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SEISMIC REHABILITATION OF HISTORICAL MASONRY VAULTS USING FRPS - A CASE STUDY

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ABSTRACT

Collapse of non-engineered historical buildings in seismically active regions of Iran has been reported widely. Masonry dome and vault, which were built by adobe or bricks with clay, lime/clay or chalk/clay mortar have often been used in these buildings to cover the roof. Conservation of historical heritage may become necessary in order to improve their seismic resistance. In this paper, potential failure of a heritage brick vault located in Yazd city, Iran built in 1935 is investigated under lateral loads. In this building, the piers were built by adobe masonry whereas the roof vault was made up of clay bricks with chalk/clay mortar. A nonlinear finite element model is used in the investigation in which the masonry is modelled as an anisotropic continuum using smeared material models. The material properties of continuum masonry are determined by testing. Finally, the brick vault is strengthened using CFRP sheets at extrados with different architecture and the failure mechanisms of the structure before and after strengthening are compared. Results show that when the vault is strengthened at extrados, the failure mechanism would improve to provide higher ultimate load capacities.

KEYWORDS

Historical buildings, brick masonry vault, carbon fibre reinforced plastic sheets.

INTRODUCTION

Masonry is a heterogeneous material composed of units connected by dry or mortar joints. As units, stones, adobes and bricks have been used which, can be joined together using mortar. The mechanical behaviour of the different types of masonry exhibits a very low tensile strength. This property is so important that it has determined the structural form of historical constructions. The curved structures, i.e. arches and vaults, represented a significant structural capacity, which were used in the past in spanning wide openings, with adobe or brick masonry. Indeed, in curved elements, it is usual to find only compressive stresses in a given section and consequently no tensile resistant materials are required. However, joints can be critical regions in brick masonry vaults against the severe seismic attack so the contribution of strengthening materials and repair techniques may be required to re-established their performances and to prevent the brittle collapse of the masonry in possible future hazardous conditions. Since the mechanisms related to failure of brick vaults under seismic action are not yet well known, attention should be given to this matter in order to perform repair/retrofitting schemes. Several researchers reported the weak performance of masonry vault. For example, recently, Maheri (2005) and Mahdi (2004) noted the poor seismic performance of traditional domes and vault roofs after 2003 earthquake, Bam, Iran. Retrofitting techniques have been examined in order to improve this weakness. Giordano et al (2001) performed a numerical investigation in order to assess of the seismic capacity of triumphal arches. Giordano et al (2001), identified a global mechanism type has been a priori selected for the element, and the critical zones in the arch which are the left side of both pier bases, intrados on the left haunch, and extrados on the right haunch. Further, Ascione *et al.'s* (2005) presented some applications of an adaptive discontinuous finite element model in order to evaluate the ultimate load and the collapse mechanism of two-dimensional FRP/reinforced masonry structures. They showed that the loading carrying capacity of the structure increased by FRP/strengthening technique.
In this paper, first the performance and the collapse mechanisms of a case study brick vault belongs to a historical building located in Yazd city, Iran subjected to lateral loads is evaluated using nonlinear finite element modelling. Then, the influence of FRP sheets on the seismic performance of the case study vault is investigated.

GEOMETRY OF THE CASE STUDY BRICK MASONRY VAULT

The brick masonry vault examined in this chapter belongs to the Egbal historical complex. This complex building was built for a textile factory called Egbal between 1932 and 1935. In the recent years, several restorations were made by the Yazd Science and Technology Park, including recovering and partitioning of the

main saloon, and now the main office of many new established research and development companies are accommodated in there. The structural system of the roof is covered by brick vaulting systems, while the side piers are made by adobe.

Generally, the geometrical parameters which can be considered of primary importance in affecting the structural behaviour of vault are: piers height, H, piers width, B, arch rise (radius for circular arch), R, arch span, L and, thickness at crown, s. In Figure 1, an external and internal view of the building and also the transversal section at the vault is provided. As is seen, the geometry parameters for this structure are: H = 3.17 m, B = 0.9 m, R = 3.70 m, L = 6.47 m and s = 200 mm.

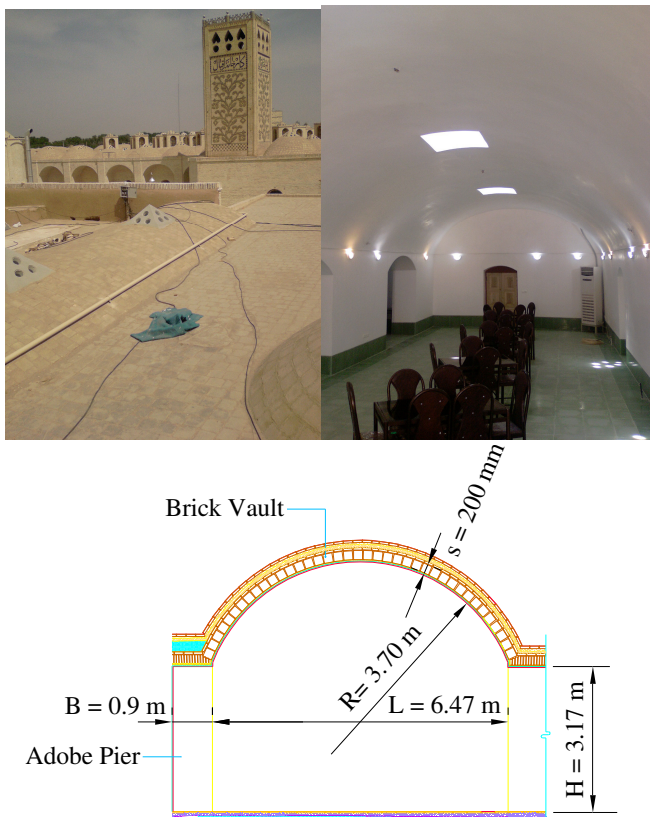


Figure 1. An internal and external view and the section at the case study vault belong to the Eghbal complex.

ELEMENT TYPES

Generally, brick masonry vault is complex structure involving interaction between the masonry material, and the overlying fill material each of which has the potential to behave in a nonlinear manner under loading. Three dimensional finite element models allow the analyst to account accurately for the extent and geometry of each of these constituents in constructing a representative numerical model of a masonry vaults. The ANSYS v.9 finite element software is used to construct the model and three-dimensional eight nodded isoparametric elements, solid65, are employed for the masonry material. This element uses a smeared crack model to allow the formations of cracks perpendicular to the direction of principal stresses that exceed the tensile strength of the masonry material. Although this element has been designed to model the concrete, but this concrete model is able to reasonably predict the masonry behaviour in monotonic loading. Macro-element modelling techniques are used for the brick vault and adobe piers with material properties based on testing measures on continuum prisms of the vault and piers. An elevation of the vault geometry is constructed using the available CAD drawing of the vault to generate the solid model. The thickness of the piers and the depth of the piers visible on the face of the structure are assumed to be constant across the width of the vault. In addition, the fill material is assumed to be uniform through its depth.

MATERIAL MODELLING

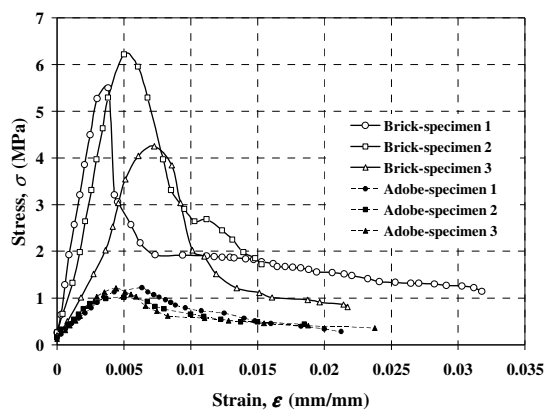
This section deals with macro-modelling of masonry and the connection with the corresponding macro-material descriptions. A brief review of the measured material properties necessary for a complete numerical description is presented.

Properties of unit and mortar

The normalized compressive strength of cubic specimen with 207×194×44 mm^3 for the adobe units, in the relevant direction of the loading is measured about 1.0 MPa. Figure 2 (a) shows an adobe unit under testing. The average compressive strength of sample brick specimens with 194×170×45 mm^3 is also captured around 5.3 MPa. Figure 2 (b) shows one of these specimens under testing. The stress-strain curve of all specimens is shown in Figure 2 (c). In addition, based on these relationships, the modulus of elasticity of adobe and brick units is estimated to 291 MPa and 1230 MPa respectively.

The compressive strength of the mortar is obtained from standard tests carried out in the cubic 50×50×50 mm^3 specimens. From these tests, the compressive strength of clay and chalk/clay mortars is estimated to be around 4.4 MPa and 5.15 MPa respectively. In addition, the tensile strength of clay and chalk/clay mortars is determined using standard tests. It is about 0.51 and 0.81 MPa for clay and clay/chalk mortars respectively.

(a) (b)



(c)

Figure 2. (a) An adobe unit under universal test; (b) a brick unit under universal test; (c) compressive stress-strain curves of all specimens

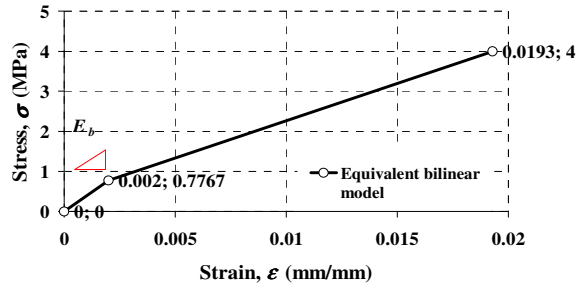
Properties of the composite material

The uniaxial compressive and tensile strength of prism samples of adobe unit with clay mortar and brick prism with chalk/clay mortar in the relevant direction of the loading are captured using standard universal testing machine. Figure 3 (a) shows an adobe prism sample under testing. Based on the test results, an equivalent bilinear model for stress-strain relation is approximated by a series of straight-line segments in order to employ in FE modelling. As is seen, the compressive strength and the modulus of elasticity of adobe prism (E_a) are estimated to an average of 1 MPa and 214 MPa respectively (see Figure 3(b)). In addition, the density of the specimens is equal to 1745 kg/m^3. Figure 3 (c) also shows a brick prism sample under testing. As the vaults behave as a plain strain problem, the sample prism is clamped in the perpendicular direction of the loading plane. Similarly, the equivalent bilinear model of stress-strain relationship for brick prism is shown in Figure 3 (d). As is seen, the strain corresponding to the brick prism compressive strength of 4 MPa under uniaxial stress conditions is taken as 0.0193. The modulus of elasticity (E_b) and the density of the brick prism are obtained around 338 MPa and 1500 kg/m^3 respectively.

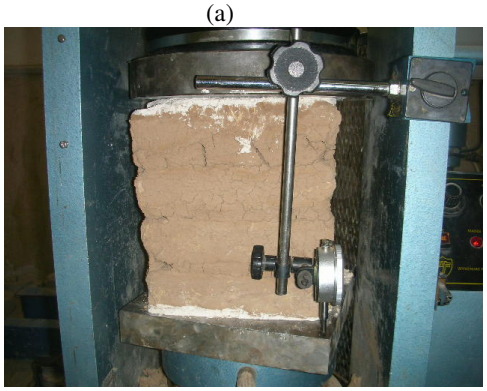
The relatively low tensile bond strength between the bed joint and the unit causes tensile failure of composite masonry. Therefore, the masonry tensile strength can be equated to the tensile bond strength between the joint

and the unit. In this paper, the related tensile strength of the adobe and brick units is determined using two points bending test. Figure 3 (e) shows a test sample under testing. It is calculated around 0.015 and 0.04 MPa for the adobe and brick prisms respectively. In addition, the Poisson's ratio is considered as 0.2 for masonry (Maheri, 2004).

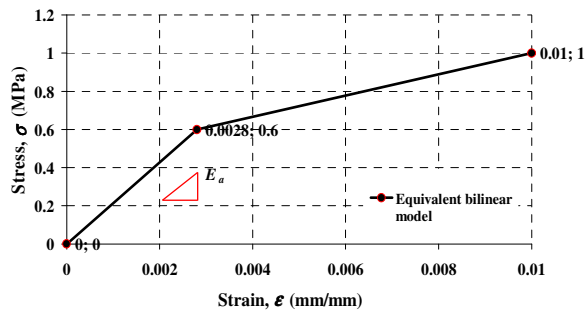
(a)



(b)



(c)



(d)

(e)

Figure 3. (a) Brick prism under compressive test (b) equivalent stress-strain relation of brick prism; (c) adobe prism under compressive test (d) equivalent stress-strain relation of adobe prism (e) brick prism under tensile test

GEOMETRY OF THE MODELS, LOADING, BOUNDARY CONDITIONS

A fairly fine 3D mesh, consisting of 18190 solid elements (solid65), is used to model the plain and retrofitted vaults, which is subjected to the vertical load deriving from the self weight, and to horizontal loads of increasing intensity, constantly distributed along the height of the element corresponding to seismic loads (see Figure 4 (a)). The lateral loads is calculated based on the Iranian Earthquake Code, 2800 (BHRC, 2003) and also the Iranian Code for Strengthening Masonry Structures (BHRC, 2006). The boundary conditions at the piers supports is also shown. Based on the elastic modulus of subgrade which is formed by a special clay/lime mortar, the elastic

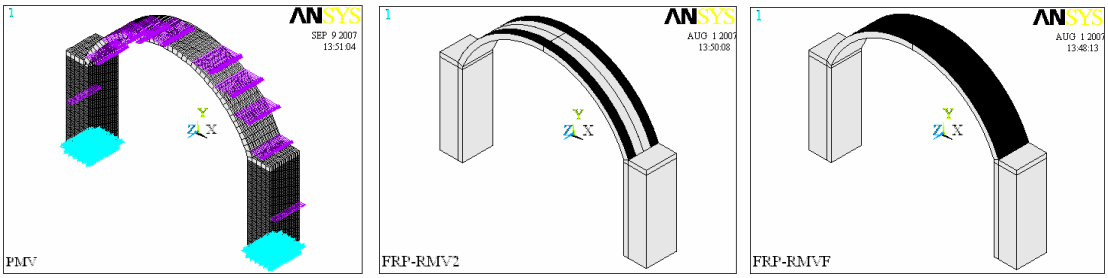
foundations are also modelled in the finite element analysis. In ANSYS, there are four convergence criteria; i.e., F (force), M (moment), U (displacement), and ROT (rotation). In this study, a full newton-raphson iterative solution algorithm with force and displacement convergence is used. The failure is defined as the situation at which the solution for the last load increment did not converge.

RETROFITTING SCHEMES

One vault sample is retrofitted with two plies FRP strips bonded at the extrados, as shown in Figure 4 (b). Each strip is 30 cm wide giving a total of 60 cm of fibre reinforcement for each 1200 millimetre of the longitudinal development of the structure. Carbon Fibre Reinforced Polymer (CFRP) sheets that are used in all specimens are uni-directional. CFRP is an MBrace Fibre sheeting from MBT (2002), which possesses a tensile strength of about 3900 MPa, a modulus of elasticity of 240 GPa and an ultimate tensile elongation of 1.55%. The thickness of fibre sheet is 0.165 mm. When the saturant is cured, the thickness of CFRP sheet is 1mm. This specimen is called FRP-RMV2. The second specimen, FRP-RMVF, (see Figure 4 (c)) is retrofitted with two plies of CFRP bonded at the extrados of the vault entirely.

FE MODELLING RESULTS

In Figure 5(a), the deformed configuration at the last load increment of the analysis of plain vault (PMV) is shown. The major stresses distribution for plain (PMV) and FRP-retrofitted (FRP-RMV2 and FRP-RMVF) vaults are also shown in Figures 5(b), 5(c) and 5(d) respectively. This distribution clearly evidences the stress flow in the element. On the basis of the results of the nonlinear analysis, a global mechanism type is occurred with four critical zones in the plain vault are identified. These are at the left side of pier bases, intrados on the left haunch, and extrados on the right haunch. In other words, it can be observed that the plain structure exhibits a 'frame' collapse mechanism in such a case (two opening hinges in the vault and two hinges in the buttresses).
The retrofitted vaults show considerable differences, since such a retrofitting scheme leads to only fracturing near vault-buttress connections. This improvement is more obvious when entire the vault is fully retrofitted by FRP sheets in which the increase in the load carrying capacity reaches up to 15%. Note that in FRP-RMVF, no opening hinges appear in extrados of the vault at collapse. However, other retrofitting schemes combined with FRPs, for example using tie-rods on the haunches or abutments as an anchoring device need to be examined in order to control fracturing in the buttresses.



(a) (b) (c)

Figure 4. (a) Typical mesh of plain vault, PMV under lateral loads; (b) FRP-retrofitted vault, FRP-RMV2 with two strips; (c) entire FRP-retrofitted vault, FRP-RMVF

CONCLUSIONS

The FRP-retrofitting schemes present in this paper can be used in order to control the opening hinges in the extrados of the masonry vault subjected to seismic loads and also to upgrade the ultimate load carrying capacity of vaulted structures. However, it accounts for the main phenomena which characterize the limit behaviour of such structures (crushing and fracturing of masonry). Finite element modelling is employed to carry out a numerical study regarding the increase in the loading carrying capacity produced by FRP/strengthening and improvement of the failure mechanism at the extrados of the vault. A wider analysis extended to a large sample of real vaults could result very useful for the assessment of seismic performance of masonry vaults. Experimental verification and application to a wide spectrum of reinforcing techniques will be presented in future works.

ACKNOWLEDGMENTS

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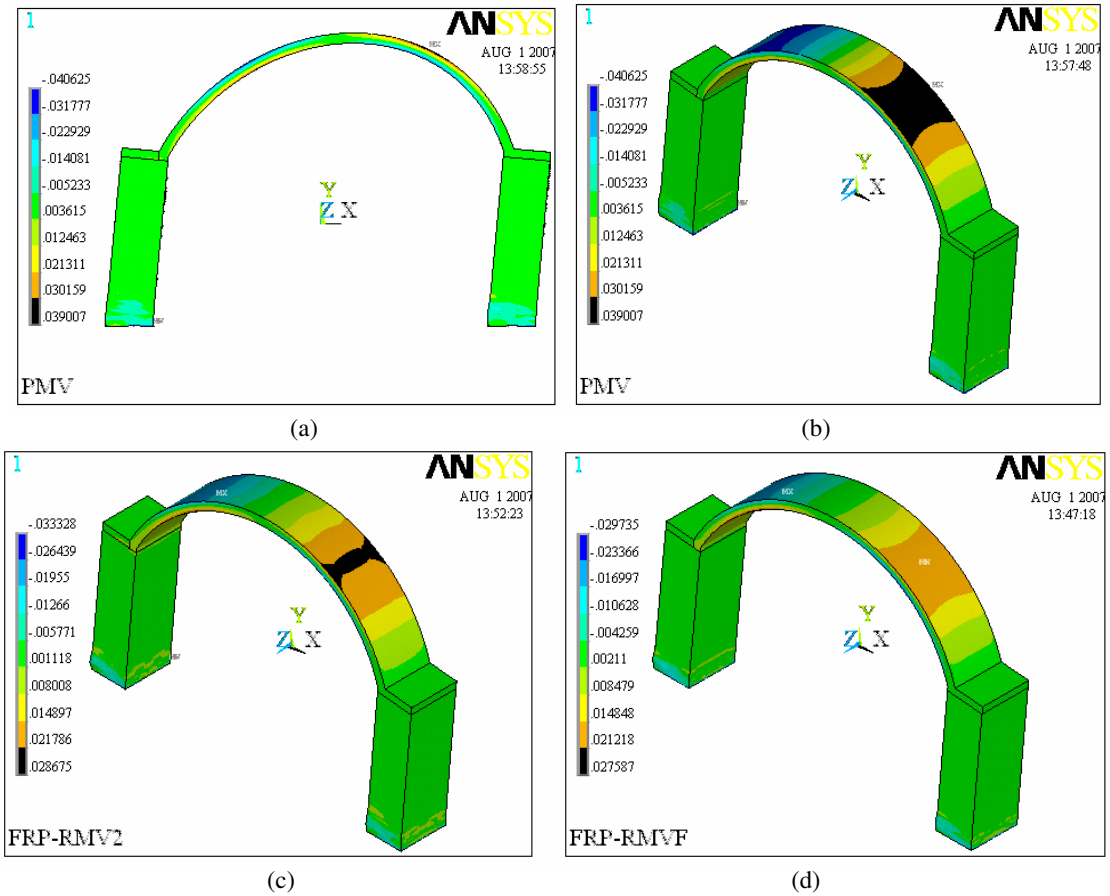

Figure 5. (a) deformed configuration of PMV; (b) major stresses distribution in PMV; (c) major stresses distribution in FRP-RMV2; (d) major stresses distribution in FRP-RMVF

REFERENCES

Ascione, L., Feo L. and Fraternali F. (2005). "Load carrying capacity of 2D FRP/strengthened masonry structures*", Composites: Part B* 36, 619–626.

Building and Housing Research Centre, (BHRC). (2003). "*Iranian Earthquake Code, Standard No.2800*"

Building and Housing Research Centre, (BHRC). (2006). "*Iranian Code for Strengthening Existing Masonry Structures*".

Giordano, A., Mele E., De Luca, A. (2001). "Assessment of the seismic capacity of triumphal arches." *University of Naples "Federico II", Department of Structural Analysis and Design, Naples, Italy* Historical Constructions, P.B. Lourenço, P. Roca (Eds.), Guimarães, 983-992.

Mahdi, T. (2004). "Performance of traditional arches, vaults and domes in the 2003 Bam Earthquake" *Asian Journal of Civil Engineering (Building and Housing)* vol. 5, nos 3-4, 209-221.

Maheri, M.R. (2004). *Seismic Design of Construction of Jack Arch Masonry Slabs,* International Institute of Earthquake Engineering and Seismology, IIEES, Iran.

Maheri, M.R. (2005). "Performance of building roofs in the 2003 Bam, Iran, Earthquake" *Earthquake Spectra,* Volume 21, No. S1, S411–S424.

MBT, MBrace, (2002). *Composite Strengthening System*, Master Builders Technologies: (MBT Australia) Pty Ltd.