International Journal on Computational Engineering

Journal Homepage www.comien.org/index.php/comien

Performance Analysis of Single and Double-Layer Barrel Vault Shells: Effects of Shell Thickness and Structural Behaviour

Neha Nawghare [a,*], Chandrakant Pol [a]

[a] *Department of Applied Mechanics Walchand College of Engineering Sangli, India*

Corresponding author: nehanawghare@gmail.com

***Abstract*— Single-layer and double-layer barrel vault shells under different shell thicknesses will be assessed for the effect of local buckling to be studied via FEM simulation. Due to the advantages of a barrel vault in terms of architectural and structural points have been well established, it now demands an equally precise level of analysis for best performance and durability. The thickness of the shell impacts its resonant behaviour, hence without an estimate about how thick a given layer will be, one cannot hope to design and implement such units in any useful way. In this paper, the FEM is used to analyse single and double-layer barrel vault shells with various thickness configurations. Within the context of this study, displacement magnitudes and directions, shear stresses, membrane stress, moments per unit width (Mx, My, Mxy), and principal stresses within the plane of the elements, etc are performance measures. The results are obvious in distinguishing between the performances of several types of single or double-layer shells and under varied thickness requirements. Thicker shells are often preferred to provide smaller displacement and stress distributions, especially for double layers. A double-layer shell always behaves better structurally than that in the single-layer class and is capable of resisting shear forces as well as membrane stresses more effectively. These findings further demonstrate that thickness in shell design and optimization for the barrel vault structure cannot be neglected. Clearly, the improved stability and alleviated stress peaks of thickening double-layer shells suggest great potential for practical application in some complicated or even extreme building designs.**

***Keywords*— barrel vault shells; Finite element method (FEM); single-layer shell analysis; double-layer shell performance; shell thickness optimization; structural stress distribution.**

Manuscript received 15 Aug. 2024; revised 29 Oct. 2024; accepted 5 Nov. 2024. Date of publication 31 Dec. 2024.

I. Introduction

"Special structure" refers to creative long-span structural designs, most commonly used for roofing and human activity shelters. Frameworks for space or grids, cabling-and-strut and rigidity, air-supported or air-inflated, self-erecting and adaptable, cables net, tension membranes, geodesic domes, folding plates, and thin shells are only a few examples of the diverse range of structures they cover. Tall buildings and long-span bridges are not included here; they are discussed elsewhere.[1].

Engineers and architects have recently found the benefits of barrel vaults as practical and often extremely appropriate roof systems for large cultural and recreational facilities, as well as affordable industrial buildings such as warehouses, large-span hangars, and indoor sporting stadiums.[2].

Barrel vaults are among the oldest structures that have been used since antiquity. Barrel vaults were used in masonry construction in the Orient and by the Romans. The dead weight of these constructions creates huge horizontal forces, which should be counteracted by thick walls. With the advancement of science and technology in the early nineteenth century, steel elements such as pipe elements replaced brickwork and concrete materials. These features provided good strength against horizontal forces, allowing the structure to be supported by slender columns or walls. Furthermore, it can be noted that the arrival of cast iron made great progress in the creation of barrel vaults with a large span.[3].

A barrel vault is made up of one or more tiers of arching pieces that face one direction [4]. Barrel vaults are given several titles based on how their surface is constructed. The oldest versions of barrel vaults were built as single-layer constructions [3], [5], [6].

Barrel vaults are given several titles based on how their surface is constructed. Earlier barrel vaults were single-layered structures. Double-layer structures are increasingly preferred as spans grow. While the members of single-layer barrel vaults are mostly subjected to flexural moments, those of double-layer barrel vaults are nearly entirely subjected to axial stresses, and the removal of bending moments allows all elements to fully utilize their strength.

Barrell vaults with two layers are usually statistically inconclusive. Such systems are stiff, which almost eliminates the risk of instability. Using this type of barrel vault increases the vault's structural integrity and provides enormous potential for structural systems that can support spans greater than 100 meters [7], [8]. Double-layer barrel vaults feature a large number of structural elements, and using optimization techniques has a significant impact on their economy and efficient structural layout [9]. Kaveh et al. assessed the best layout for a double-arch barrel vault as well as a few single-layer barrel vaults in a different study[10].

A parametric study of barrel vault shell structures looks at how various factors affect how these structures perform and behave. One of the factors that would alter these studies would involve the thickness of the shell. For a barrel vault structure, the efficiency, stability, and overall performance would be vastly affected by the thickness of the shell.

Shell thickness in the context of a barrel vault structure needs to be regarded as quite an important part. First, thicker shells support more significant weights, be it live or dead loads. Second, thicker shells enhance their stability by reducing buckling under large compressive stresses which is often quite critical for the integrity of a curved geometry. Moreover, thicker shells would bend and stretch to a lesser extent under load, which is important to maintain the shape of a structure for functional and aesthetic purposes. Finally, thicker shells have greater resistance to external variables such as wind, seismic activity, and temperature changes, which are important in increasing the life of the structure and reducing maintenance costs.

The objectives of the study, to understanding the effect of shell thickness on structural performance (e.g., stress levels, deformation, stability).

Parameters: Shell thickness variations- 1.5mm, 3mm, 6mm.

II. Material and Methods

A. Sample Collection

This research study identifies & concludes with the selection of case studies: The roofing structure on the Navi Mumbai Metro building is a special covering over its uppermost part which protects against rain, snow, heat, wind, and sunlight. Another rendered image showing the detailed specification of an elevated metro station for Navi Mumbai, Maharashtra from India. It spans 70 meters long and some 35 m wide. This truss system reaches a maximum height of 13.255 meter which means that there is plenty of space underneath it. Every 5 meters, a transverse truss is placed as reinforcement. Columns are arranged in two rows along the longitudinal axis at a spacing of 20 m from one another and each station has 8 columns, giving it well-balanced structure facets. Uniquely in this construction there is no brick infill incorporated; it makes the overall design a modern look.

The proposed Roofing structure is modelled as a space frame, The Following are the properties of sections used in the Structure:

TABLE I
PROPERTIES OF SECTION

Sr. No.	Properties of Section	Description
1	a)UC 254x254x89 with 230mm wide and 16mm thk. Top/bottom plate b)UC 254x254x73 with 230mm wide and 16mm thk. Top/bottom plate	Column
2	NB 250 (H)	Inclined Column
3	NB 200 (H)	Rafter & Tie members
4	NB 150 (H)	Rafter & Internal member of Truss
5	NB 125 (M)	Rafter & Internal member of Truss
6	NB 100 (M)	Rafter
7	NB 80 (M)	Rafter, Tie & Bracing members
8	NB 65 (M)	Tie & Internal member of Truss
9	NB 50 (M)	Internal member of Truss
10	NB 40 (M)	Internal member of Truss
11	Z-section	Purlins
12	12mm Φ	Sag rod

TABLE II
MATERIAL PROPERTIES

Material	Description
Concrete Grade	
• Concrete Grade	M40
• P. C. C. Grade	M14
Steel Grade	
• Structural Steel	Fy 310 & Fy 350
• Bolt Grade	8.8, 10.9, 12.9
• Reinforcement	Fe500, Conforming to IS 1786- 2008

Basic modeling and analysis is done in FEM software. The output of the analysis is taken into consideration for the design.

This document discusses the structural system, the various acceptance parameters to which it will comply, and the material standards that the construction will be expected to achieve as per the design intent.

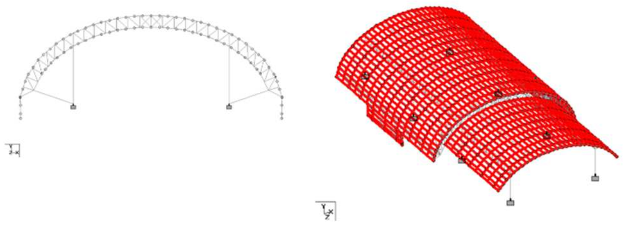

Fig. 1 Single layer Barel vault shell

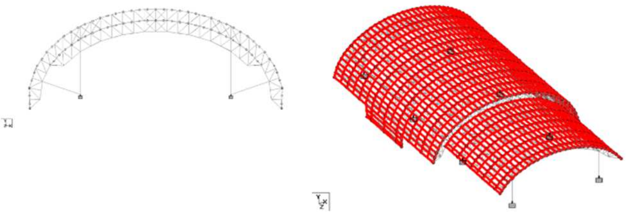

Fig. 2 Double layer Barel vault shell

B. Dead Load

Dead Load shall include weight of all Structural and system components. Self-weight of the materials shall be calculated on the basis of unit weight given in IS: 875-1987[11].

C. Live Load

The imposed load or otherwise live load is assessed based on the occupancy classifications as per IS: 875 (Part –2) – 1987.[12]

1) Live load on Purlin = 0.75kN/m2 (Table no.2 IS: 875 (Part –2) – 1987)

D. Wind Load

The imposed load or otherwise wind load is assessed based on the occupancy classifications as per IS: 875 (Part – 3) – 2015.[13]

The parameters for calculation of design wind speed as per IS: 875 (Part 3)- 2015 as follows:
(Mumbai Region)

Basic wind speed (Vb) = 44 m/s
Design life of the structure = 100 years
Risk coefficient (k1) (table-1) = 1.07
Terrain category = 2
Height of the structure above ground level = 25 m
Structure size factor k2 (table 2) = 1.095
Topography factor (k3) = 1.0
Importance factor for cyclonic region (k4) = 1.0
Design wind velocity (Vz) = Vb.k1.k2.k3.k4
= 51.55 m/sec

Depending upon k1.k2.k3 ,k4 values and windward, leeward coeff.
2
Design wind pressure at height 'z' (Pz) = 0.6 Vz
= 1.595 kN/m2

Wind directionality factor(Kd) = 1.0
Area averaging factor(Ka) = 1.0
Combination factor(Kc) = 0.9
Design wind pressure (pd) = Kd.Ka.Kc.pz
= 1.436 kN/m2

E. Temperature Load

Temperature loads due to seasonal and diurnal fluctuations may expected to affect the structure type to be adopted. The average seasonal temperature difference is considered as +/- 27° C for analysis of steel structure. Design temperature change is considered based on the difference between the maximum temperature(42°C) and mean temperature(27°C) or minimum temperature(10°C) and mean temperature(27°C) whichever is greater as per Fig.1 and Fig.2 of I.S. 875: Part-5-1987 We have considered ±17°C as the temperature difference during analysis of structure.[14]

F. Seismic Load

TABLE III
SEISMIC LOADS FOR THE DESIGN OF STRUCTURES SHALL BE CONSIDERED AS PER IS 1893-2016

Parameters	Values	IS 1893-Related Sections
Zone	Zone III	Figure 1 and Appendix E
Zone factor (z)	0.16	Cl. 6.4.2 and Table 3
Importance factor (I)	1.5	Cl. 7.2.3 and Table 8
Response reduction factor (R)	3	Cl. 7.2.6 Table 9
Damping	2%	Cl. 7.2.4
Analysis type	Equivalent Static Method	Cl. 7.6

III. RESULTS AND DISCUSSIONS

This work compares the analysis of single- and double-layer shell structures of varying thicknesses using FEM software. Variable thickness analysis shall be used to determine the stresses, moments, and forces that act on the surface of shells.

The output in regard to the stress element gives important parameters related to the behavior of shell structures under different conditions. Shear stresses, SQX and SQY, are a measure of the force per unit length and thickness acting along axes X and Y, locally. Membrane stresses, SX and SY, express the force per unit length and thickness along axes X and Y, showing that the material has some resistance to stretching or compressing; the in-plane shear stresses quantify the shearing forces within the same plane of the shell. The in-plane stress resultants, SXY, are combined with the moments per unit width, MX, MY, and MXY, to give a quantification of the bending and twisting forces that the shell is subjected to. Principal stresses, SMAX and SMIN, provide the maximum and minimum forces per unit area within the plane of the element; crucial for evaluating the structure's strength and overall performance.

Results for single-layer And double-layer barrel vault shell:

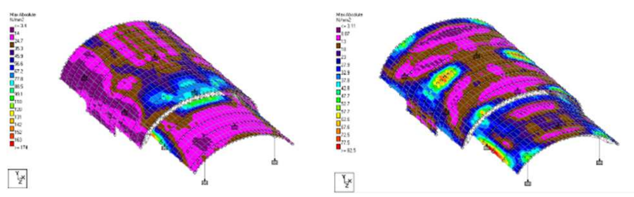

Fig. 3 Single- and Double-layer Shell Stress Contour for critical load case (DL+LL) *1.5

The red and orange regions indicate areas of high stress. These regions are likely to be the most critical points under the EQX load, potentially requiring reinforcement or design adjustments. The purple and blue regions represent lower stress areas. These areas are less critical and may not require significant structural changes.

A. For shear stress

For the Single Layer, For the Dead Load (DL) case, shear stresses in the X direction range from a maximum of 0.013 N/mm² to a minimum of -0.014 N/mm², and in the Y direction, from a maximum of 0.01 N/mm² to a minimum of -0.013 N/mm². Under Live Load (LL), the maximum shear stresses are 0.025 N/mm² in the X direction and 0.008 N/mm² in the Y direction, while the minimums are -0.025 N/mm^2 and -0.023 N/mm^2 respectively. For the Critical Load Case (1.5DL + 1.5LL), shear stresses peak at 0.053 N/mm^2 in the X direction and 0.023 N/mm^2 in the Y direction, with minimum values of -0.053 N/mm^2 and -0.062 N/mm^2. Shear stresses under Earthquake X (EQX) and Earthquake Z (EQZ) loads are zero in all directions.

For Double layer shell , For DL and LL, the maximum shear stresses in the X direction are 24.460 N/mm^2 and -25.598 N/mm^2, and in the Z direction, 13.362 N/mm^2 and -4.154 N/mm^2 respectively. Under the Critical Load Case, the maximum shear stress in the X direction is 10.622 N/mm^2, with a minimum of -49.854 N/mm^2. Shear stresses for earthquake loads are zero.

B. *Membrane Stresses*

For the Single Layer, For DL, membrane stresses reach a maximum of 38.019 N/mm^2 in the X direction and 34.257 N/mm^2 in the Y direction, and a maximum of 24.345 N/mm^2 in the XY plane. Minimums are -66.263 N/mm^2, -65.534 N/mm^2, and -27.399 N/mm^2 respectively. For LL, maximum membrane stresses are 121.352 N/mm^2 in the X direction, 103.35 N/mm^2 in the Y direction, and 74.442 N/mm^2 in the XY plane, with minimums of -171.717 N/mm^2, -169.99 N/mm^2, and -75.174 N/mm^2. Under the Critical Load Case (1.5DL + 1.5LL), maximum stresses rise to 249.295 N/mm^2 (X), 211.072 N/mm^2 (Y), and 148.427 N/mm^2 (XY plane), with minimums of -332.433 N/mm^2, -329.666 N/mm^2, and -149.872 N/mm^2. Earthquake loads (EQX and EQZ) produce very small stresses, with maximums of 0.005 N/mm^2 and 0.001 N/mm^2 and minimums near zero.

For the double layer shell , For DL, membrane stresses reach up to 11.834 N/mm^2 (X), 11.778 N/mm^2 (Y), and 5.686 N/mm^2 (XY plane). Minimums are -4.043 N/mm^2, -6.751 N/mm^2, and -5.728 N/mm^2. For LL, maximums are 25.343 N/mm^2 (X), 24.822 N/mm^2 (Y), and 11.582 N/mm^2 (XY plane), with minimums of -11.138 N/mm^2, -13.254 N/mm^2, and -11.756 N/mm^2. Under the Critical Load Case, stresses peak at 81.719 N/mm^2 (X), 80.52 N/mm^2 (Y), and 28.548 N/mm^2 (XY plane), with minimums of -18.55 N/mm^2, -26.425 N/mm^2, and -28.691 N/mm^2. Earthquake load cases produce very small membrane stresses, near zero.

C. *Bending Moments*

For the Single Layer, For DL, bending moments reach a maximum of 0.011 kNm/m (Mx), 0.005 kNm/m (My), and 0.005 kNm/m (Mxy). Minimums are -0.023 kNm/m, -0.013 kNm/m, and -0.005 kNm/m. In the LL case, maxima are 0.035 kNm/m (Mx), 0.012 kNm/m (My), and 0.005 kNm/m (Mxy), with minima of -0.04 kNm/m, -0.037 kNm/m, and -0.005 kNm/m. For the Critical Load Case, the maximum moments are 0.07 kNm/m (Mx), 0.023 kNm/m (My), and 0.015 kNm/m (Mxy), with minima of -0.081 kNm/m, -0.075 kNm/m, and -0.015 kNm/m. Earthquake load cases show zero moments in all directions.

For the double layer shell, For DL, the bending moments are up to 0.003 kNm/m (Mx), 0.001 kNm/m (My), and 0 (Mxy). Minimums are -0.002 kNm/m, -0.003 kNm/m, and 0. For LL, maximum bending moments are 0.002 kNm/m (Mx), 0.001 kNm/m (My), and 0 (Mxy), with minima of -0.001 kNm/m, -0.001 kNm/m, and 0. For the Critical Load Case, maximum moments are 0.003 kNm/m (Mx), 0.002 kNm/m (My), and 0.001 kNm/m (Mxy), with minimums of -0.003 kNm/m, -0.002 kNm/m, and -0.001 kNm/m. Earthquake loads show zero bending moments.

D. *Principal Stresses*

For the Single Layer, For DL, principal stresses at the top are up to 37.814 N/mm^2 and at the bottom 38.381 N/mm^2. Minimum values are -77.749 N/mm^2 and -80.629 N/mm^2. For LL, maximum principal stresses are 120.691 N/mm^2 (top) and 123.699 N/mm^2 (bottom), with minimums of -192.547 N/mm^2 and -197.82 N/mm^2. Under the Critical Load Case, maximum principal stresses are 247.62 N/mm^2 (top) and 254.343 N/mm^2 (bottom), while minimums are -378.048 N/mm^2 and -390.735 N/mm^2. EQX and EQZ cases show very small principal stresses, close to zero.

For double layer shell, For DL, maximum principal stresses are 12.607 N/mm^2 (top) and 12.665 N/mm^2 (bottom), with minimums of -6.991 N/mm^2 and -6.871 N/mm^2. For LL, maximums are 27.042 N/mm^2 (top) and 27.013 N/mm^2 (bottom), with minimums of -15.782 N/mm^2 and -15.163 N/mm^2. Under the Critical Load Case, maximum principal stresses rise to 82.111 N/mm^2 (top) and 82.458 N/mm^2 (bottom), and minimums are -30.358 N/mm^2 and -30.313 N/mm^2. Earthquake cases result in minimal principal stresses, near zero.

E. *Displacement*

Single Layer Shell (3 mm Thickness): Under critical loads (1.5DL + 1.5LL), horizontal displacements are very high, reaching up to 1176.111 mm in the X direction and 273.124 mm in the Z direction, with extreme vertical displacements up to 30.32 mm. Under standard loads (DL + LL), horizontal displacements are still significant, up to 46.111 mm (X) and 32.124 mm (Z), with vertical displacements ranging from -49.59 mm to 30.32 mm.

Double Layer Shell (3 mm Thickness): Displays significantly smaller displacements, with maximums of 24.460 mm (X) and 13.362 mm (Z) horizontally, and 10.622 mm vertically. The reduced displacements highlight its superior stability and performance under similar loading conditions.

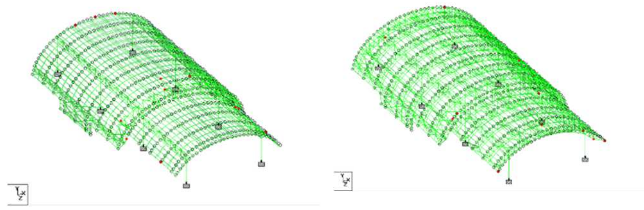

Fig. 4 Nodal displacement of Single and Double-layer

F. *Single Layer Barrel Vault*

The parametric study of the single-layer barrel vault shows that increasing shell thickness significantly impacts structural performance. Shear stresses rise from 0.013 N/mm^2 to 0.063 N/mm^2 and bending moments increase from 0.011 kNm/m to 0.125 kNm/m as thickness grows from 1.5 mm to 6 mm. Membrane stresses and displacements also increase with thickness, with displacements growing from 44.587 mm to 50.181 mm. Thicker shells enhance strength but result in greater deformation, highlighting the need to balance

TABLE IV
SHEAR STRESSES FOR SINGLE LAYER SHELL

Shear Stresses	1.5mm thickness		3mm thickness		6mm thickness	
	In X direction N/mm2	In Y direction N/mm2	In X direction N/mm2	In Y direction N/mm2	In X direction N/mm2	In Y direction N/mm2
For Dead load (DL) Case						
Max	**0.003**	**0.003**	**0.013**	**0.01**	**0.063**	**0.034**
Min	**-0.003**	**-0.003**	**-0.014**	**-0.013**	**-0.063**	**-0.058**
For Live load (LL) Case						
Max	**0.006**	**0.003**	**0.025**	**0.008**	**0.089**	**0.025**
Min	**-0.008**	**-0.007**	**-0.025**	**-0.023**	**-0.088**	**-0.055**
For Critical load Case 1.5DL+1.5LL						
Max	**0.013**	**0.007**	**0.053**	**0.023**	**0.211**	**0.085**
Min	**-0.014**	**-0.019**	**-0.053**	**-0.062**	**-0.209**	**-0.171**
For EQX Load case						
Max	**0.007**	**0.007**	**0**	**0**	**0**	**0**
Min	**-0.006**	**-0.006**	**0**	**0**	**0**	**0**

TABLE V
MEMBRANE STRESSES FOR SINGLE-LAYER SHELL

Membrane Stress	1.5 mm thickness			3 mm thickness			6 mm thickness		
	In X direction N/mm2	In Y direction N/mm2	In XY PlaneN/ mm2	In X direction N/mm2	In Y direction N/mm2	In XY PlaneN/ mm2	In X direction N/mm2	In Y direction N/mm2	In XY PlaneN/ mm2
For Dead load (DL) Case									
Max	**44.842**	**36.777**	**33.469**	**38.019**	**34.257**	**24.345**	**34.04**	**33.201**	**25.237**
Min	**-69.692**	**-70.65**	**-38.91**	**-66.263**	**-65.534**	**-27.399**	**-63.102**	**-61.271**	**-25.411**
For Live load (LL) Case									
Max	**186.847**	**143.5**	**97.269**	**121.352**	**103.35**	**74.442**	**73.759**	**69.46**	**53.334**
Min	**-128.261**	**-131.071**	**-103.127**	**-100.717**	**-109.99**	**-75.174**	**-117.566**	**-114.363**	**-53.681**
For Critical load Case 1.5DL+1.5LL									
Max	**164.108**	**179.417**	**183.999**	**149.295**	**111.072**	**148.427**	**168.177**	**156.262**	**117.723**
Min	**-113.811**	**-120.667**	**-101.474**	**-132.433**	**-129.666**	**-149.872**	**-254.222**	**-147.321**	**-118.61**
For EQX Load case									
Max	**0.007**	**0.004**	**0.004**	**0.005**	**0.004**	**0.003**	**0.003**	**0.003**	**0.002**
Min	**-0.006**	**-0.005**	**-0.005**	**-0.004**	**-0.004**	**-0.003**	**-0.003**	**-0.003**	**-0.002**
For EQZ Load case									
Max	**0.001**	**0.002**	**0.001**	**0.001**	**0.002**	**0.001**	**0**	**0.001**	**0.001**
Min	**-0.001**	**-0.002**	**-0.001**	**-0.001**	**-0.002**	**-0.001**	**-0.001**	**-0.001**	**-0.001**

TABLE VI
BENDING MOMENT FOR SINGLE-LAYER SHELL

Bending Moment	1.5 mm thickness			3 mm thickness			6 mm thickness		
	Mx kNm/m	My kNm/m	Mxy kNm/m	Mx kNm/m	My kNm/m	Mxy kNm/m	Mx kNm/m	My kNm/m	Mxy kNm/m
For Dead load (DL) Case									
Max	**0.001**	**0.001**	**0.001**	**0.011**	**0.005**	**0.005**	**0.125**	**0.045**	**0.043**
Min	**-0.003**	**-0.001**	**-0.001**	**-0.023**	**-0.013**	**-0.005**	**-0.204**	**-0.132**	**-0.043**
For Live load (LL) Case									
Max	**0.005**	**0.001**	**0.001**	**0.035**	**0.012**	**0.005**	**0.263**	**0.088**	**0.035**
Min	**-0.005**	**-0.005**	**-0.001**	**-0.04**	**-0.037**	**-0.005**	**-0.304**	**-0.281**	**-0.036**
For Critical load Case 1.5DL+1.5LL									
Max	**0.009**	**0.003**	**0.002**	**0.07**	**0.023**	**0.015**	**0.584**	**0.196**	**0.12**
Min	**-0.01**	**-0.009**	**-0.002**	**-0.081**	**-0.075**	**-0.015**	**-0.672**	**-0.624**	**-0.124**

structural capacity with flexibility when selecting shell thickness.

A. Double Layer Comparison

The analysis of double-layer barrel vaults shows that increasing shell thickness significantly impacts structural performance. Shear stresses for the double-layer shell increase from 0.003 N/mm² to 0.025 N/mm² as the thickness grows from 1.5 mm to 6 mm, compared to single-layer shells where shear stresses rise from 0.013 N/mm² to 0.211 N/mm². Membrane stresses in double-layer shells are lower, peaking at 94.569 N/mm² versus 183.999 N/mm² for single-layer shells. Bending moments also increase but are generally smaller in double-layer designs. Displacements are reduced in

TABLE VII

PRINCIPAL STRESSES FOR SINGLE-LAYER SHELL

Principal	1.5 mm thickness		3 mm thickness		6 mm thickness	
	Top N/mm2	Bottom N/mm2	Top N/mm2	Bottom N/mm2	Top N/mm2	Bottom N/mm2
For Dead load (DL) Case						
Max	**44.806**	**45.067**	**37.814**	**38.381**	**34.264**	**35.389**
Min	**-89.176**	**-91.587**	**-77.749**	**-80.629**	**-74.175**	**-77.141**
For Live load (LL) Case						
Max	**186.675**	**187.91**	**120.691**	**123.699**	**74.124**	**75.244**
Min	**-173.381**	**-176.195**	**-152.547**	**-197.82**	**-129.246**	**-134.56**
For Critical load Case 1.5DL+1.5LL						
Max	**163.755**	**166.269**	**147.62**	**154.343**	**169.656**	**171.765**
Min	**-115.64**	**-113.701**	**-178.048**	**-190.735**	**-189.721**	**-199.911**
For EQX Load case						
Max	**0.007**	**0.007**	**0.005**	**0.005**	**0.003**	**0.003**
Min	**-0.006**	**-0.006**	**-0.004**	**-0.005**	**-0.003**	**-0.003**
For EQZ Load case						
Max	**0.002**	**0.002**	**0.001**	**0.002**	**0.001**	**0.001**
Min	**-0.002**	**-0.002**	**-0.002**	**-0.002**	**-0.001**	**-0.001**

TABLE VIII

DISPLACEMENT FOR SINGLE-LAYER SHELL

Horizontal	L/C	1.5 mm thick shell		3 mm thick shell		6 mm thick shell	
		X mm	Z mm	X mm	Z mm	X mm	Z mm
Max	(DL+LL)*1.5	**44.587**	**31.12**	**46.111**	**32.124**	**50.181**	**35.619**
Min	(DL+LL)*1.5	**-44.334**	**-48.989**	**-46.76**	**-49.318**	**-50.288**	**-50.952**

TABLE IX

SHEAR STRESSES FOR DOUBLE-LAYER SHELL

Shear Stress	1.5 mm thick shell		3 mm thick shell		6 mm thick shell	
	In X direction N/mm2	In Y direction N/mm2	In X direction N/mm2	In Y direction N/mm2	In X direction N/mm2	In Y direction N/mm2
For Dead load (DL) Case						
Max	**0.003**	**0.003**	**0.01**	**0.01**	**0.024**	**0.024**
Min	**-0.001**	**-0.001**	**-0.002**	**-0.004**	**-0.009**	**-0.015**
For Live load (LL) Case						
Max	**0.001**	**0.001**	**0.003**	**0.002**	**0.01**	**0.009**
Min	**-0.001**	**-0.001**	**-0.003**	**-0.003**	**-0.01**	**-0.009**
For Critical load Case 1.5DL+1.5LL						
Max	**0.003**	**0.002**	**0.011**	**0.007**	**0.025**	**0.028**
Min	**-0.002**	**-0.002**	**-0.007**	**-0.007**	**-0.022**	**-0.028**

TABLE X

MEMBRANE STRESSES FOR DOUBLE LAYER SHELL

Membrane Stresses	1.5 mm thick shell			3 mm thick shell			6 mm thick shell		
	In X direction N/mm2	In Y direction N/mm2	In XY Plane N/mm2	In X direction N/mm2	In Y direction N/mm2	In XY Plane N/mm2	In X direction N/mm2	In Y direction N/mm2	In XY Plane N/mm2
For Dead load (DL) Case									
Max	**12.838**	**11.274**	**8.34**	**11.834**	**11.778**	**5.686**	**12.932**	**12.882**	**4.431**
Min	**-5.41**	**-7.969**	**-8.41**	**-4.043**	**-6.751**	**-5.728**	**-3.089**	**-6.398**	**-4.463**
For Live load (LL) Case									
Max	**34.642**	**30.572**	**20.148**	**25.343**	**24.822**	**11.582**	**20.168**	**20**	**6.881**
Min	**-19.549**	**-18.839**	**-20.434**	**-11.138**	**-13.254**	**-11.756**	**-6.048**	**-9.579**	**-6.998**
For Critical load Case 1.5DL+1.5LL									
Max	**94.569**	**93.178**	**45.01**	**81.719**	**80.52**	**28.548**	**67.674**	**66.758**	**18.537**
Min	**-27.807**	**-32.007**	**-45.372**	**-18.55**	**-26.425**	**-28.691**	**-11.69**	**-23.027**	**-18.592**
For EQX load Case									
Max	**0.003**	**0.003**	**0.002**	**0.002**	**0.003**	**0.001**	**0.001**	**0.002**	**0.001**
Min	**-0.004**	**-0.003**	**-0.002**	**-0.003**	**-0.002**	**-0.001**	**-0.003**	**-0.002**	**-0.001**
For EQZ load Case									
Max	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0**	**0.001**	**0**
Min	**-0.001**	**-0.002**	**-0.001**	**-0.001**	**-0.001**	**-0.001**	**-0.001**	**-0.001**	**0**

TABLE XI
BENDING STRESS FOR DOUBLE-LAYER SHELL

Bending Moment	1.5 mm thick shell			3 mm thick shell			6 mm thick shell		
	In X direction kNm/m	In Y direction kNm/m	In XY Plane kNm/m	In X direction kNm/m	In Y direction kNm/m	In XY Plane kNm/m	In X direction kNm/m	In Y direction kNm/m	In XY Plane kNm/m
For Dead load (DL) Case									
Max Mx	**0**	**0**	**0**	**0.003**	**0.001**	**0**	**0.017**	**0.006**	**0.002**
Min Mx	**0**	**0**	**0**	**-0.002**	**-0.003**	**0**	**-0.009**	**-0.017**	**-0.003**
For Live load (LL) Case									
Max Mx	**0**	**0**	**0**	**0.002**	**0.001**	**0**	**0.01**	**0.006**	**0.002**
Min Mx	**0**	**0**	**0**	**-0.001**	**-0.001**	**0**	**-0.011**	**-0.006**	**-0.002**
For Critical load Case 1.5DL+1.5LL									
Max Mx	**0**	**0**	**0**	**0.003**	**0.002**	**0.001**	**0.021**	**0.016**	**0.006**
Min Mx	**0**	**0**	**0**	**-0.003**	**-0.002**	**-0.001**	**-0.03**	**-0.017**	**-0.006**

TABLE XII
PRINCIPAL STRESSES FOR DOUBLE-LAYER SHELL

Principal Stresses	1.5 mm thick shell		3 mm thick shell		6 mm thick shell	
	Top N/mm2	Bottom N/mm2	Top N/mm2	Bottom N/mm2	Top N/mm2	Bottom N/mm2
For Dead load (DL) Case						
Max	**13.179**	**13.185**	**12.607**	**12.665**	**14.068**	**14.12**
Min	**-9.87**	**-9.637**	**-6.991**	**-6.871**	**-6.665**	**-6.273**
For Live load (LL) Case						
Max	**36.222**	**36.151**	**27.042**	**27.013**	**20.294**	**20.465**
Min	**-24.335**	**-24.318**	**-15.782**	**-15.163**	**-10.877**	**-9.903**
For Critical load Case 1.5DL+1.5LL						
-6.273	**96.297**	**96.44**	**82.111**	**82.458**	**68.473**	**68.287**
Min	**-46.536**	**-46.242**	**-30.358**	**-30.313**	**-24.7**	**-23.549**
For EQX load Case						
Max	**0.004**	**0.004**	**0.003**	**0.003**	**0.003**	**0.003**
Min	**-0.004**	**-0.004**	**-0.004**	**-0.004**	**-0.003**	**-0.003**
For EQZ load Case						
Max	**0.002**	**0.002**	**0.001**	**0.001**	**0.001**	**0.001**
Min	**-0.002**	**-0.002**	**-0.001**	**-0.001**	**-0.001**	**-0.001**

TABLE XIII
HORIZONTAL DISPLACEMENT FOR DOUBLE-LAYER SHELL

Horizontal	L/C	1.5 mm thick shell		3 mm thick shell		6 mm thick shell	
		X mm	Z mm	X mm	Z mm	X mm	Z mm
Max X	(DL+LL)*1.5	**22.955**	**13.762**	**24.460**	**13.362**	**26.602**	**12.855**
Min X	(DL+LL)*1.5	**-24.061**	**-4.709**	**-25.598**	**-4.154**	**-27.778**	**-3.632**

50.181 mm in single-layer shells. Double-layer shells offer enhanced structural efficiency with reduced deformations and stresses.

IV. CONCLUSION

The results in the analysis for single- and double-layer barrel vault shell structures with different parameters, considering thickness, can be summarized as follows: In the comparison of single- and double-layer constructions with a set of different thicknesses, that is, 1.5 mm, 3 mm, and 6 mm, at different loading circumstances, there is a considerable amount of structural change. Thicker layers have higher strength and stability, thus enabling loads to be dispersed with less bending of a structure. This makes them a better alternative for circumstances that require increased strength and durability. It is easy to see that the double-layered structure will resist load factors more appropriately for a single reason: there is more uniform stress distribution and reduced distortion. In general, they have reduced shear, membrane, and main stresses and, hence are more stable when under pressure. Single-layered constructions, on the other hand, often undergo greater stress and deformation, especially when higher loads are applied. Generally, doubled-layered designs offer more strength and durability.

REFERENCES

[1] R. Bradshaw, D. Campbell, M. Gargari, A. Mirmiran, and P. Tripeny, “Special Structures: Past, Present, and Future”, doi:10.1061/ASCE0733-94452002128:6691.

[2] A. Kaveh and M. Ilchi Ghazaan, “Optimal Design of Double-Layer Barrel Vault Space Structures,” in Meta-heuristic Algorithms for Optimal Design of Real-Size Structures, Springer International Publishing, 2018, pp. 85–99. doi: 10.1007/978-3-319-78780-0_6.

[3] Z. S. Makowski, Makowski ZS, editor. Analysis, design and construction of braced barrel vaults. . CRC Press, 1986.

[4] A. Kaveh, “Optimal Design of Double-Layer Barrel Vaults Using CBO and ECBO Algorithms,” in Applications of Metaheuristic Optimization Algorithms in Civil Engineering, Springer International Publishing, 2017, pp. 147–164. doi: 10.1007/978-3-319-48012-1_8.

[5] A. Kaveh, B. Mirzaei, and A. Jafarvand, “Optimal Design of Single-Layer Barrel Vault Frames Using Improved Magnetic Charged System

Search," 2013.
[6] A. Kaveh, B. Mirzaei, and A. Jafarvand, "Shape-size optimization of single-layer barrel vaults using improved magnetic charged system search," 2014.
[7] A. Kaveh, B. Mirzaei, and A. Jafarvand, "Optimal Design of Double Layer Barrel Vaults Using Improved Magnetic Charged System Search," 2014.
[8] A. Kaveh, "Optimal Design of Double-Layer Barrel Vaults Using CBO and ECBO Algorithms," in Applications of Metaheuristic Optimization Algorithms in Civil Engineering, Springer International Publishing, 2017, pp. 147–164. doi: 10.1007/978-3-319-48012-1_8.
[9] A. Kaveh and B. Eftekhar, "Optimal Design of Double Layer Barrel Vaults Using An Improved Hybrid Big Bang-Big Crunch Method," 2012.
[10] A. Kaveh and N. Shojaei, "Optimal design of barrel vaults using charged search system," 2012. [Online]. Available: https://www.researchgate.net/publication/287868671
[11] B. of Indian Standards, "IS 875-1 (1987): Code of Practice For Design Loads (Other Than Earthquake)For Buildings And Structures, Part 1: Dead Loads - Unit Weights of Building Material And Stored Materials (Incorporating IS 1911 : 1967)."
[12] B. of Indian Standards, "IS 875-2 (1987): Code of Practice for Design Loads (Other Than Earthquake) For Buildings And Structures, Part 2: Imposed Loads."
[13] Code of Practice for Design Loads for Building and Structures, Part-3 Wind Loads IS-875 (Part-3), 2015. Bureau of Indian Standards.
[14] Code of Practice for Design Loads for Building and Structures, Part-3 Wind Loads IS-875 (Part-3), 1987. Bureau of Indian Standards.