

# Seismic Behavior of Masonry Cloister Vaults

*Comportamiento sísmico de bóvedas de claustro de mampostería*

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## Abstract

This paper presents the results of an investigation into earthquake resistance and the behavior of historical masonry cloister vaults. In a previous paper,<sup>1</sup> the authors presented a simplified structural analysis approach, called the 'strip method of analysis,' to assess the lateral load behavior of a relatively shallow cloister vault. In this paper, two cloister vaults with the same span but with different crown heights are studied. The vault material is assumed to be elastic and a linear thin shell F.E.A. is used for analysis under gravity loads and seismic loads. Nodal reaction components and diaphragm shears are compared for the two cloister vaults, along with those obtained using the strip method of analysis. A compression surface is determined for a selected finite element strip based on in-plane compression forces and out-of-plane bending moments. This is to indicate where tensile stresses will develop due to bending and hence where the vault will develop cracking and go into a limit state. The results include contour plots of membrane stresses, shear stresses, bending stresses and deformations in the masonry cloister vaults under gravity and lateral loads, as well as a representation of the lateral load resistance mechanism of masonry cloister vaults when subjected to earthquakes.

**Keywords:** historical masonry vaults, earthquake resistance, cloister vaults, funicular vaults, structural analysis

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<sup>1</sup> Satwant Rihal and John Edmisten, "Funicular Forms and Earthquake Performance of Low-Strength Masonry Buildings," (ICSA Conference Proceedings, Portugal, July 2013).

## Resumen

Este artículo presenta los resultados de una investigación sobre resistencia sísmica y el comportamiento de bóvedas de claustro de mampostería históricas. En un artículo previo, los autores presentaron un acercamiento a un análisis estructural simplificado, denominado el “análisis del método de banda,” para determinar el comportamiento de carga lateral de una bóveda de claustro con flecha relativamente pequeña. En este artículo, se estudiaron dos bóvedas de claustro con el mismo claro pero con diferentes flechas. El material de la bóveda se asume como elástico y se aplica un análisis del elemento finito lineal para el análisis bajo cargas de gravedad y cargas sísmicas. Se comparan las componentes de las reacciones en los nodos y los cortantes de diafragma en dos bóvedas de claustro, con los resultados obtenidos usando el análisis del método de banda. Se determina una superficie a compresión para la banda de elemento finito seleccionada con base a fuerzas de compresión sobre un plano y momentos flectores fuera del plano. Esto es para indicar dónde se desarrollarán esfuerzos de tensión debidos a la flexión y consecuentemente donde la bóveda desarrollará grietas y alcanzará un estado límite. Los resultados incluyen los trazos del contorno de los esfuerzos de membrana, de los esfuerzos cortantes, de los esfuerzos a flexión y las deformaciones en las bóvedas de claustro de mampostería bajo cargas gravitacionales y laterales, y así como una representación del mecanismo de resistencia de carga lateral de las bóvedas de claustro de mampostería cuando son sometidas a sismos.

**Palabras clave:** bóvedas históricas de mampostería, resistencia sísmica, bóvedas de claustro, bóvedas de cañon, análisis estructural

## Introduction

Historic masonry vaults have been an integral part of the rich architectural heritage of Europe, the U.K., U.S.A., Latin America and beyond. A significant portion of these low-strength masonry vaults are located in seismic zones. The widespread inventory of cloister vaults in historic structures around the world requires an examination of their performance and behavior during recent destructive earthquakes and the lessons that can be derived therefrom. The observed damage data on historic vaults and domes from past destructive earthquakes suggests that low-strength masonry vault structures provide improved performance during severe earthquakes. In general, the state of knowledge of the performance and behavior of low-strength masonry buildings has advanced a great deal during the past several decades. Despite these advances in the state of knowledge, there is a need for practical structural analysis approaches to understanding the seismic resis-

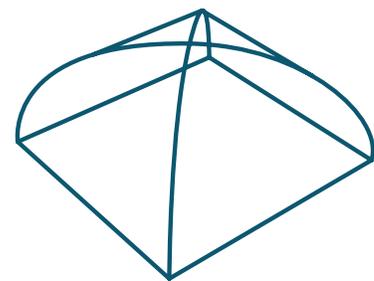


Figure 1: Cloister Vault.

tance mechanism of historic masonry cloister vaults. A cloister vault is defined as a structure consisting of four singly curved surfaces intersecting along ridges that span diagonally across to opposite corners of a square plan, as shown in figure 1. The ridges meet at the crown of the vault (the high point).

### Previous work

In a previous paper,<sup>2</sup> the authors used a simplified structural analysis approach, known as the strip method of analysis, to assess the gravity and lateral load behavior of a cloister vault. This vault was relatively shallow, that is, the crown-height-to-span ratio was low. The authors were interested in diaphragm action and out-of-plane bending in the vault. Diaphragm action consists of in-plane resistance of shear forces in the planes of the vault that are parallel to the applied lateral loads. Out-of-plane bending was assumed to be prevalent in planes perpendicular to the motion of the lateral loads. Tensions due to bending, combined with shear forces, would be an indication of the limit state of the cloister vault.

### Performance of historic masonry vaults during earthquakes

Widespread devastation, loss of life and significant damage have affected cultural heritage structures during the many catastrophic earthquakes that have struck Italy, e.g. Friuli 1976, L'Aquila 2009, Emilia Romagna 2012 and others. Extensive data on the damage observed on masonry vaults during these devastating earthquakes in Italy has been collected over the years. The observed damage and performance evaluation of churches during the 2012 Pianura Padana Emiliana earthquake was reported by Maurizio Indirli, Marghella and Anna Marzo.<sup>3</sup> An overview of the damage and performance evaluation of masonry churches in the 2009 L'Aquila earthquake has been presented by Giuseppe Brandonino, Giuseppe Lucibello, Elena Mele and Antonello de Luca.<sup>4</sup> A survey of the damage to cultural heritage structures in the 2009 L'Aquila and 2012 Emilia Romagna earthquakes has been presented by Fluvio Parisi and

- 2 Rihal and Edmisten, "Funicular Forms and Earthquake Performance of Low-Strength Masonry Buildings".
- 3 Maurizio Indirli and others, "Damage and collapse mechanisms in churches during the Pianura Padana Emiliana earthquake," (ENEA, Italy, 2012).
- 4 See: Giuseppe Brandonino and others, "Damage and performance evaluation of masonry churches in the 2009 L' Aquila earthquake," *Engineering Failure Analysis* 34 (2013): 693-714.

Nicola Augenti.<sup>5</sup> Furthermore, the observed damage of the cross vaults in the Cathedral of Modena during the 2012 Emilia, Italy earthquake and a detailed study of its seismic behavior and safety has been carried out and presented by Tomaso Trombetti, Simonetta Baracanni, Stefano Silvestri, Giada Gasparini and Michele Palermo.<sup>6</sup>

A significant knowledge base of the observed damage to historic masonry vaults is further provided by the observed damage data from destructive earthquakes in Portugal, Turkey, Greece, Iran and India, among others, in recent decades.

### Lateral (seismic) load analysis

The authors are interested in developing a better understanding of the mechanism of earthquake resistance and seismic behavior in low-strength masonry cloister vaults. The cloister vaults selected for analysis have a square plan configuration and variable height, as shown in figures 2 and 3.

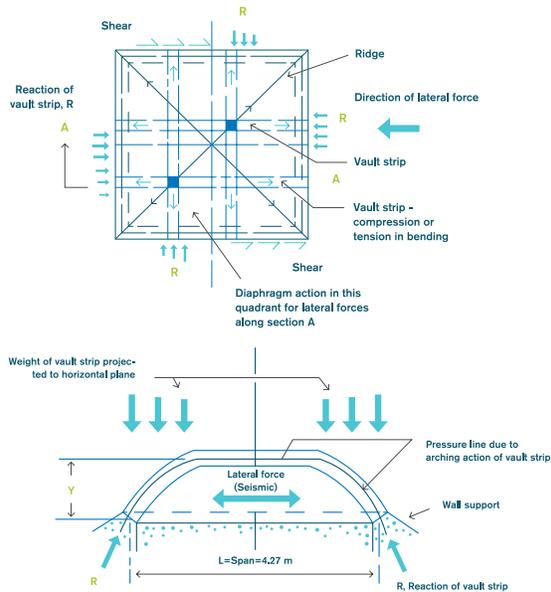


Figure 2: Plan View of Cloister Vault.

Figure 3: Section A-A View of Cloister Vault.

- 5 See: Fulvio Parisi and Nicola Augenti, "Earthquake damages to cultural heritage constructions and simplified assessment of artworks," *Engineering Failure Analysis* 34 (2013): 735-760.
- 6 Tomaso Trombetti and others, "Structure Safety of the Modena Cathedral," (SAHC 2014: 9<sup>th</sup> International Conference on Structural Analysis of Historical Constructions, Mexico City, October 14-17, 2014); and Simonetta Baraccani and others, "The Assessment of the Seismic Behavior of the Cathedral of Modena, Italy," (Second European Conference on Earthquake Engineering and Seismology, Istanbul, Turkey, August, 2014).

**Assumptions:**

Material: For the purpose of this investigation, masonry is assumed to be 'unfired brick' / 'adobe.'

Density: Assumed to be 18.84 kN/m<sup>3</sup>

Strength Properties:  $f'_m = 1033.62 \text{ kN/m}^2$ ;  
 $f'_b = 207.90 \text{ kN/m}^2$ ;  
 $f'_v = 137.88 \text{ kN/m}^2$

Allowable Stresses:  $f_c = f_m = 516.81 \text{ kN/m}^2$ ;  
 $f_b = 103.95 \text{ kN/m}^2$ ;  
 $f_v = 68.94 \text{ kN/m}^2$

Modulus Elastic:  $E = 344704 \text{ kN/m}^2$

Seismic loading for seismic analysis is based on an approximate Peak Ground Acceleration (PGA) of 0.25g. Therefore, lateral (seismic) loading is applied as equivalent to 25% of the weight of the vault system.

**Strip method of analysis**

In this practical analysis method, the vault is assumed to be divided into a series of parallel strips, as shown in figure 4. Each of the strips is assumed to act as an arch spanning the edge supports and the diagonals. A free-body diagram of a typical arched strip is also presented in the lower part of figure 4.

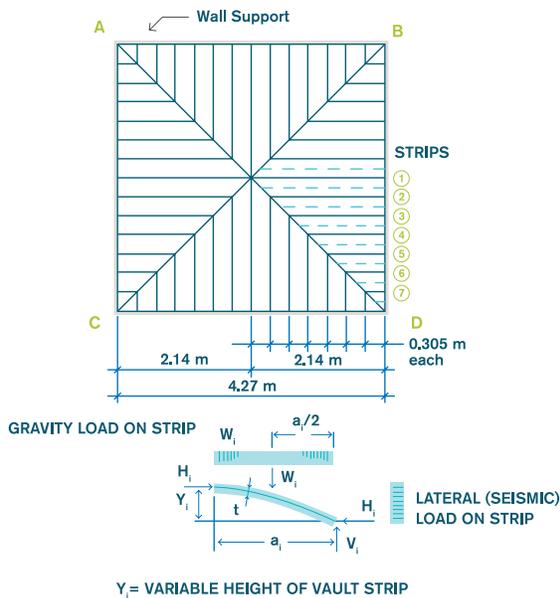


Figure 4: Plan View - Cloister Vault - Strip Method of Analysis.

Based on the mass distribution along the finite arched strips, the seismic loads were assumed to be 25% of the strip weight and the resulting seismic load distribution for the strips was determined for 0.574m and 1.07m high cloister vaults, as presented in figure 5.

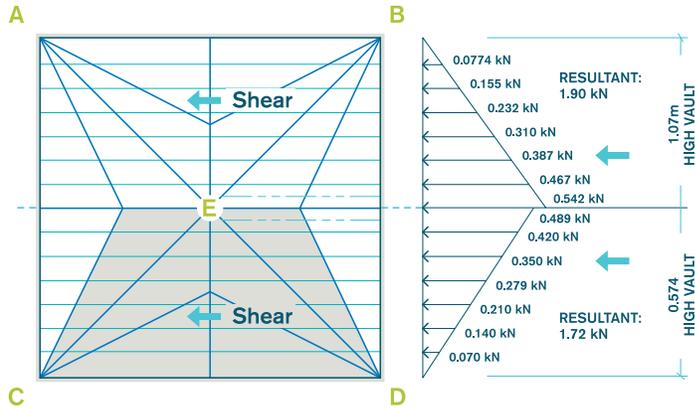


Figure 5: Plan View - Cloister Vault - of Lateral (Seismic) Loads - Strip Method Shaded area indicates tributary loading for diaphragm action.

### Finite element model

A 3D finite element analysis model of the cloister vault was developed for each of the two masonry cloister vaults using SAP 2000 software,<sup>7</sup> and thin shell elements with the masonry properties defined above. The undeformed geometry of the 3D F.E.A. model of a cloister vault with a height of 1.07m is presented in figure 6.

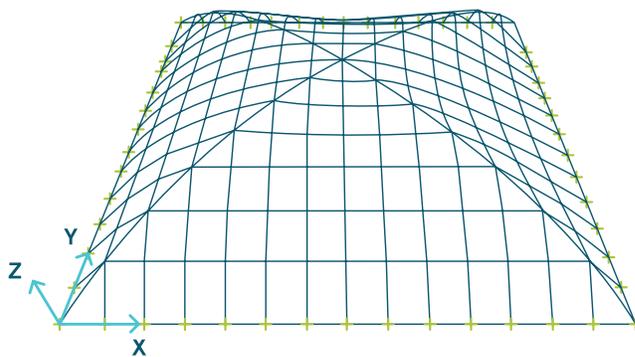
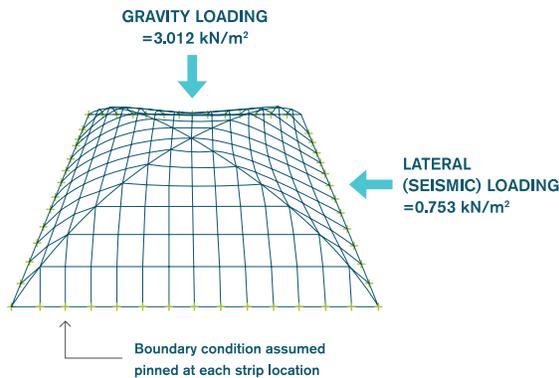


Figure 6: 3D Finite Element Model of Cloister Vault - Undeformed Shape.

7 SAP2000, Computers and Structures, Inc., Walnut Creek, California.

### Results

The masonry cloister vaults of the two proportions investigated, i.e. heights of 0.574m and 1.07m with the material properties defined above, were analyzed using SAP 2000 under the action of gravity and lateral (seismic) loads. The typical deformed shape of the 1.07m high cloister vault obtained from the 3D F.E.A. model structural analysis is presented in figure 7.



Max. Horizontal Deflection for 0.574m Vault=0.063mm  
Max. Horizontal Deflection for 1.07m Vault=0.106mm

Max. Base Shear for 0.574m Vault = 14.68 kN  
Max. Base Shear for 1.07m Vault = 17.09 kN

Figure. 7: Deformed Shape of Cloister Vault – 3D F.E.A. Model - Dead Load Plus Lateral (Seismic) Loading.

The horizontal and vertical reactions to gravity loads are compared using the strip method and the F.E.A. model for the two vault heights in figures 8 and 9. The F.E.A. model shows lower maximum values at the centerline strip and distribute more across adjacent strips.

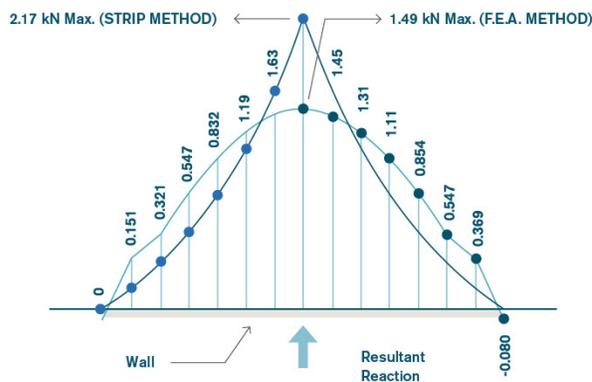


Figure 8: 1.07m High Cloister Vault – Plot of Horizontal Reactions – Perpendicular to Walls – Under Gravity Loading – Strip Method vs. 3D F.E.A. Method.

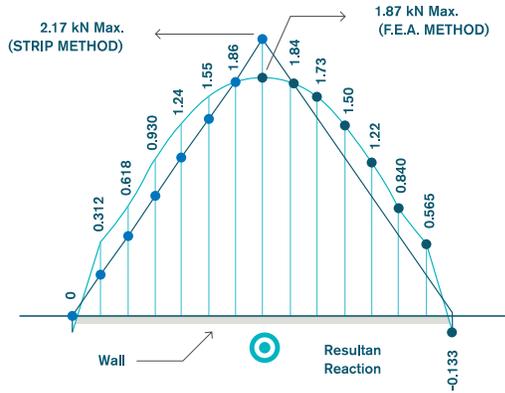


Figure 9: 1.07m High Cloister Vault – Plot of Vertical Reactions – Under Gravity Loading – Strip Method vs. 3D F.E.A. Method.

The distribution of seismic force in the walls parallel to the lateral force is presented in figure 10; diaphragm action can be seen in the vault planes connected to the walls. Diaphragm action appears to be greater in the 1.07m high vault due to its greater weight.

The distribution of seismic force in the walls perpendicular to the lateral force is presented in figure 11 for across the wall shears on top of the walls. It can be noted that the 1.07-meter-high vault has smaller reactions at or near the centerline of the vault. It appears that this vault is more ‘flexible’ when bending.

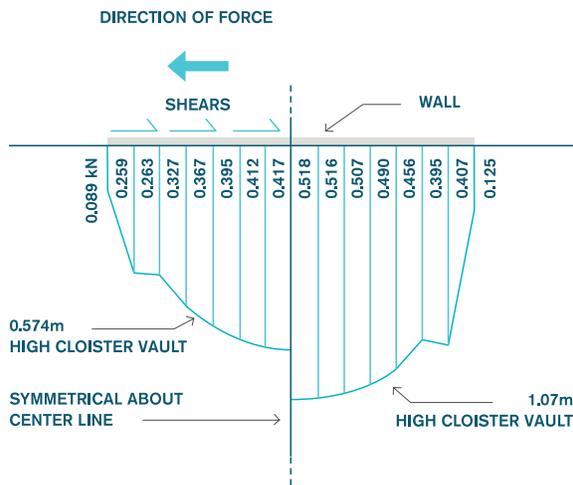


Figure 10: Plots of Shears along Supports – Lateral (Seismic) Loading F.E.A. Method - 0.574m vs. 1.07m High Cloister Vaults.

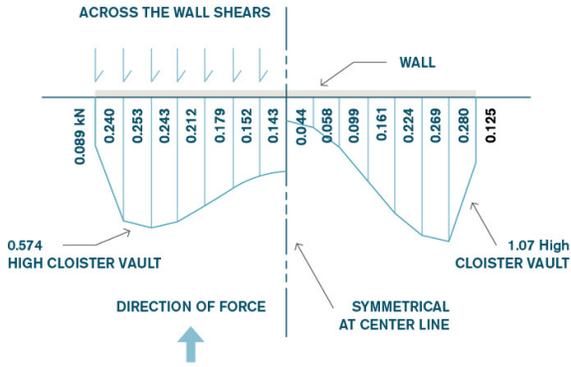


Figure 11: Plots of Shears across the Wall Support – Lateral (Seismic) Loading F.E.A. Method - 0.574m vs. 1.07m High Cloister Vaults.

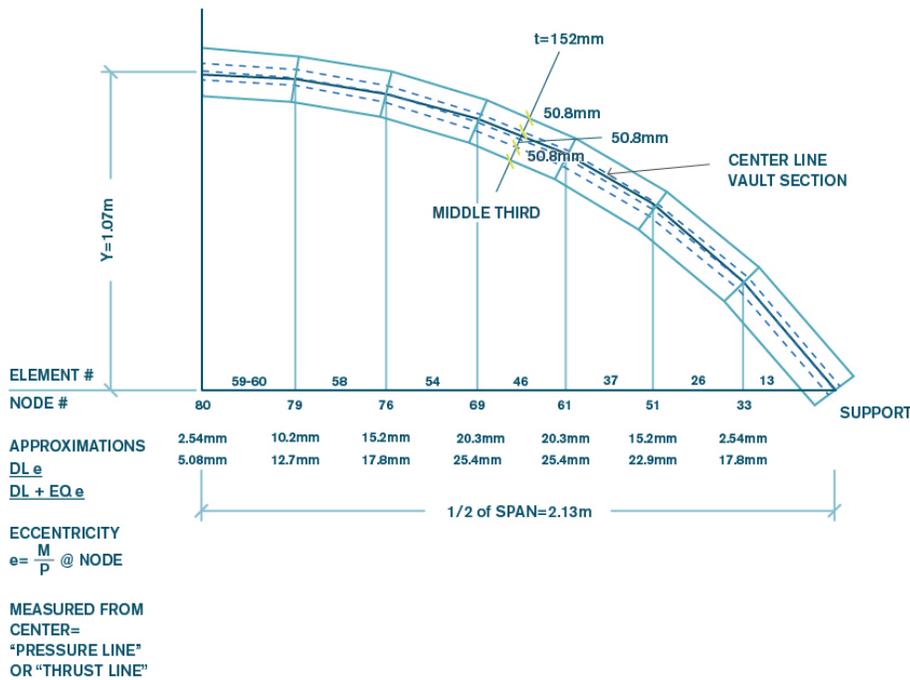


Figure 12: Pressure Line Diagram of 1.07m High Cloister Vault - 3D F.E.A. Method.

The thrustline diagram for the 1.07m high cloister vault with a center parallel to the line of action of the lateral (seismic) force is presented in figure 12. This figure indicates where the tensile and compressive stresses due to bending occur in the vault due to gravity and lateral (seismic) loads. The strip method indicates tensile stresses at the surface of the vault due to gravity and seismic loads. The F.E.A. method indicates the 'thrustline' to be within the 'middle third' of the vault section. Hence no or very low tensile stresses develop in the vault due to bending.

A comparison of the lateral (seismic) load transfer through diaphragm action and bending action was made for the shallow and the tall cloister vault based on the strip method of analysis and the F.E.A. model. These results are presented in tables 1 and 2.

0.574m High Cloister Vault	Transfer of Lateral Load by Diaphragm Action	Transfer of Lateral Load in Bending
Strip Method of Analysis	75%	25%
F.E.A. Method	63%	37%

Table 1: Transfer of Lateral (Seismic) Load Through Diaphragm Action, 0.574m High Cloister Vault

1.07m High Cloister Vault	Transfer of Lateral Load by Diaphragm Action	Transfer of Lateral Load in Bending
Strip Method of Analysis	75%	25%
F.E.A. Method	74%	26%

Table 2: Transfer of Lateral (Seismic) Load Through Diaphragm Action, 1.07m High Cloister Vault

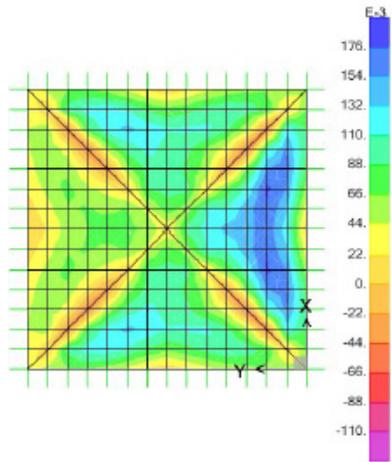


Figure 13: 0.574m Vault – 3D Plot of Principal Moments under Dead Load plus Lateral (Seismic) Load [Unit: kN-m]

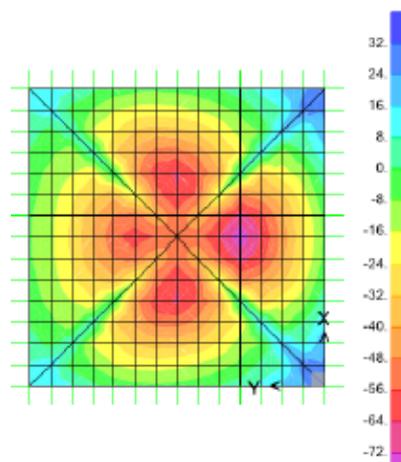


Figure 14: 0.574m Vault – 3D Plot of Principal Stresses under Dead Load plus Lateral (seismic) Load [Unit: kN-m<sup>2</sup>]

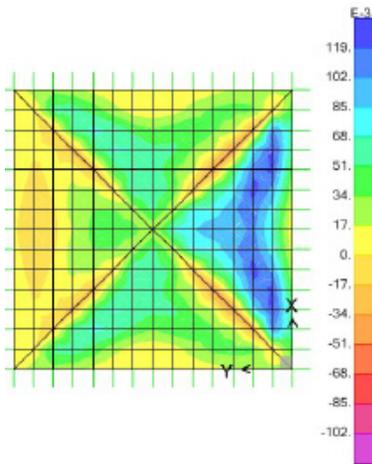


Figure 15: 1.07m Vault – 3D Plot of Principal Moments under Dead Load plus Lateral (Seismic) Load [Unit: kN-m]

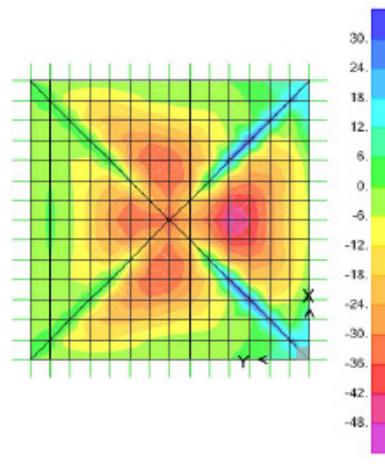


Fig. 16: 1.07m Vault – 3D Plot of Principal Stresses under Dead Load Plus Lateral (Seismic) Load [Unit: kN/m<sup>2</sup>]

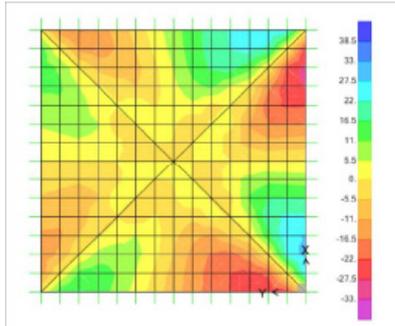


Figure 17: 0.574m Vault – 3D Plot of Shear Stresses Dead Load plus Lateral (Seismic) Load [Unit: kN/m<sup>2</sup>]

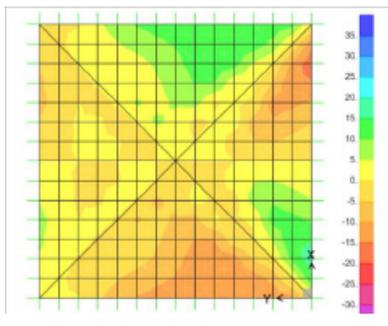


Figure 18: 1.07m Vault – 3D Plot of Shear Stresses under Dead Load plus Lateral (Seismic) Load [Unit: kN/m<sup>2</sup>]

## Conclusions

- A comparison of the mechanism of lateral (seismic) load transfer for the shallow cloister vault (0.574m height) and the tall cloister vault (1.07 m height) shows that the strip method of analysis is conservative for the shallow cloister vault and about the same for the tall cloister vault when compared to results from the F.E.A. method, as shown in tables 1 and 2.
- The Finite Element Analysis method indicates that both cloister vaults will be able to safely resist the lateral (seismic) loads of 25% of the vault weight and transfer them to the supporting walls.
- The shear forces along the walls and across the walls are low for the assumed material. The shear stresses that develop, as presented in figures 17 and 18, are well within the material's limits.
- A study of the 3D plots of maximum principal moments and principal stresses indicates the occurrence of higher stresses in the

same general area as compared to those shown on the thrust line diagram shown in figure 12 and the 3D plots presented in figures 13-16.

- The 'thrust-line' diagram from the F.E.A. model analysis results indicates that the 1.07m high vault will be able to withstand seismic forces through bending in the vault planes perpendicular to the line of action of the lateral (seismic) loads.
- Tension stresses develop along the diagonals and at the corners, but are well within the material's limits, as shown in figures 14 and 16. The cloister vault will likely develop fracture lines across the vault where tension due to bending begins to develop across the vault, rather than in shear at the wall supports, for lateral forces greater than indicated in the paper (see figures 13 and 15).

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