# PERFORMANCE OF REINFORCED CONCRETE MULTI-BAY BARREL VAULT SHELL STRUCTURE USING NONLINEAR STATIC ANALYSIS

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## ABSTACT

*Reinforced concrete barrel vault shell structures are widely used for large-span applications due to their efficiency in transferring loads with minimal material consumption. However, their nonlinear behavior under various loading conditions remains a subject of research. This study evaluates the performance of multi-bay reinforced concrete barrel vault shell structures using nonlinear static analysis. The research focuses on the structural response, stress distribution, deformation characteristics, and failure mechanisms under different loading conditions. Finite element modeling (FEM) is used to analyze the structure's behavior, and results are validated against experimental or previous analytical studies. The study identifies key parameters influencing structural performance and provides insights into optimizing the design of such vaults for enhanced strength and durability.*

***Keywords-*** *Multi-bay RC Shell, Pushover Analysis, SAP2000, Response of RC Shell under Non Linear Static Approach*

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## INTRODUCTION

### 1.1 Background

Reinforced concrete (RC) barrel vault shell structures are commonly used in industrial buildings, auditoriums, and hangars due to their high strength-to-weight ratio and aesthetic appeal. However, their structural behavior, particularly under nonlinear loading conditions, is complex due to material nonlinearity, geometric effects, and cracking patterns.

Reinforced concrete multi-bay barrel vault shell structures are widely used in civil engineering due to their ability to cover large spans without internal supports. These structures are often employed in industrial buildings, sports arenas, and other large facilities. The unique geometry of barrel vaults allows them to efficiently distribute loads, making them ideal for such applications.

A barrel vault is a continuous series of arches, forming a tunnel-like structure. When multiple such arches are connected, they form a multi-bay barrel vault. These structures are characterized by their curved geometry, which efficiently transfers loads through compression and tension. In reinforced concrete constructions, steel reinforcement is strategically placed to handle tensile stresses, while the concrete mass resists compressive forces.

### 1.2 Importance of Nonlinear Static Analysis

Nonlinear static analysis, also known as pushover analysis, is a method used to evaluate the performance of structures under increasing lateral loads. This type of analysis is particularly useful for assessing the seismic performance of structures. Unlike linear static analysis, which assumes that the structure's response is directly proportional to the applied loads, nonlinear static analysis accounts for the material and geometric nonlinearities that occur as the structure deforms.

Traditional linear analysis methods often fail to accurately predict the behavior of structures under extreme loading conditions, such as earthquakes. Nonlinear static analysis, commonly known as pushover analysis, addresses this limitation by considering the nonlinear behavior of materials and structural components. This method involves applying a monotonically increasing lateral load to the structure until a target displacement is reached, allowing for the assessment of the structure's performance beyond its elastic limit.

### 1.3 Application to Multi-Bay Barrel Vault Shell Structures

Applying nonlinear static analysis to multi-bay barrel vault shell structures involves several key steps:

- **Modeling the Structure:** A detailed three-dimensional finite element model is developed, incorporating the geometry, material properties, and boundary conditions of the structure. Software tools like SAP2000 are commonly used for this purpose.

- **Defining Load Patterns:** Lateral load patterns are defined based on the structure's fundamental mode shapes. The first mode lateral loading pattern is often adopted, as it represents the most significant mode of vibration under seismic forces.

- **Conducting Pushover Analysis:** The lateral loads are incrementally applied to the structure, and the resulting displacements and internal forces are recorded. This analysis helps in identifying potential failure mechanisms and assessing the structure's capacity to withstand seismic forces.

### 1.4 Comparison with Other Analysis Methods

To validate the results obtained from nonlinear static analysis, comparisons are made with linear static, linear dynamic, and nonlinear time history analyses. While linear methods may provide a quick assessment, they often underestimate the structure's true capacity under nonlinear behavior. Nonlinear time history analysis offers a more detailed evaluation by simulating the structure's response to actual earthquake records, but it is computationally intensive. Nonlinear static analysis strikes a balance by providing a reasonable approximation with less computational effort.

### 1.5. Key Findings and Recommendations

Studies have shown that nonlinear static analysis is effective in predicting the seismic performance of reinforced concrete multi-bay barrel vault shell structures. The analysis helps in identifying critical regions susceptible to failure and provides insights into the structure's overall behavior under seismic loading. It is recommended to incorporate nonlinear static analysis in the design and assessment of such structures to enhance safety and performance.

### 1.5. Key Findings and Recommendations

Studies have shown that nonlinear static analysis is effective in predicting the seismic performance of reinforced concrete multi-bay barrel vault shell structures. The analysis helps in identifying critical regions susceptible to failure and provides insights into the structure's overall behavior under seismic loading. It is recommended to incorporate nonlinear static analysis in the design and assessment of such structures to enhance safety and performance.

### 1.6. Methodology

The nonlinear static analysis of reinforced concrete multi-bay barrel vault shell structures involves several steps:

1. **Modeling the Structure**: The first step is to create a detailed finite element model of the structure. This model includes the geometry of the barrel vault, the material properties of the concrete and reinforcement, and the boundary conditions.
2. **Applying Loads**: The next step is to apply the loads to the model. In a pushover analysis, the structure is subjected to a gradually increasing lateral load pattern, typically representing seismic forces. The load is applied incrementally until the structure reaches a target displacement or collapses.
3. **Analyzing the Response**: As the loads are applied, the structure's response is monitored. This includes tracking the displacements, internal forces, and stresses in the structure. The analysis continues until the structure reaches its ultimate capacity.
4. **Interpreting Results**: The results of the analysis are used to evaluate the performance of the structure. This includes identifying the critical failure modes, such as yielding of the reinforcement, crushing of the concrete, or buckling of the shell. The capacity curve, which plots the base shear versus the roof displacement, is a key output of the analysis.

### 1.7. Performance Evaluation

The performance of reinforced concrete multi-bay barrel vault shell structures is evaluated based on several criteria:

1. **Strength**: The structure must have sufficient strength to resist the applied loads without collapsing. This is assessed by comparing the capacity curve to the demand curve, which represents the expected seismic forces.

2. **Ductility**: Ductility is the ability of the structure to undergo large deformations without losing its load-carrying capacity. This is important for ensuring that the structure can absorb and dissipate energy during an earthquake.

3. **Stiffness**: Stiffness is a measure of the structure's resistance to deformation. A stiffer structure will experience smaller displacements under the same load, which can reduce the risk of damage.

4. **Stability**: Stability refers to the structure's ability to maintain its overall shape and configuration under load. This includes preventing buckling of the shell and ensuring that the structure does not collapse in a sudden and catastrophic manner.

### 1.8. Case Studies

Several case studies have been conducted to evaluate the performance of reinforced concrete multi-bay barrel vault shell structures using nonlinear static analysis. These studies typically involve analyzing different configurations of barrel vaults, varying the material properties, and applying different load patterns.

One such study focused on the seismic performance of multi-bay cylindrical shell structures. The researchers used a finite element model to perform pushover analysis and compared the results with linear static, linear dynamic, and nonlinear time history analyses. The study found that nonlinear static analysis provided a more accurate prediction of the structure's seismic response, particularly for identifying the critical failure modes.

Another study examined the performance-based seismic design of reinforced concrete frames with shear walls. The researchers used nonlinear static analysis to evaluate the capacity curves of different structural configurations and identified the key factors affecting the performance of the shear walls.

### 1.9 Problem Statement

Despite extensive research on RC shell structures, the nonlinear behavior of multi-bay barrel vaults remains inadequately studied. The influence of load distribution, cracking, and reinforcement detailing on their performance requires further investigation.

### 1.11 Scope of the Study

The study focuses on nonlinear static analysis using numerical simulation tools like ANSYS, SAP2000 or ABAQUS etc. It considers different loading conditions, span lengths, reinforcement configurations, and shell thicknesses.

## LITERATURE REVIEW

**Vijay Kumar Shukla et. At. (2020) (1),** 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. 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.

**Qingqing Yu et. At. (2024) (2),** In this paper, we extend our previous work on the dynamic buckling analysis of isogeomet ric shell structures to the stochastic situation where an isogeometric deterministic dynamic buckling analysis method is combined with spectral-based stochastic modeling of geometric imperfections. To be specific, a modified Generalized-α time integration scheme combined with a nonlinear isogeo metric Kirchhoff–Love shell element is used to simulate the buckling and post-buckling problems of cylindrical shell structures. Additionally, geometric imperfections are constructed based on NURBS surface fitting, which can be naturally incorporated into the isogeometric analysis framework due to its seamless CAD/CAE integration feature. For stochastic analysis, the method of separation is adopted to model the stochastic geometric imperfections of cylindrical shells based on a set of measurements. We tested the accuracy and convergence properties of the proposed method with a cylindrical shell example, where measured geometric imperfections were incorporated. The ABAQUS reference solutions are also presented to demonstrate the superiority of the inherited smooth and high-order continuous properties of the isogeometric approach.

**Jianhui Si et. At. (2023) (3),** The research objective is to investigate the multi-span hyperbolic brick arch thin-shell structure located in Changleyuan, Baoji City, Shaanxi Province. The study utilizes on-site dynamic testing and finite element numerical simulation methods to analyze the dynamic characteristics of the thin-shell structure and its seismic response under various seismic waves and directions. The simulation results indicate the following findings: Vertical earthquakes cause more severe damage to structures compared to horizontal earthquakes. Bidirectional seismic excitation has a greater impact on the structure than unidirectional and three-dimensional seismic excitation. The obtained results provide a scientific basis for the seismic protection, reinforcement, and repair of this multi-span double-curved brick arch thin-shell structure.

RW factor to introduce inelastic behavior during the initial elastic design.

**Giuseppe Sciascia et. At. (2022) (4),** variable sti ness composites have been found to improve buckling performance and dynamic stability, and to tune the structures dynamic response by tailoring structural sti ness. Thus, in order to exploit this wider design space, e cient linear analysis tools have an important role in preliminary design of variable sti ness structures, enabling designers to nd more e ective solutions when considering prestressed dynamically excited aerospace components. Considering this, a multi-domain Ritz method for eigenfrequency, transient and dynamic instability analysis of prestressed variable sti ness laminated doubly-curved shell structures is presented. Working within the rst-order shear deformation theory, Sanders-Koiter shell kinematics allow general orthogonal surfaces to be modelled without further assumptions on the shallowness or on the thinness of the structure. The e ciency of the proposed Ritz method is granted by using Legendre orthogonal polynomials as displacement trial func tions, while exibility in modelling and design is given by penalty techniques that allow sti ened variable angle tow shell structures to be modelled as an assembly of Corresponding author Email address: Vincenzo.Oliveri@ul.ie (Vincenzo Oliveri) Preprint submitted to Thin-Walled Structures January 23, 2022 shell-like domains. The proposed approach is veri ed by comparison with published benchmark results and nite element solutions. Original solutions are presented for a prestressed sti ened variable angle tow shell structure, which show great accu racy with an order of magnitude fewer variables when compared to standard nite element procedures, proving the reliability and e ciency of the present method in dealing with the dynamic analysis of multi-part aerospace structures

**Wei-Xin Ren et. At. (1999) (5),** This paper investigates the elastic-plastic seismic behavior of long span cable-stayed steel bridges through the plane finite-element model. Both geometric and material nonlinearities are involved in the analysis. The geometric nonlinearities come from the stay cable sag effect, axial force-bending moment interaction, and large displacements. Material nonlinearity arises when the stiffening steel girder yields. The example bridge is a cable-stayed bridge with a central span length of 605 m. The seismic response analyses have been conducted from the deformed equilibrium configuration due to dead loads. Three strong earthquake records of the Great Hanshin earthquake of 1995 in Japan are used in the analysis. These earthquake records are input in the bridge longitudinal direction, vertical direction, and combined longitudinal and vertical directions. To evaluate the residual elastic-plastic seismic response, a new kind of seismic damage index called the maximum equivalent plastic strain ratio is proposed. The results show that the elastic-plastic effect tends to reduce the seismic response of long span cable-stayed steel bridges. The elastic and elastic-plastic seismic response behavior depends highly on the characteristics of input earthquake records. The earthquake record with the largest peak ground acceleration value does not necessarily induce the greatest elastic-plastic seismic damage.

## OBJECTIVE

1. To evaluate the nonlinear static response of RC multi-bay barrel vault shell structures.
2. To analyze stress distribution, deformation, and failure mechanisms.
3. To optimize reinforcement detailing for improved performance.
4. To compare finite element analysis (FEA) results with experimental or theoretical benchmarks.

## RESULTS

SAP2000 software is used to perform the Pushover and Nonlinear Dynamic Analysis of RC Shell Structure using displacement control strategy, where gravity load applied prior to the pushover analysis. The pushover analysis is performed for 6 analysis cases, as listed in Table 5.1.1.

**Table 5.1.1:** Loading direction and pattern for each pushover analysis case

| Analysis case | Loading direction | Loading pattern |
|---|---|---|
| 1 | X | Acceleration load |
| 2 | Y | Acceleration load |
| 3 | Z | Acceleration load |

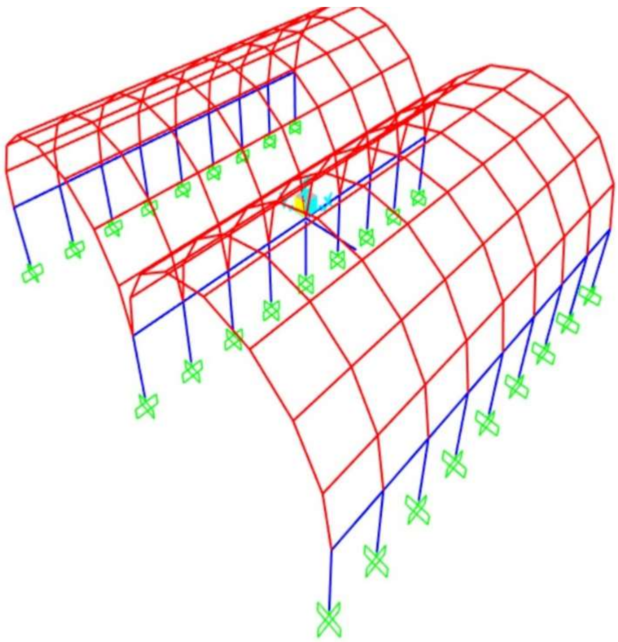


**Fig 15:** 3D model of Two Bay RC Shell Structure

**PARAMETER OF RC SHELL USED**

| | |
|---|---|
| Span in X direction | 36 m |
| Span in Y direction | 20 m |
| Thickness | 0.25 m |
| Dead Load + Live load | 2.5 kN/m$^2$ |
| Grade of Concrete | M-25 |
| Type of Steel | HYSD bars |
| Column Height | 6.0 m |
| Column Size | 0.6m X 0.6m |
| Column Longitudinal reinforcement | 1.5 % reinforcement |
| Column transverse reinforcement | 12d @ 150 centre to centre |
| Column Support condition | Fixed |
| Beam Size ( As Area Element) | 0.60 m x 0.6 m |
| Shell reinforcement | 8d @ 200 centre to centre in both-faces & in both-ways. |

**Table Parameter of RC Shell Structure**

**Table Displacement of RC shell For Different Analysis cases**

| Analysis Case | Displacement (m) | | |
|---|---|---|---|
| | X | Y | Z |
| DL + LL | 0.000194 | 0.063953 | 0.004799 |
| Quake (X,Y,Z) | 0.000043 | 0.048823 | 0.032899 |

## Maximum Rotation (In Joints) in X,Y & Z by Pushover Analysis Cases :

Maximum Rotation of Joints in RC shell Linear Analysis

| Analysis Case | Rotation (rad) | | |
|---|---|---|---|
| | Rx | Ry | Rz |
| DL + LL | 0.009328 | 0.000419 | 0.00502 |
| Quake (X,Y,Z) | 0.005526 | 0.00014 | 0.000141 |

## RESULT FROM PUSHOVER ANALYSIS OF RC SHELL STRUCTURE

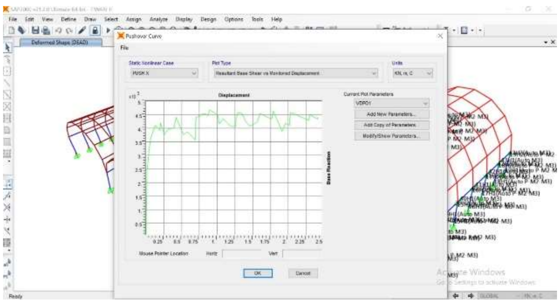


**Fig – Resultant Base Shear vs Monitored Displacement (PUSH X)**

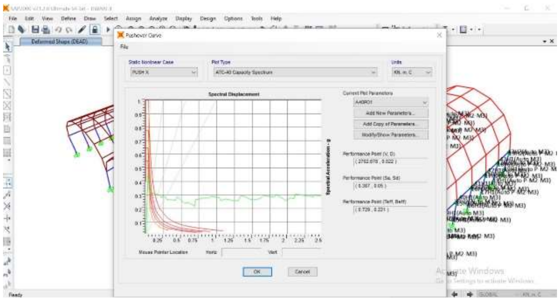


**Fig – ATC -40 Capacity Spectrum (PUSH X)**

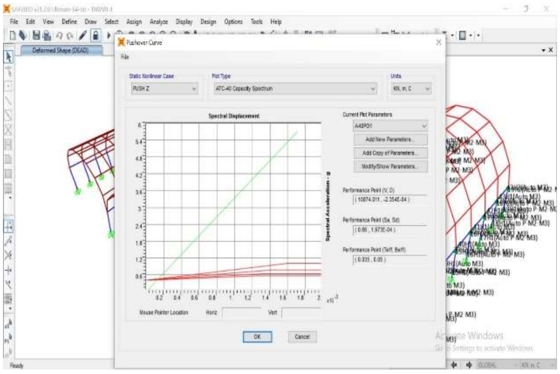


**Fig – ATC -40 Capacity Spectrum (PUSH Z)**

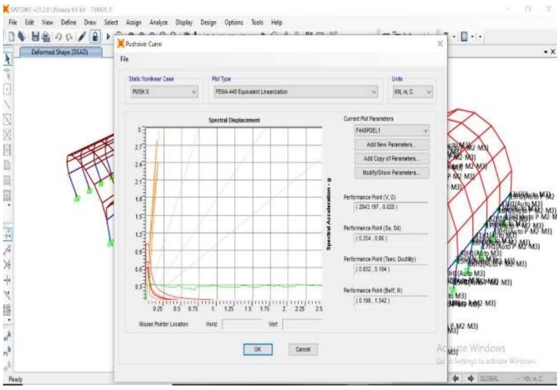


**Fig – Performance Point Base Shear vs Displacement as per FEMA 440 (PUSH X)**

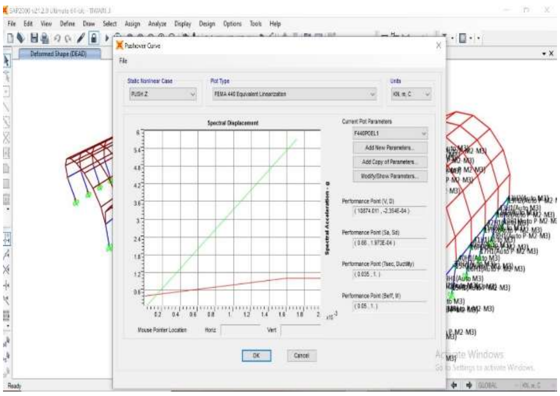


**Fig – Performance Point Base Shear vs Displacement as per FEMA 440 (PUSH Z)**

**Performance of RC Shell Structure:**

**Table** Performance point and Target Displacement of RC Shell

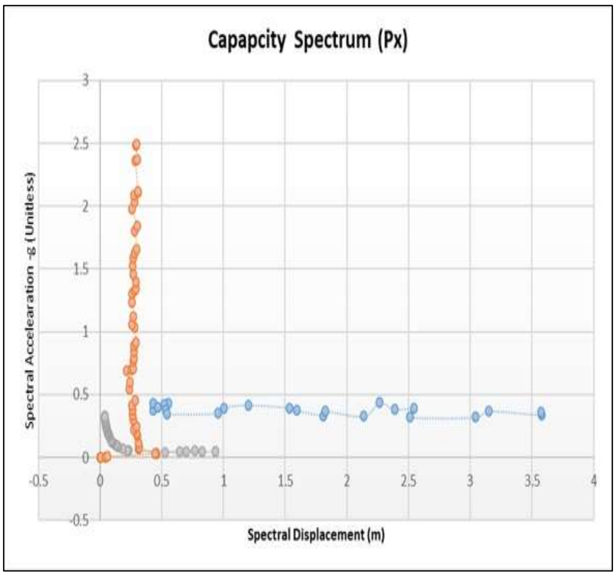
| Analysis Case | Performance Case | | Target | |
|---|---|---|---|---|
| | **Base Shear (kN)** | **Displacement (m.)** | **Base Shear (kN)** | **Displacement (m)** |
| Push X | 2702.678 | 0.222 | 2616.105 | 0.018 |
| Push Y | - | - | - | - |
| Push Z | 10874.011 | 0.000235 | - | - |

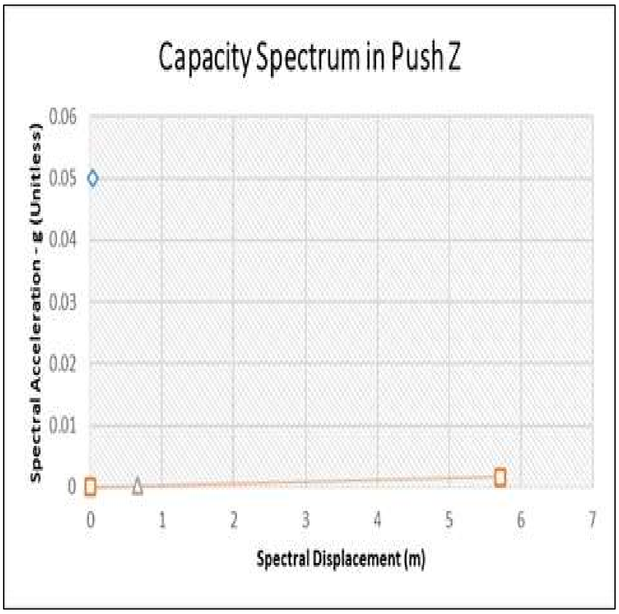
**Maximum Rotation (In Joints) in X,Y & Z by Pushover Analysis Cases :**

**Table** Maximum Rotation of Joints in RC shell For Different Analysis cases

| Analysis Case | Rotation (rad) | | |
|---|---|---|---|
| | **Rx** | **Ry** | **Rz** |
| Push X | 0.043042 | 0.000229 | 0.006723 |
| Push Y | 0.010741 | 0.000307 | 0.000695 |
| Push Z | 0.010821 | 0.000605 | 0.001438 |

**Capacity Spectrum Curve –**




**Comparison of Maximum Joint Reactions in Linear and Nonlinear Static Analysis**

| Type of Analysis | Type of Load | Fx (kN) | Fy (kN) | Fz (kN) | Mx (kN-m) | My (kN-m) | Mz (kN-m) |
|---|---|---|---|---|---|---|---|
| **Linear Analysis** | **DL + LL** | 3.56 | 184.19 | 1355.24 | 961.886 | 9.027 | 6.647 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Quake** | 0.41 | 74.781 | 54.427 | 465.895 | 1.34 | 4.351 |
| **Nonlinear Static Analysis** | **Push X** | 3.592 | 206.61 | 1483.30 | 698.13 | 269.89 | 254.76 |
| | **Push Y** | 3.524 | 119.37 | 1360.246 | 363.91 | 8.164 | 12.496 |
| | **Push Z** | 13.074 | 221.99 | 1360.246 | 363.91 | 43.047 | 24.07 |

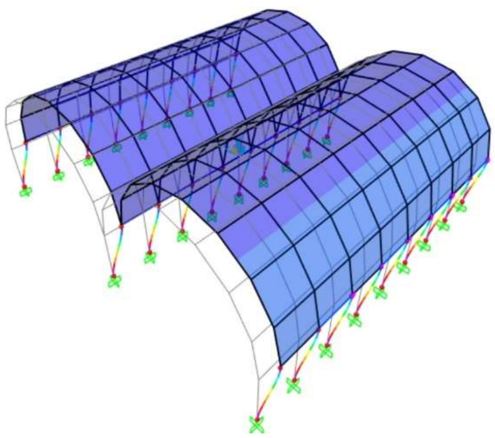


**Fig – Deformation of Multibay Shell Structure under PUSH X**

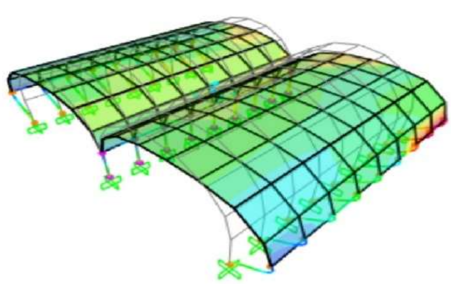


**Fig - Deformation of Multibay Shell Structure under PUSH Z**

# CONCLUSION

Based on the linear and nonlinear (pushover) analysis results of the RC multibay shell structure, the following conclusions are drawn:

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### *1. Displacement Response*

- **Linear Analysis:**
  - The maximum displacement occurs in the **Y-direction (0.063953 m)** under **DL + LL**, indicating the structure is more flexible in that direction under gravity loading.
  - Under **quake loads**, significant displacement is observed in the **Z-direction (0.032899 m)**, suggesting vertical components of seismic load have a noticeable effect.
- **Pushover Analysis:**
  - **Push X** produces the highest displacement of **2.349136 m in the X-direction**, showing substantial lateral flexibility under extreme conditions.
  - **Push Z** shows notable vertical displacement (**0.063399 m in Z-direction**), but it is far less than that from Push X in lateral direction, confirming directional stiffness variation.
  - **Push Y** results in **zero displacement**, indicating symmetry or insufficient lateral demand/load in that direction.

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*2. Joint Rotation Behavior*

- **Linear Analysis:**
  - The maximum rotation is observed in the **X-direction (Rx = 0.009328 rad)** for the **DL + LL** case.
  - Seismic (quake) cases result in reduced rotations, with all values under **0.006 rad**.
- **Pushover Analysis:**
  - A significant increase in rotation is observed, particularly under **Push X (Rx = 0.043042 rad)**, highlighting the inelastic deformation potential of the structure.
  - Lower joint rotations in **Push Y and Push Z** indicate these directions are less critical under pushover loading.

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*3. Seismic Performance and Capacity*

- The structure under **Push X** reaches a **base shear of 2702.678 kN** at a **displacement of 0.222 m**, which exceeds the **target displacement of 0.018 m**, suggesting the structure surpasses acceptable deformation thresholds in this direction.
- **Push Z** reaches a significantly high **base shear (10874.011 kN)** at very low displacement (**0.000235 m**), indicating strong vertical load resistance.

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*4. Joint Reaction Forces Comparison*

- From **linear to nonlinear analysis**, joint forces and moments increase significantly:
  - Fx and Fy rise from **3.56 kN / 184.19 kN** (DL + LL) to **13.074 kN / 221.99 kN** (Push Z).
  - Moment components, especially **Mx**, rise substantially in nonlinear analysis (e.g., from **961.886 kN-m** in linear to **698.13 kN-m** in Push X), showing redistribution under inelastic action.
  - Torsional moments (**Mz**) also increase, particularly under **Push X and Push Z**, suggesting potential torsional vulnerabilities.

**Overall Conclusion**

The RC multibay shell structure demonstrates **adequate stiffness and limited displacement under service (linear) loading**, but exhibits **significant nonlinear behavior under extreme seismic (pushover) loading**, especially in the **X-direction**. The analysis reveals that:

- The structure has **strong vertical resistance** (high base shear in Z).
- **Lateral performance in X-direction requires attention** due to excessive displacement and joint rotation.
- **Pushover analysis provides critical insights** into inelastic behavior not evident in linear analysis.

**Recommendation**: Reinforcement or design optimization in the X-direction is advised to enhance seismic performance and ensure compliance with displacement-based design criteria.

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