All Sciences Proceedings
http://as-proceeding.com/

5th International Conference on Applied Engineering and Natural Sciences

July 10-12, 2023 : Konya, Turkey

https://www.icaens.com/

Seismic Strengthening of Stone Barrel Vault Structures by Foam Concrete

Furkan Günday*

[1] Department of Civil Engineering, Faculty of Engineering, Giresun University, Turkey

*furkan.gunday@giresun.edu.tr

Abstract – Historical buildings are the cultural heritage of the world. Preservation of historical buildings is important in the past and today. In particular, material fatigue, environmental vibration effects and natural disasters that occur over time cause great damage to historical structures. It is thought that many historical buildings will not reach the next years due to neglect. In order to prevent this situation, historical buildings should be maintained and strengthened if necessary. In addition, historical buildings should have sufficient stiffness to prevent collapse against pre-disaster situations. Stone barrel vaults are one of these historical cultural heritages. Many stone barrel vault type historical structures are frequently encountered today. In order for stone barrel vaults to be transferred to the future, care should be taken and they may need to be strengthened periodically, especially after disasters. For all these reasons, in this study, the foam concrete method, which is one of the retrofitting methods of buildings, is mentioned. Thus, the effect of the foam concrete method applied on an exemplary stone barrel vault on modal parameters has been demonstrated. In this comparative study, it was observed that the stiffness of the stone barrel vault increased with the foam concrete method. As a result of this study, it is suggested to retrofitting the stone barrel vault with the foam concrete method, taking into account the state of the stone barrel vault and environmental factors.

Keywords – Stone Barrel Vault, Foam Concrete, Modal Analysis, Retrofitting

I. INTRODUCTION

Many types of structures are damaged as a result of natural disasters (such as floods, landslides, earthquakes). According to the degree of damage received, loss of life and property occurs with the collapse. In some structures, collapse does not occur as a result of disasters, but damage is observed [1], [2], [3], [4]. Various reinforcement methods are applied in such structures. Thus, the structures are restored to their former bearing strength and stiffness, thus avoiding possible collapse. Various proven popular retrofit methods are available to solve such problems. The use of foam concrete is one of these retrofit methods which popular method.

Barrel vault is a type of vault that consists of a single curve, which can be semicircular or pointed according to the arch profile. It is generally used to form a cylindrical-concave cover with a semicircular cross-section. The barrel vault, which is the simplest type of vault, basically consists of arches placed side by side. The load created by the weight of the barrel vault is transferred to the load-bearing walls, which creates a pushing force that pushes the walls to the sides. A number of mechanisms have been developed to solve this problem. The simplest method is to increase the thickness of the walls or to construct iron struts to support the wall [5]. Another solution is to build multiple barrel vaults side by side parallel to each other. In such cases, the thrust against the walls inside the building is mutually balanced, while the outermost walls still need to be thick or supported by buttresses. Alternatively, the cross vault, developed during the Roman Empire, consisting of two-barrel vaults intersecting at right angles to each other, requires finer stonework but transfers the load only to the stirrups, thus eliminating the need to thicken the entire wall. It is a type of vault that has been used since ancient Egypt. In the 19th century, with the spread of lighter construction materials, the pushing problem decreased, and the barrel vaults were used again in large structures such as railway stations. The barrel vault, which we frequently encounter in the upper covers of architectural structures, is the structures that are frequently used especially in the spaces of monumental buildings such as courtyards, porticoes, galleries, corridors, and on the upper covers of long rectangular and planned structures such as inns and bazaars. It is in the form of a semi-cylindrical structure and the arches forming the section curve are in the form of a semicircle. The vault and the arch are among the indispensable elements of Roman architecture. The most commonly used type in architecture is the barrel vault. A cross or cross vault is obtained when two-barrel vaults placed perpendicular to each other intersect. In historical buildings, many different types of vaults have been developed and applied according to the function of the space it covers, its geometric shape and the structure of the curve that forms its section [6].

It is called foam concrete consisting of a mixture of foam concrete, cement, water and special aggregates (fly ash, pumice, perlite, pumice, basalt, dolomite, limestone and similar) and has 75-80% independent closed air spaces in its structure. It is also called foamed concrete, aircrete, foamcrete, cellular lightweight concrete or reduced density concrete. Foam concrete, also known as Lightweight Cellular Concrete (LCC), Low Density Cellular Concrete (LDCC), and other terms is defined as a cement-based slurry, with a minimum of 20% (per volume) foam entrained into the plastic mortar [7]. As mostly no coarse aggregate is used for production of foam concrete the correct term would be called mortar instead of concrete; it may be called "foamed cement" as well. The density of foam concrete usually varies from 400 kg/m3 to 1600 kg/m3. The density is normally controlled by substituting fully or part of the fine aggregate with foam. More recently, foam concrete is being made with a continuous foam generator. The foam is produced by agitating a foaming agent with compressed air to make "aircrete" or "foamcrete". This material is fireproof, insect proof, and waterproof. It offers significant thermal and acoustic insulation and can be cut, carved, drilled and shaped with wood-working tools. This construction material can be used to make foundations, subfloors, building blocks, walls, domes, or even arches that can be reinforced with a construction fabric [8]. Foam concrete is generally used instead of screed concrete as a wall material for insulation purposes on interior and exterior walls of buildings. Foam concrete, due to its lightness, provides advantages in thermal insulation, reduces costs and is an environmentally friendly building material [9], [10].

Researchers have carried out many studies using both the retrofitting and the finite element method. Researchers have conducted studies [11], [12], [13], [14], [15], [16] about barrel vaults which also contributed to this study. Also, researchers have conducted studies [17], [18], [19], [20], [21], [22], [23] about foam concrete which also contributed to this study.

The aim of this study is to contribute to the retrofitting of stone barrel vaults according to their pre-disaster and post-disaster stiffness conditions. It is known that there are many retrofitting methods available for the stone barrel vault to regain their former stiffness. In this study, the effects of the foam concrete method on stone barrel vault periods and mode shapes are investigated.

II. Materials and Method

In this study, stone barrel vault model was created and modal analysis was carried out with the finite element method. The stone barrel vault model was retrofitted with foam concrete and two stone barrel vault model was created for comparison. Variables on the model should be minimized in order to better see the reinforcement effects. Therefore, it was emphasized that the models should be designed simply and symmetrically. Thus, it is aimed that the only variable between both models is the retrofitting method. In the application of the finite element method, the SAP2000 package program, which is used in the field of academic and engineering applications all over the world, was used.

A. *Description of Stone Barrel Vault Model*

The model barrel vault is designed as masonry stone. The stone barrel vault has a semicircular cross-section with a diameter of 6 m, total height is 6 m, length is 15 m, wall thickness is 0.20 m, side wall of height is 3 m. The mechanical parameters of masonry stone in model are; poisson's ratio: 0.2, modulus of elasticity: 2.5 GPa, density: 20 kN/m^3. The stone barrel vault finite element model was created using the SAP2000 software. The finite element model of the stone barrel vault is given in fig. 1.

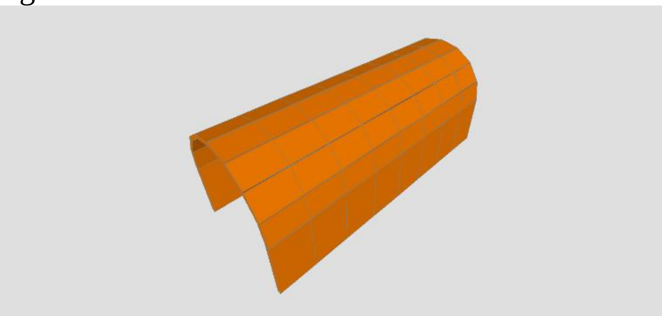

Fig. 1 3D Finite element model of the stone barrel vault

B. *Description of Stone Barrel Vault Retrofitted Model*

0.05 m foam concrete process was applied to the all-inner surface of the existing stone barrel vault model. Mechanical properties of the applied foam concrete; poisson's ratio: 0.2, modulus of elasticity: 12 GPa, density: 16 kN/m^3.

III. RESULTS AND DISCUSSION

Stone barrel vault model and stone barrel vault retrofitted model were analysed using SAP2000 software. The period and mode shapes obtained for both models are obtained for each mode.

A. *Results of Stone Barrel Vault Model*

The modal analysis of the stone barrel vault model was performed with FEM. The first 5 modes were taken into account in the analysis. Obtained results are presented in figures 2,3,4,5,6 as periods and mode shapes.

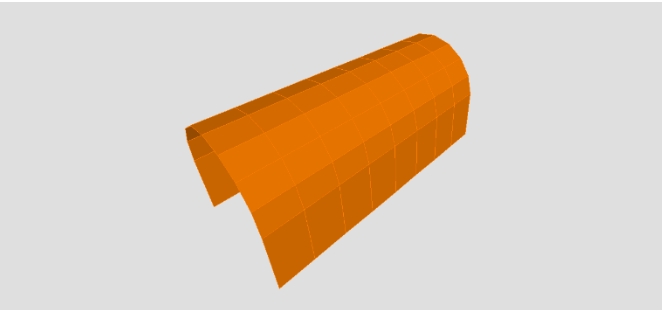

Fig. 2 Mode shape (Period value = 0.726 s)

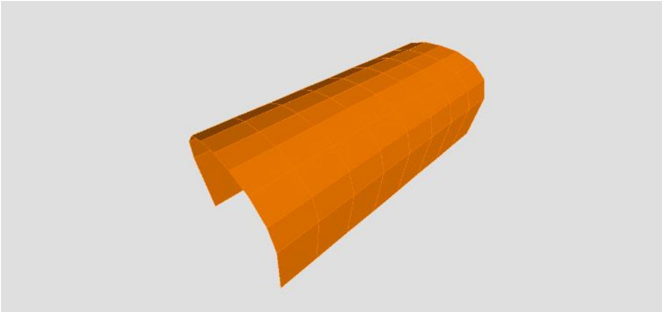

Fig. 3 Mode shape (Period value = 0.251 s)

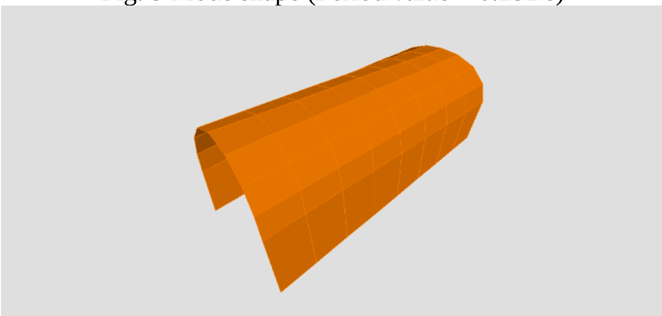

Fig. 4 Mode shape (Period value = 0.248 s)

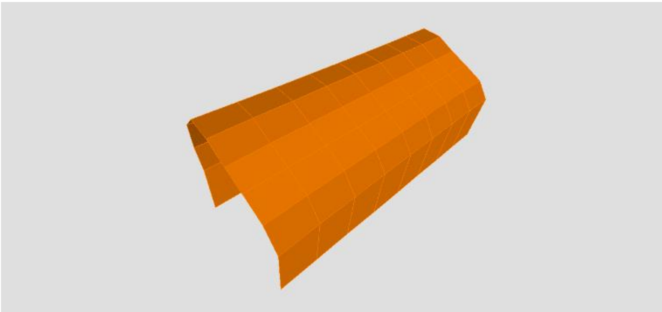

Fig. 5 Mode shape (Period value = 0.128 s)

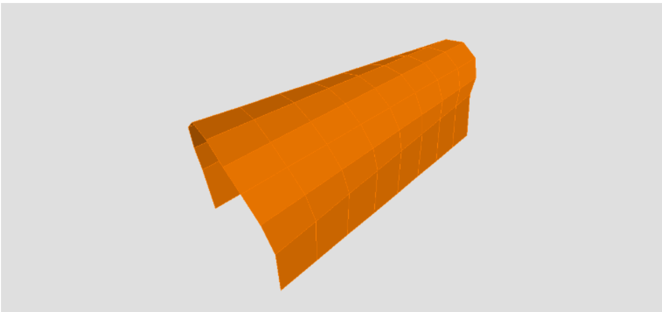

Fig. 6 Mode shape (Period value = 0.126 s)

B. *Results of Stone Barrel Vault Retrofitted Model*

The modal analysis of the stone barrel vault retrofitted model was performed with FEM. The first 5 modes were taken into account in the analysis. Obtained results are presented in figures 7,8,9,10,11 as periods and mode shapes.

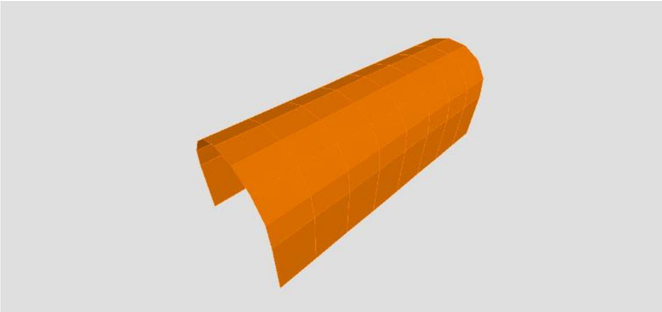

Fig. 7 Mode shape (Period value = 0.375 s)

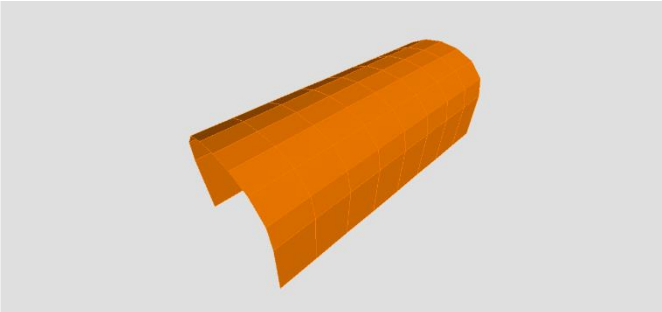

Fig. 8 Mode shape (Period value = 0.120 s)

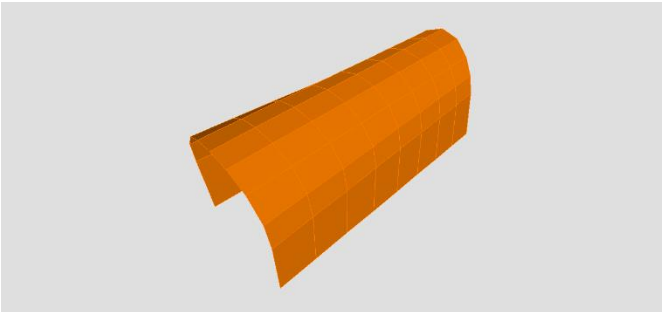

Fig. 9 Mode shape (Period value = 0.071 s)

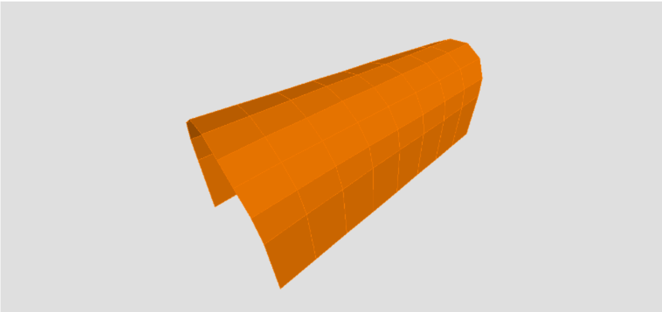

Fig. 10 Mode shape (Period value = 0.059 s)

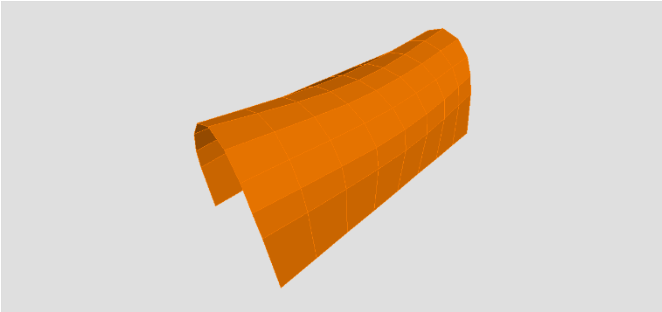

Fig. 11 Mode shape (Period value = 0.054 s)

C. *Comparison of Modal Analysis Results*

The comparison of periods of the model non-retrofitted and retrofitted are given in Table 1.

Table 1. Comparison of period values

Mode	**1**	**2**	**3**	**4**	**5**
Non-retrofitted	0.726	0.251	0.248	0.128	0.126
Retrofitted	0.375	0.120	0.071	0.059	0.054
Difference (s)	0.351	0.131	0.077	0.069	0.072
Difference (%)	48.35	52.19	31.05	53.91	57.14

When the mode shapes are examined in general, translations are seen in the 1st and 2nd mode shapes in both models. Torsions dominate in the 3rd, 4th and 5th mode shapes. With the retrofitting, some minor change in translation and torsion was observed.

IV. CONCLUSION

In the mode 1, the period difference between non-retrofitted and retrofitted status was obtained as 0.351 s. The effect of period retrofitting with foam concrete as a percentage was determined as 48.35.

In the mode 2, the period difference between non-retrofitted and retrofitted status was obtained as 0.131 s. The effect of period retrofitting with foam concrete as a percentage was determined as 52.19.

In the mode 3, the period difference between non-retrofitted and retrofitted status was obtained as 0.077 s. The effect of period retrofitting with foam concrete as a percentage was determined as 31.05.

In the mode 4, the period difference between non-retrofitted and retrofitted status was obtained as 0.069 s. The effect of period retrofitting with foam concrete as a percentage was determined as 53.91.

In the mode 5, the period difference between non-retrofitted and retrofitted status was obtained as 0.072 s. The effect of period retrofitting with foam concrete as a percentage was determined as 57.31.

With the retrofitting, some minor change in translation and torsion was observed. It is thought that these changes are not very important.

In the light of all these results, it is clearly seen that the stiffness of the stone barrel vault model increases by retrofitting the stone barrel vault model with foam concrete. In the 1st mode, in other words, there is a decrease of 48.35 percent in the dominant period value. It is known that this is a very positive situation in terms of retrofit. The maximum decrease in period values was observed in the 4th mode. The lowest period decrease was seen in the 3rd mode with approximately 31.05 percent. It can be said that the drop value obtained in this period is quite positive in terms of the increase in model stiffness. As a result of this study, the stone barrel vaults can retrofit with the foam concrete method.

References

[1] Tuhta, S. (2018). GFRP retrofitting effect on the dynamic characteristics of model steel structure. Steel and Composite Structures, 28(2), 223–231.

[2] Tuhta, S. (2021). Analytical and Experimental Modal Analysis of Model Wind Tunnel using Microtremor Excitation. Wind & Structures, 32(6), 563–571.

[3] Tuhta, S., Abrar, O., & Günday, F. (2019). Experimental Study on Behavior of Bench-Scale Steel Structure Retrofitted with CFRP Composites under Ambient Vibration. European Journal of Engineering Research and Science, 4(5), 109–114.

[4] Tuhta, S., & Günday, F. (2019). Application of Oma on The Bench-scale Aluminum Bridge Using Micro Tremor Data. İnternational Journal of Advance Research and Innovative İdeas in Education, 5(5), 912–923.

[5] Roth, L. M. (1993). Understanding architecture: its elements, history, and meaning, New York, NY.

[6] Mahrebel, H. A. (2006). Tarihi yapılarda taşıyıcı sistem özellikleri, hasarlar, onarım ve güçlendirme teknikleri, Yüksek lisans tezi, İstanbul Teknik Üniversitesi.

[7] The Concrete Institute, Midrand, 2013

[8] Jones, M. Roderick; Zheng, Li (2013). "Energy absorption of foamed concrete from low-velocity impacts". Magazine of Concrete Research. 65 (4): 209–219.

[9] Khawaja, S. A., Javed, U., Zafar, T., Riaz, M., Zafar, M. S., & Khan, M. K. (2021). Eco-friendly incorporation of sugarcane bagasse ash as partial replacement of sand in foam concrete. Cleaner Engineering and Technology, 4, 100164.

[10] Koru, M. (2017). Köpük Betonun Yoğunluk ve Sıcaklığa Bağlı Isıl İletkenlik Katsayısının Isı Akış Ölçer Yöntemiyle Belirlenmesi. Süleyman Demirel Üniversitesi Fen Bilimleri Enstitüsü Dergisi, 21(2), 614-622.

[11] Romano, A., & Grande, E. (2008). Masonry barrel vaults: influence of the pattern. In 14th Conference on Earthquake Engineering (pp. 12-17).

[12] Fernández, S., & Manzanares, G. (1997). Stability and consolidation of an ashlar barrel vault with great deformations: the church of Guimarei.

[13] Alejo, L. E., Mendes, N., Lourenço, P. B., & Martínez, G. (2021). Protecting the historic buildings of Mexico: the barrel vault of San Agustin church in morelia. Journal of Performance of Constructed Facilities, 35(2), 04020146.

[14] Alexakis, H., & Makris, N. (2018). Minimum uplift horizontal acceleration of the single-nave barrel vault and the rocking frame. ISSMGE Int J Geoeng Case Histories, 4(4), 275-288.

[15] Bove, M., Castellano, A., Fraddosio, A., Scacco, J., Milani, G., & Piccioni, M. D. (2019). Experimental and numerical analysis of FRCM strengthened parabolic tuff barrel vault. Key Engineering Materials, 817, 213-220.

[16] Scacco, J., Milani, G., Bove, M., Castellano, A., Fraddosio, A., & Piccioni, M. D. (2019). Experimental and numerical analysis of the effectiveness of FRCM strengthening on a parabolic tuff barrel vault. In AIP Conference Proceedings (Vol. 2186, No. 1). AIP Publishing.

[17] Amran, Y. M., Farzadnia, N., & Ali, A. A. (2015). Properties and applications of foamed concrete; a review. Construction and Building Materials, 101, 990-1005.

[18] Jalal, M. D., Tanveer, A., Jagdeesh, K., & Ahmed, F. (2017). Foam concrete. International Journal of Civil Engineering Research, 8(1), 1-14.

[19] Aldridge, D. (2005). Introduction to foamed concrete: what, why, how? In Use of foamed concrete in construction: Proceedings of the international conference held at the University of Dundee, Scotland, UK on 5 July 2005 (pp. 1-14). Thomas Telford Publishing.

[20] Raj, A., Sathyan, D., & Mini, K. M. (2019). Physical and functional characteristics of foam concrete: A review. Construction and Building Materials, 221, 787-799.

[21] Kozłowski, M., & Kadela, M. (2018). Mechanical characterization of lightweight foamed concrete. Advances in Materials Science and Engineering, 2018.

[22] Nakamura, H., Ninomiya, T., Sakaguchi, T., Nakano, Y., Konagai, K., Hisada, Y., & Takahashi, A. (2012). Seismic isolation retrofit of Susano City Hall situated above lava tubes. In Proceedings of the 15th World Conference on Earthquake Engineering, Lisbon, Portugal (pp. 24-28).

[23] Aghdamy, S., Wu, C., & Griffith, M. (2013). Simulation of retrofitted unreinforced concrete masonry unit walls

under blast loading. International journal of protective structures, 4(1), 21-44.

[24] SAP2000 (1997). Integrated Finite Element Analysis and Design of Structures, Computers and Structures Inc., Berkeley, California, USA.