NONLINEAR STATIC ANALYSIS OF LONG REINFORCED CONCRETE CYLINDRICAL BARREL VAULT (SHELL) STRUCTURES

Vijay Kumar Shukla[1] , Dr. R. N. Khare [2] Vivek Mishra[3]
[1] Assistant Professor, Department of Civil Engineering, VEC Lakhnapur, Ambikapur (C.G),
[2] Principal VEC Ambikapur (C.G)
[3]M.Tech, Structural Engineering, VEC Lakhanpur, Ambikapur (C.G.)

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. Nonlinear 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 Barrel Vault structures or not. In this paper, Nonlinear Static analysis of Cylindrical Barrel Vault structures is introduced. The first mode lateral loading pattern for the Cylindrical Barrel Vault structure with nine other cases is adopted to perform the pushover analysis. The Nonlinear Static analyses results are compared with linear static, linear dynamic and nonlinear time history analyses results. All the analyses were performed using SAP2000.

Keywords – Long Reinforced Concrete Shell structures, Non-linear static analysis, Earthquake response of structure.

1. Introduction

This study deals with an application of shell structures called cylindrical barrel vault 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

2.1. 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 cylindrical barrel vault structure. Table 1 gives the details of parameters considered for cylindrical barrel vault 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.

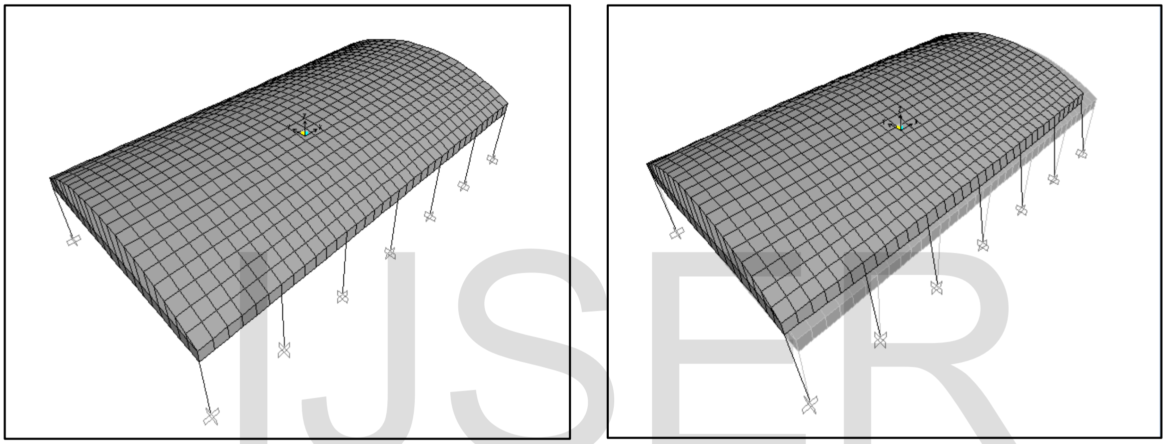


Fig.1 Meshing view and First Mode Shape of Cylindrical Barrel Vault Structure

Table 1 Selected parameters for Long Cylindrical Barrel Vault Structure

No.	Description	Parameter
1.	Span in X direction	36 m
2.	Span in Y direction	20 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 @ 200 c/c in both-faces & in both-ways.
11.	Diaphragm thickness	0.50 m
12.	Radius of Shell	20 m
13.	Thickness of Shell	0.25 m

2.2. Finite Element Model

The so-called Mindlin finite element is used for the structural analysis. 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 cylindrical barrel vault 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.

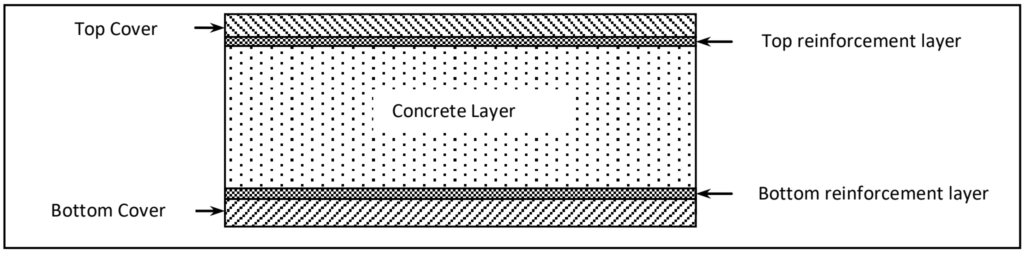


Fig.2 Layered Shell Model

3. NON-LINEAR STATIC ANALYSIS

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. 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. Ten pushover analysis cases, as listed in Table 2, 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]. Cylindrical barrel vaults are supported on edge beams and columns. M3 auto hinges are provided in edge beams and PMM auto hinges are provided in columns.

Table 3 Loading direction and pattern for each pushover analysis case

Analysis case	Loading direction	Loading pattern
1	X	The first mode shape in the x direction
2	X	Acceleration load
3	Y	The first mode shape in the y direction
4	Y	Acceleration load

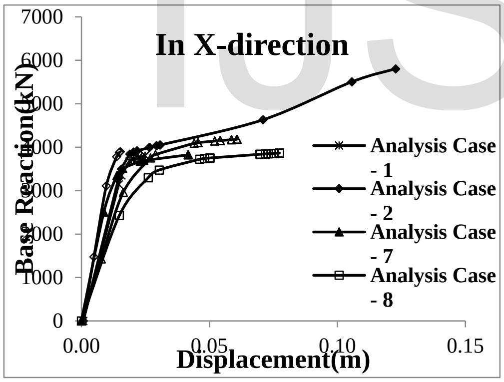
5	Z	The first mode shape in the z direction
6	Z	Acceleration load
7	X and Y	Acceleration load (A_X:A_Y=1:0.85)
8	X and Y	Acceleration load (A_X:A_Y =0.85:1)
9	X, Y and Z	Acceleration load (A_X:A_Y:A_Z =1:0.85:0.65)
10	X, Y and Z	Acceleration load (A_X:A_Y:A_Z =0.85:1:0.65)

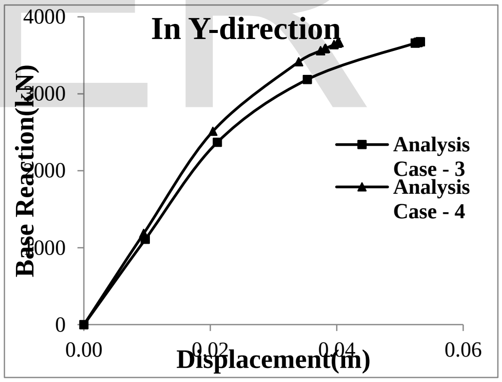
4. RESULTS OF NON LINEAR STATIC ANALYSIS

The outcomes from pushover analysis are capacity curves, capacity-demand curves, performance points, drift ratios, base shear, plastic hinge mechanism, deflection and stresses in shell.

1) Capacity curve

The resulting capacity curves for the long cylindrical barrel vault structure are shown in Fig.3. The curves are represented separately for different three directions. They are initially linear but start to deviate from linearity as the beams and the columns undergo inelastic actions. When the buildings are pushed well into the inelastic range, the curves become linear again but with a smaller slope.





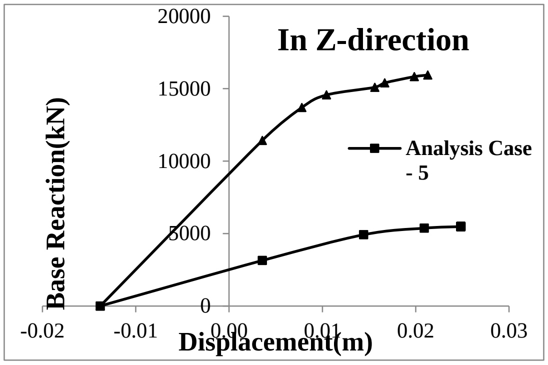


Fig.3 Capacity Curve for Cylindrical Barrel Vault Structure

2) Capacity Demand Curve

Capacity Demand Curves are plotted between Spectral Displacement, S_d (m) and Spectral Acceleration S_a (g). The performance point for each analysis case is obtained from Fig.4.

Table 4 Response of the long cylindrical barrel vault structure by pushover analysis

Analysis case	Yield point of control node		Performance point of control node		F/W	Displacement of column node	
	dy (m)	Fy (kN)	d (m)	F (kN)		Δ (m)	Δ/H
1	0.0156	3385	-	-	-	0.0233	0.0039
2	0.0178	3840	0.0530	4364.6	1.263	0.1200	0.0200
3	0.0216	2383	-	-	-	0.0475	0.0079
4	0.0205	2558	-	-	-	0.0363	0.0061
5	0.0145	4978	-	-	-	0.0010	0.0002
6	0.0081	13885	0.0100	14552.0	4.211	0.0009	0.0001
7	0.0141	3384	-	-	-	0.0350	0.0058
8	0.0147	2459	-	-	-	0.0755	0.0126
9	0.0096	3120	-	-	-	0.0229	0.0038
10	0.0165	3004	-	-	-	0.0588	0.0098

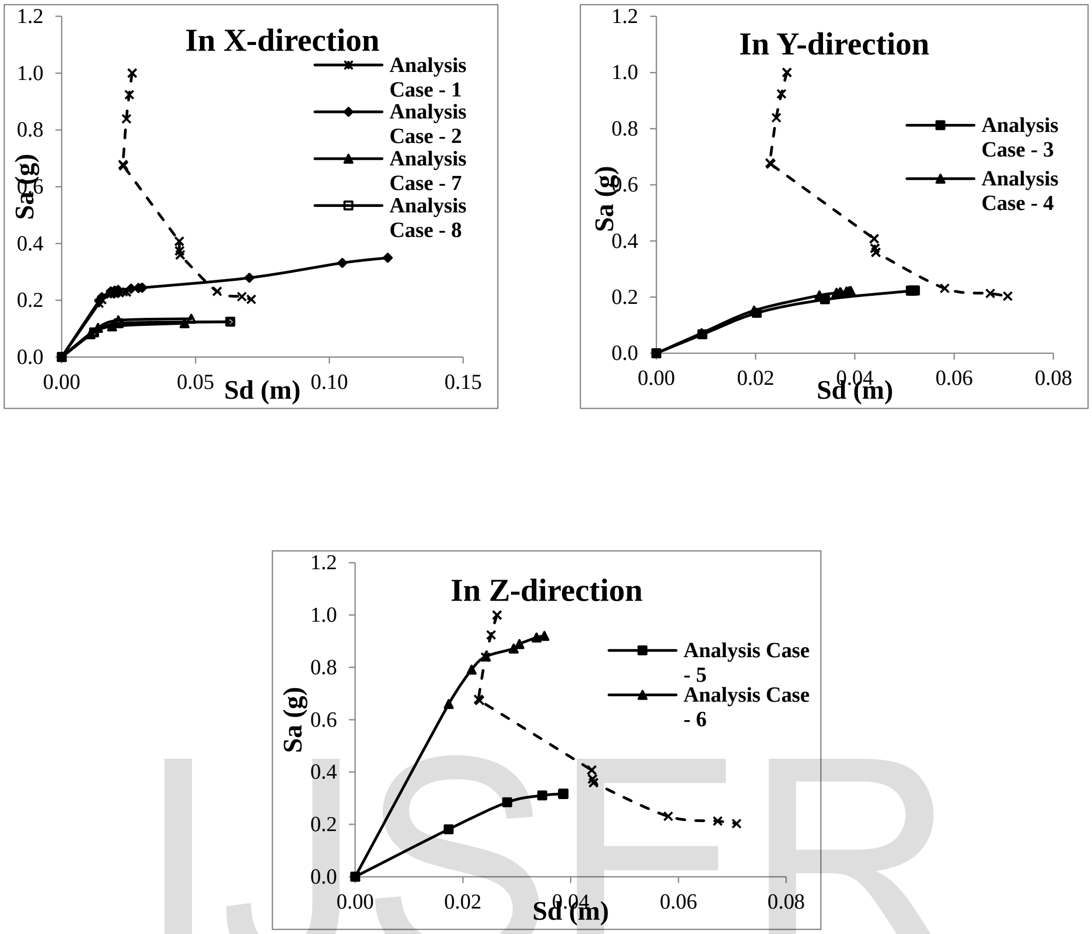


Fig.4 Capacity-Demand Curves for Cylindrical Barrel Vault Structures

3) Performance Point, Drift Ratio & Base Shear

Performance points are obtained by the intersection of capacity and demand curves. Drift ratio is the ratio of differential displacement Δ, between each end of the component over the effective height of the component (H). The base-reaction and displacement of control node at performance point and drift ratio for column node are listed in Table 4. W is the seismic weight of the structure.

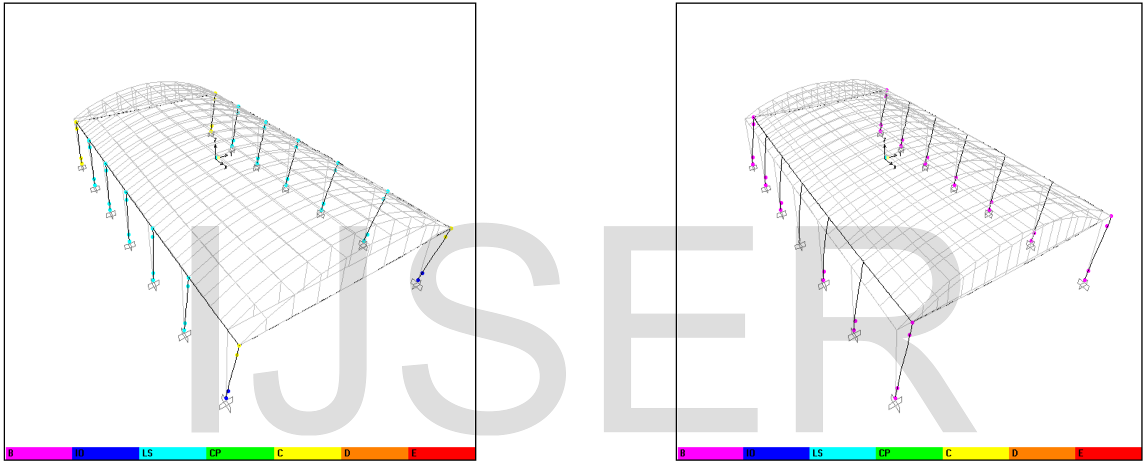
4) Plastic Hinge Mechanism

Table 5 shows statistics of plastic hinges obtained by pushover analysis for long cylindrical barrel vault structure from different pushover analysis cases. Step number in which hinges are formed is mentioned in bracket. Plastic hinges appear mainly in the columns and a few in the beams. In Z direction the plastic hinges are not formed as the entire load is taken by barrel vault. Maximum hinges are in the phase of B-IO, means the member need not be repaired after earthquakes. The hinge formation represents the performance level of the structure. The number of plastic hinges formed in the 1st and 2nd analysis case is the maximum among the 10 analysis cases.

Table 5 Statistics of plastic hinges obtained by pushover analysis

Analysis case	Percentage (%) of Plastic Hinge Obtained (Step No.)			
	B	IO	LS	CP
1	28(4)	-	-	-

2	28(4)	28(13)	24(15)	6(15)
3	15(3)	5(4)	-	-
4	17(10)	-	-	-
5	-	-	-	-
6	-	-	-	-
7	28(4)	20(6)	-	-
8	24(4)	23(10)	-	-
9	23(5)	-	-	-
10	26(5)	-	-	-



(a) Acceleration in X-direction (Case 2) *(b) Acceleration in Y-direction (Case 4)*

Fig.5 Plastic Hinge Mechanisms for Cases 2 and 4

5) Deflection in Shell

The deflections in cylindrical barrel vault structure for 10 analysis cases in X, Y & Z directions are listed in Table 6. The maximum deflection is 0.1250 in X direction, 0.0814 m in Y direction and 0.0317 m in Z direction.

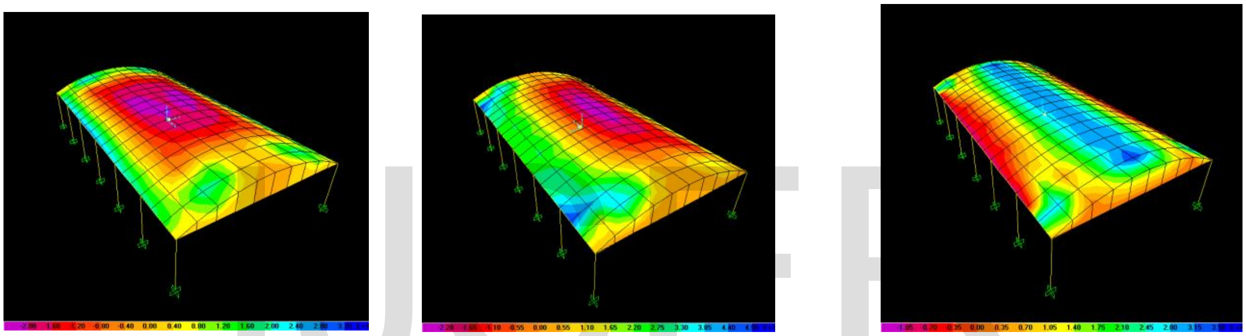
Table 6 Deflection in Shell by pushover analysis for long cylindrical barrel vault structure

Analysis case	**Deflection (m)**		
	In X	**In Y**	**In Z**
1	0.0265	0.0063	0.0197
2	**0.1250**	0.0089	0.0214
3	0.0014	0.0585	**0.0317**
4	0.0011	0.0444	0.0267
5	0.0011	0.0070	0.0289

6	0.0021	0.0069	0.0236
7	0.0451	0.0587	0.0248
8	0.0540	**0.0814**	0.0270
9	0.0165	0.0273	0.0189
10	0.0397	0.0639	0.0223

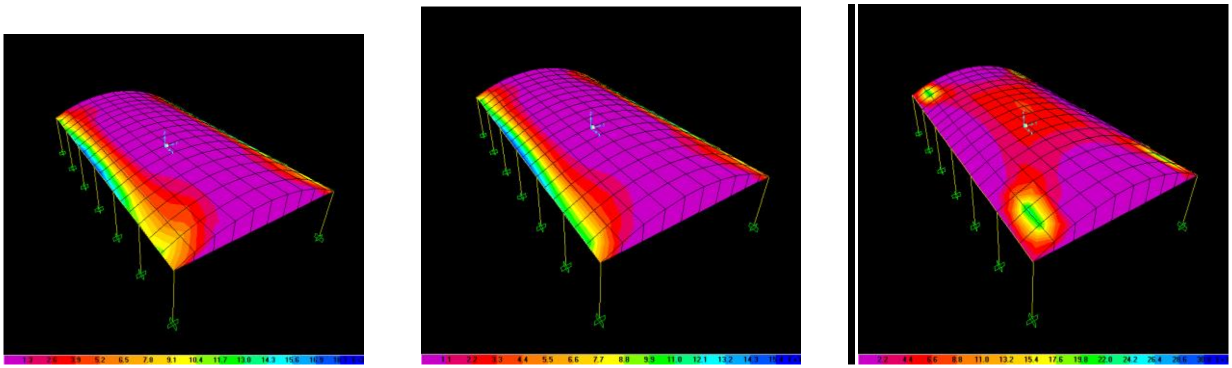
6) Stresses in Shell & Shell Layers

Maximum principle stress, S_{MAX} and minimum principle stress, S_{MIN} for whole thickness and different layers are tabulated in Table 7. SAP 2000 provides the facility to find stresses for defined layers separately. Maximum and minimum principle stresses for shell, concrete layer, top reinforcement bar and bottom reinforcement bar are then compared with permissible stresses.



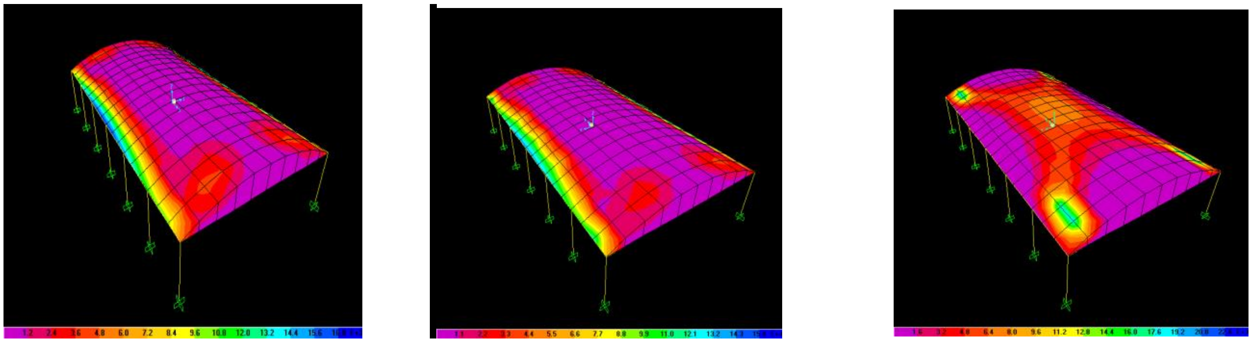
Max stresses for Case 2 = 3.065 N/mm^2 *Max stresses for Case 4 = 4.91 N/mm^2* *Max stresses for Case 6 = 3.69 N/mm^2*

Fig.6 Maximum concrete stresses for Analysis Cases 2, 4 and 6



Max stresses for Case 2 = 18.845N/mm^2 *Max stresses for Case 4 = 15.55 N/mm^2* *Max stresses for Case 6 = 31.305 N/mm^2*

Fig.7 Maximum bottom steel reinforcement stresses for Analysis Cases 2, 4 and 6



Max stresses for Case 2 = 17.32N/mm² *Max stresses for Case 4 = 15.89 N/mm²* *Max stresses for Case 6 = 22.81 N/mm²*

Fig.8 Maximum top steel reinforcement stresses for Analysis Cases 2, 4 and 6

5. DISCUSSION

The permissible storey drift as per IS 1893:2002[8] due to the lateral force, with partial load factor of 1.0, is H/250 where H is the storey height. The permissible storey drift is 0.024 m for 6 m storey height. The storey drift is in within limit for all cases. All of the hinges are developed in the columns and a few hinges are observed in the beams. Maximum hinges are obtained in columns in X-direction. In Y-direction and Z-direction, hinges are observed in columns only up to IO. The permissible vertical deflection in shell as per IS-456:2000[9] 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.

Table 7 Stresses in long cylindrical barrel vault structure by pushover analysis

Analysis case	Maximum principal stress, S_{MAX}				Minimum principal stress, S_{MIN}			
	Shell Stresses	Shell Layer Stresses			Shell Stresses	Shell Layer Stresses		
		Concrete Layer	Top Bar	Bottom Bar		Concrete Layer	Top Bar	Bottom Bar
1	3.339	3.115	13.924	14.252	11.855	11.855	16.373	15.018
2	4.796	3.066	18.464	18.846	13.757	13.757	20.402	18.900
3	5.348	5.348	17.097	16.760	16.789	16.789	17.938	16.340
4	4.836	4.836	15.772	15.415	15.350	15.350	17.580	16.055
5	5.458	3.511	15.184	17.909	7.593	7.593	13.883	13.798
6	6.183	3.698	22.840	31.040	4.506	4.506	11.823	9.082
7	4.910	4.910	17.290	17.748	14.984	14.984	18.520	16.970
8	5.084	4.663	18.300	18.527	15.551	15.551	19.040	17.370

9	4.500	4.500	11.753	12.004	11.926	11.926	13.544	12.388
10	4.953	4.877	14.325	14.650	12.991	12.991	15.116	13.723

6. CONCLUSIONS

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 and same is here applied for long cylindrical barrel vault 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 long 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.

References

[1] Chopra A.K. and Goel R., “A modal pushover analysis procedure for estimating seismic demands for buildings”, [J].*Earthquake Engineering and Structural Dynamics*, 2002; 31(3): 561-582.

[2] Luo Y. F. and Yang M.W., “Static elasto-plastic analysis of long-span rigid spatial structures under vertical earthquake”, *Proceedings of the 6th International Conference on Computation of Shell and Spatial Structures*, May, 2008, NY, USA.

[3] American Society of Civil Engineers, “Prestandard and Commentary for the Seismic Rehabilitation of Buildings”. FEMA-356, Washington D.C.: Federal Emergency Management Agency, 2000.

[4] Seismic evaluation and retrofit of concrete buildings ATC 40, Redwood City, California: Applied Technology Council, 1996.

[5] Habibullah, A. and Pyle, S. (1998) “Practical Three Dimensional Nonlinear Static Pushover Analysis”, *Structure Magazine*, winter.

[6] Hua, L.W., Shan, Y.Q. and Yu-Ji, T. “Response analysis of national stadium under spatially varying earthquake ground motions”, *Journal of international association for shell and spatial structures: IASS.*

[7] Pathak, R, Khare, R and Shukla, V. K. “ Nonlinear Seismic Analysis of Reinforced Concrete Shell (Singl Bay) Strucutre Under Seismic Loading”, *Jounrnal of of Civil Engineering Researchm: JCER*

[8] IS 1893:2002(Part-1) “Criteria for Earthquake Resistant Design of Structures”.

[9] IS-456:2000 “Indian Standard Plain and reinforced Concrete-Code of Practice”.