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Research Article

Investigation of the Structural Behavior of Barrel Vault Roofs on the Rigidity of Hinged and Moment Frames

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ABSTRACT

The aim of the present research is to investigate the structural behavior of barrel vault roofs on the rigidity of hinged and moment frames. In this study, by numerical modeling using ABAQUS software, a barrel vault roof is modeled on top of one-storey and two-storey structures with hinged and rigid (moment) connections, and is reinforced using cross-bracing methods under and above the roof, using secondary beams and a reinforced concrete slab.In this research, in-plane behavior of barrel vault roof under the vertical force on the roof or the vertical force on the roof beams has been investigated. According to the pushover analysis, a displacement load of about 5 cm is applied to the moment frame structure, and the analysis is performed to examine the stress, displacement, and strain. By around 0/8 seconds, the moment frame structure has completely yielded. There are several reasons for the yielding of the structure: the analysis time remained constant and progressed very slowly, the yield strength of steel materials is defined as 360 MPa, and when the structure's stress is examined, it is observed that the maximum stress has reached 360 MPa, occurring at the beam-column connections. The roof has also experienced severe stress. By performing a linear static pushover analysis on rigid and braced structures, both one-storey and two-storey, and reinforcing with cross-bracing, secondary beams, and a concrete slab, it was found that reinforcement with a concrete slab increases the stiffness of the structure in all cases. The secondary beam reinforcement method is effective in increasing the stiffness of two-storey structures in this study, but has a greater effect on the rigid two-storey structure. The cross-bracing method has no effect on reinforcing the structures.

Keywords: *Barrel Vault Roof, Rigidity of Hinged Frames, Moment and Hinged Frames, Structural Stress*

Introduction

One of the important and influential components on the behavior of buildings is diaphragms. Rigid diaphragms have sufficient strength and stiffness to distribute forces between vertical lateral load-bearing elements, but flexible diaphragms cannot effectively perform their role as distributors of lateral forces and distribute lateral loads proportional to their stiffness and strength. One of the common diaphragms in the country in previous decades is the barrel vault roof, which is considered a flexible diaphragm according to definitions (1).
The general weakness of traditional barrel vault roofs against earthquake vibrations is due to the lack of homogeneity and integrity. The separation of unsecured steel beams from each other causes the brick vaults to collapse. In roofs where the beams are connected to each other at certain points, especially at both ends, the separation of the beams from each other will not occur, and the roofs will have significant resistance to vibrations. It has been observed that the dynamic interaction of inhomogeneous elements, steel beams, and barrel vaults during strong earthquake vibrations can cause the destruction and collapse of the weaker element. This weaker element is usually the brick vault. Simple construction and implementation technology, no need for special training, availability of materials, high speed of execution, low cost, and roof stability under normal static conditions are advantages of the barrel vault roof. If the poor behavior of the roof against earthquakes

and the increase in its resistance to dynamic loads are considered, this roof can be considered as an engineered roof, with principles and design, one of the most suitable roofs to be implemented in Iran.
Alireza Mirjalili and colleagues (2009) stated that the in-plane stiffness of the barrel vault roof arises from the stiffness of the brick vault. Creating a separation in the brick vault, i.e., using secondary beams, leads to a reduction in the roof's stiffness (1).
Isa Salajagheh and colleagues (2013) stated that if the adhesion of gypsum and soil mortar with steel and the friction between the brick vault and the steel beam are neglected, the brick vault must be within a closed steel frame to have a significant effect on stiffness (2).
Mousa Mahmoudi Sahebi and colleagues (2009) arrived at a formula for roof rigidity (3).
Saeed Pourfalah and colleagues (2009) stated that the Standard 2800 method has no effect on out-of-plane resistance and is for collar-beaming the roof beams; the two-way slab method has higher efficiency (4).
Hamzeh Shakib and colleagues (2014) stated that in the in-plane seismic behavior of the barrel vault roof, this roof does not have sufficient shear capacity and cohesion; the use of diagonal belt and tension belt increases stiffness and shear capacity.
Maheri in 2003 conducted experiments on the materials of this type of roof and modeled this type of roof in the linear range and under vertical load using SAP90, introducing the two-way slab (2).
Haj Esmaeili and colleagues in 2001 tested the behavior of the barrel vault roof in unreinforced masonry buildings and focused on the effect of collar-beaming on the behavior factor of the structure (2).
Moienfar in 1968 suggested connecting the beams to each other with belt or rebar in a crossing pattern to overcome the weakness of the barrel vault roof against earthquakes (3).
Shakib and mirjalili in 2005 investigated the in-plane seismic behavior of the barrel vault roof. They stated that the use of diagonal belts and tension belt in the last span increases stiffness and shear capacity, but this added stiffness is not sufficient to meet the rigid diaphragm criterion (5).
The unsuitability of the roof system in masonry buildings is the cause of many collapses during earthquakes. The use of heavy materials or re-asphalting on roofs causes them to become heavier over time, which not only increases the lateral force on the building during an earthquake but also causes vertical vibration of the roof. The lack of rigid roofs with collar-beaming causes vertical cracks in the wall-to-wall connection or wall intersections and out-of-plane bending in the walls. Walls that become detached from other structural elements may even collapse when the building is subjected to moderate earthquakes. Flexible roofs can also cause cracking in deep lintels above openings.
Additionally, the presence of large openings in the roof has led to a reduction in diaphragm performance and severe damage. Excessive dimensions of the roof slab or a large ratio of span length to slab width are also factors that can cause roof flexibility and large out-of-plane deformations. Diaphragm failure alone is rarely observed during earthquakes, but because the behavior of the flexible roof diaphragm is like deep beams between bearing walls, in-plane rotation of the diaphragm end and improper shear transfer between the diaphragm and shear walls cause damage to the corners of the walls (2).
The failure to consider the actual behavior of the diaphragm leads to serious errors in the distribution of earthquake-induced forces. However, in designs with uncertain assumptions, the actual behavior of the diaphragm is overlooked. Given that a large number of retrofitting projects use barrel vault roofs as the horizontal member of the lateral load-bearing system, the aim of this research is to investigate the structural behavior of barrel vault roofs on the rigidity of hinged and moment frames.

Materials and Methods

Retrofitting Methods for Barrel Vault Roofs

a) The distance between steel beams should not exceed one meter.
b) The steel beams should be suitably connected to the horizontal collar beam. These beams should either be anchored within the collar beam or connected to steel plates placed on the reinforced concrete horizontal collar beam and anchored within the collar beam, or suitably tied to the steel collar beam.
c) The steel beams should be tied to each other with rebar or steel straps in a cross-bracing pattern, such that firstly, the length of the cross-braced rectangle does not exceed 1/5 times its width, and secondly, the area covered by each cross-brace does not exceed 25 square meters.
d) A suitable support should be provided for the last span of the barrel vault. This support can be provided by placing a steel profile and connecting it to the underlying collar beam, or by embedding it in a concrete collar beam. If this support is steel, it should be connected to the last roof steel beam with fully tensioned and straight rebars or straps at both ends of the beam, as well as at intervals of less than 2 meters.
e) The minimum cross-sectional area of the rebar or strap used for cross-bracing the roof steel beams or securing the last span should be a 14 mm rebar or an equivalent strap.

f) if secondary beams that are welded within the main roof beams in accordance with the provisions of the Eighth Topic of the National Building Regulations are used, it is not mandatory to comply with the stipulation of clause (c).

The bearing length of the beams of the barrel vault roof should not be less than the height of the beam or 20 centimeters, whichever is greater. Otherwise, the roof is considered vulnerable. If the ratio of length to width of the diaphragm span in flexible roofs exceeds 3, the diaphragm is vulnerable due to excessive deformations. Common flexible roofs in masonry buildings include barrel vault roofs, wooden roofs, and precast elements without a concrete topping. The presence of large openings in the roof reduces the ability of the roof to transfer lateral forces to the walls. The total area of openings should be less than 50 percent of the total diaphragm area, and the length of the opening adjacent to the load-bearing wall should be less than 25 percent of the wall length. The maximum length of the opening adjacent to load-bearing walls is 2 meters.

Findings:

1. Initial model analysis without reinforcement

In the first stage, based on the pushover analysis, a displacement-inducing load of about 5 centimeters is applied to the moment structure. The analysis is then conducted, examining stress, displacement, and strain. Within approximately 0/8 seconds, the moment structure is fully yielded. Several reasons contribute to the yielding of the structure. The analysis time remains constant and progresses very slowly. The stress value for structure's yielding in the steel material definition is 360 megapascals. When the structure's stress is examined, it is observed that the maximum stress has reached 360 megapascals after the structure has been yielded. This occurred at the connection point of the beam to the columns (Figure 1). The barrel vault roof has also experienced significant stress (Figure 2).

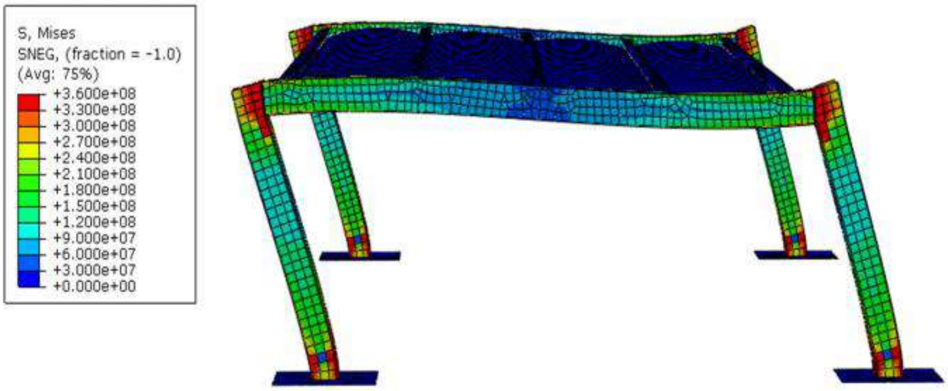

Figure 1: Stress analysis in the moment structure.

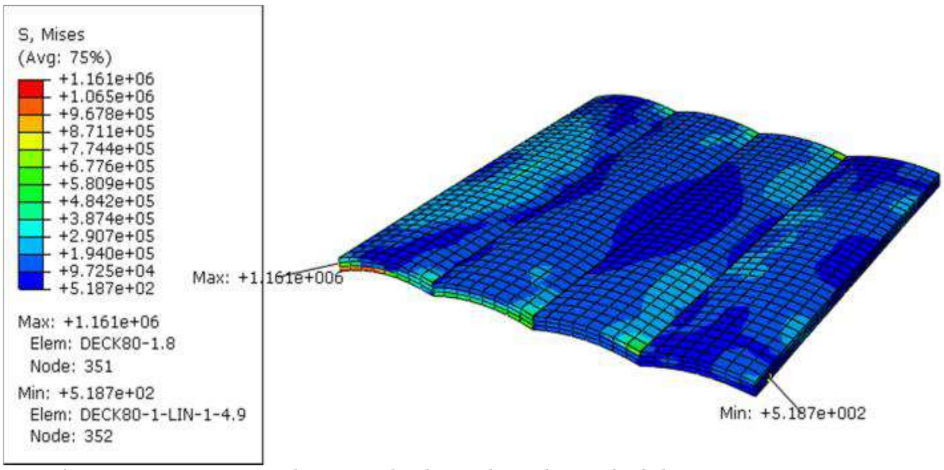

Figure 2: Stress analysis in the barrel vault roof of the moment structure.

The fact that the structural analysis proceeds very slowly at 0/8 seconds with a very low speed means that a very large strain has occurred in the structure and the structure has entered the nonlinear stage. If the equivalent plastic strain option is used, it can be seen that the strain is intensified at the beam-to-column connection and the connection is broken. This strain is about 2 centimeters, which is a significant amount (Figure 3).

A general view of the reciprocating motion of a two-storey moment structure under load application is shown in Figure 4.

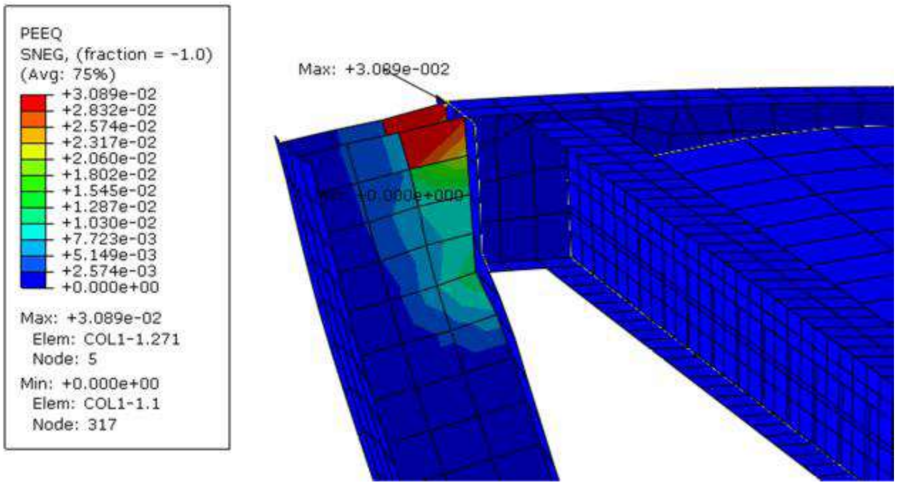

Figure 3: Investigation of severe strain at the beam-to-column connection

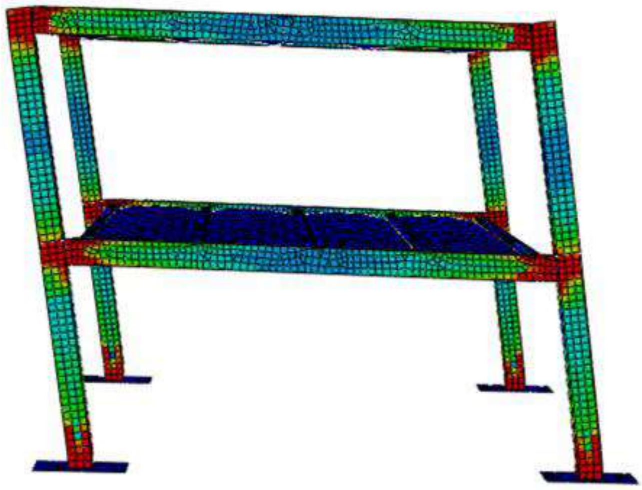

Figure 4: Showing the movement of a two-storey bending structure

In the braced structure as well, with the application of load, the structure has yielded, the maximum stress at the beam-to-column connection has reached 360 megapascals (Figure 5). The maximum displacement in the braces has occurred in the order of 2 centimeters, so the braces have buckled (Figure 6). There is also a large stress in the ceiling (Figure 7).

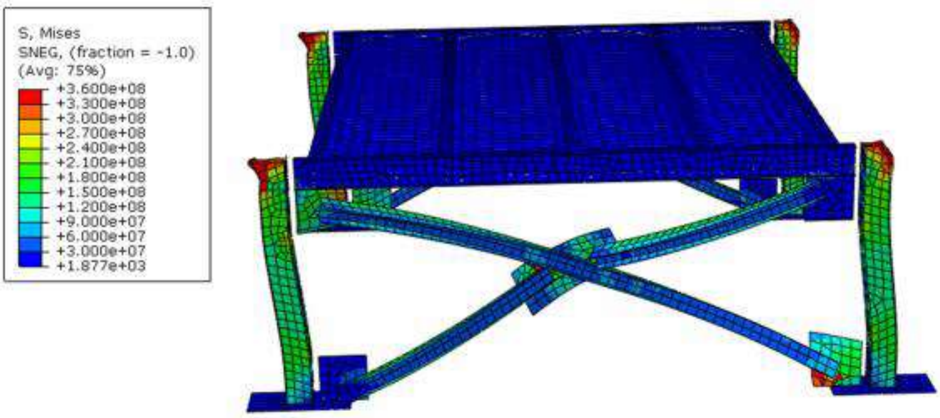

Figure 5: Stress analysis in the hinged structure

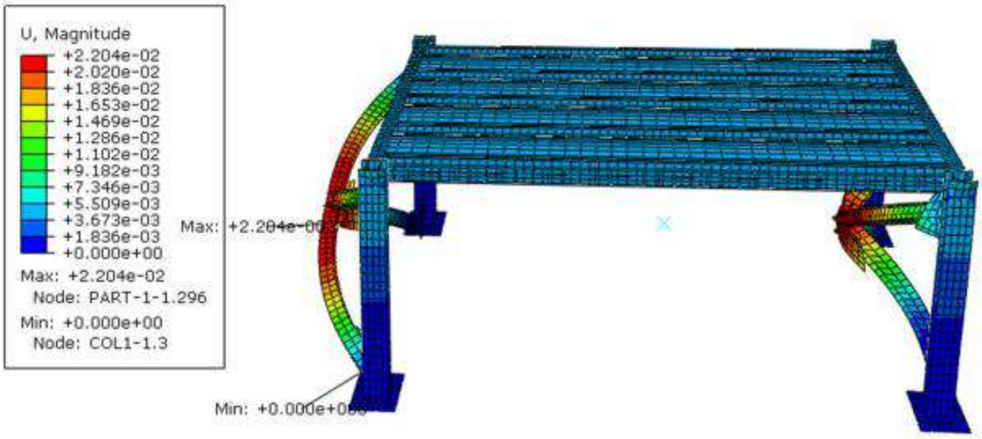

Figure 6: Investigation of buckling in the brace of the hinged structure

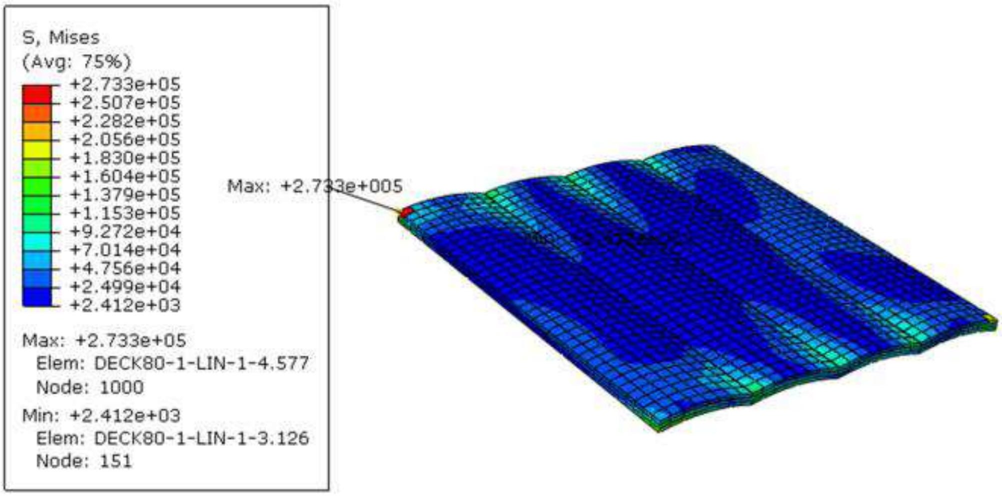

Figure 7: Stress analysis in the roof of the hinged structure

Results of pushover analysis

By performing a linear static pushover analysis, on rigid and braced structures, both single and double storey, and retrofitting with diagonal bracing and secondary beam and concrete slab, the displacement diagrams versus shear force are obtained (Figures 8 to 11).

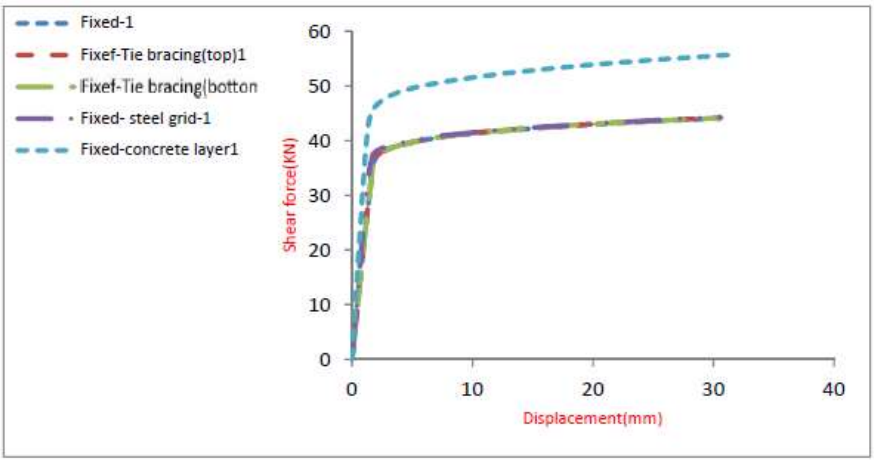

Figure 8: Pushover curve of the barrel vault roof in a single-storey rigid structure

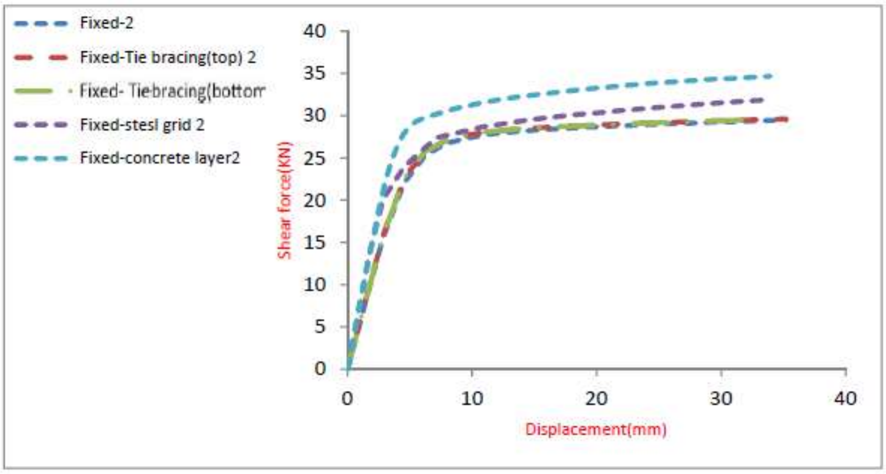

Figure 9: Pushover curve of the barrel vault roof in a two-storey rigid structure

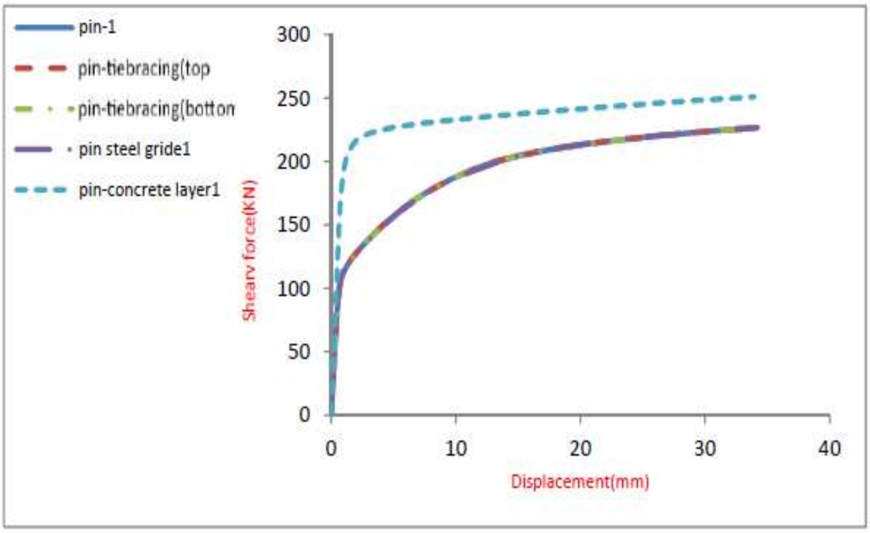

Figure 10: Pushover curve of the barrel vault roof in a single-storey braced structure

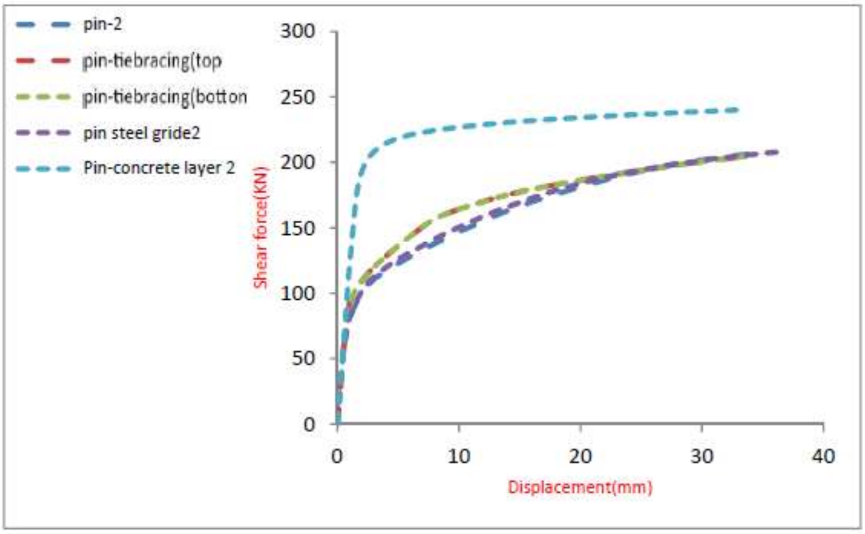

Figure 11: Pushover curve of the barrel vault roof in a two-storey braced structure

It can be seen from the diagrams that retrofitting with a concrete slab increases the stiffness of the structure in all cases, and the secondary beam retrofitting method is effective in the stiffness of two-storey structures, but it has a greater effect in two-storey rigid structures. The diagonal bracing method has no effect on the retrofitting of structures.

Conclusion:

According to the pushover analysis, the moment frame structure experiences a displacement load of around 5 centimeters, and the analysis examines the stress, displacement, and strain within it. By about 0/8 seconds, the moment frame has completely yielded. There are numerous reasons for the yielding of the structure; the analysis time remains constant and progresses very slowly. The yield stress value for steel material is defined as 360 MPa, and upon examining the structure's stress, it is observed that the maximum stress has reached 360 MPa, which occurred at the beam-column connections. The roof has also experienced severe stress.
The fact that the structural analysis progresses extremely slowly at 0/8 seconds indicates that a very large strain has occurred in the structure, and it has entered the nonlinear stage. If the equivalent plastic strain option is used, it can be seen that severe strain has occurred at the beam-column connections, and the connection has fractured. This strain is around 2 centimeters, which is a considerable amount.
In the braced frame, the structure has also yielded due to the applied load. The maximum stress at the beam-column connections has reached 360 MPa. The maximum displacement in the braces is around 2 centimeters, indicating that the braces have buckled. The roof has also experienced significant stress.
By performing a linear static pushover analysis on the rigid and braced frames, both single-storey and two-storey, with diagonal bracing, secondary beams, and concrete slabs for retrofitting, force-displacement plots are obtained. The plots show that retrofitting with concrete slabs increases the stiffness of the structures in all cases. The secondary beam retrofitting method is effective in increasing the stiffness of two-storey structures, but it has a greater effect on the rigid two-storey structure. The diagonal bracing method has no effect on retrofitting the structures.
It is recommended to investigate the behavior of the retrofitted barrel vault roof in the direction of the roof beams; for example, in the direction of the beams, the displacement of the roof is less due to the restraint at the end of each beam by the end collar beam, compared to when the displacement is examined perpendicular to the beams, where there is no restraint, resulting in larger displacement. It is also suggested to study the behavior of the barrel vault roof with two and three spans in two and three-storey moment and hinged frames.

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