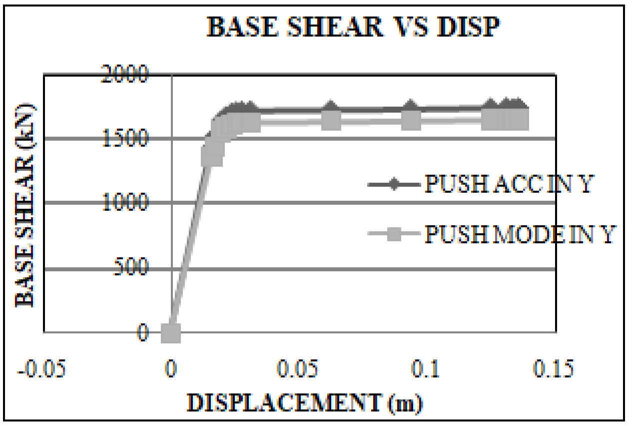

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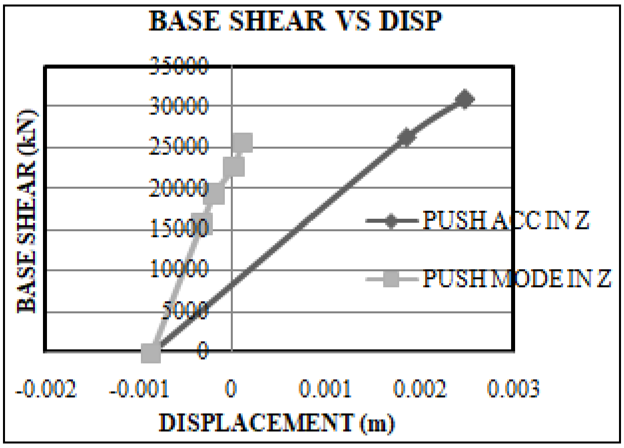

(c)

Figure 4 Base Shear Vs Displacement for Pushover Analysis in X, Y & Z direction

Lateral displacement and Base shear has been compared for the Nonlinear Static and Nonlinear Dynamic Analysis procedures. Table 5 shows the comparison of results for analysis cases in X, Y and Z directions. Base Shear Vs Displacement plots for Pushover Analysis procedure and Time History Analysis procedure in X, Y and Z direction are shown in Figure 3 and Figure 4.

4. Conclusions

By modeling the shell, in layer it is possible to observe the behavior of each layer. The Non linear analysis is way to explore the seismic behavior of structures and same is here applied for cylindrical barrel vault structures.

A three dimensional finite element analysis was performed to assess the seismic performance of the concept subjected to earthquake actions. Multi-bay cylindrical barrel vault structures exhibit a very low period of vibration. Finally, a very satisfactory behavior under seismic actions is observed for the cylindrical barrel vault structures. We can conclude that the Multi-bay cylindrical barrel vault structures can be recommended for regions with a high seismicity. This is due to the most profound and efficient structural performance of shell concept.

The permissible vertical deflection in shell as per IS-456: 2000 [11] is 0.08 m (span/250). The vertical deflection is within the permissible limit. The permissible stresses in concrete and steel as per IS-456: 2000 are 13.38 N/mm² (0.446*f_{ck}) and 361.05 N/mm² (0.87*f_y). The stresses in steel layer are within the permissible limit.

By modeling the shell, in layer it is possible to observe the behavior of each layer. The pushover analysis is relatively a simpler way to explore the nonlinear behavior of structures. For large span structures, pushover analysis is accurate enough provided the modal participating mass ratio is larger than 0.90 and according to our study it can be said that pushover analysis gives us approximate behavior in x and y direction does not give true behavior in z direction as modal participating mass ratio is very less. From the capacity demand curves, it can be said that shell structures though have a very high capacity; still they will collapse at an earlier stage due to high demand. In cylindrical barrel vault structures number of diaphragms may be increased to improve seismic capacity in Y-direction. For cylindrical barrel vault structures, pushover analysis has high efficiency to find out the weak part of the structure.

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