SEISMIC ASSESSMENT OF ADOBEVAULTED ARCHITECTURE IN IRAN

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ABSTRACT

Adobe architecture has shown poor performance during past earthquakes and can be identified as one of the most vulnerable building typology to earthquakes. On the other hand, past earthquakes prove that adobe vaulting, a typical roofing system for adobe architecture located in hot and dry areas, plays a significant role in seismic behavior of adobe buildings.

This paper reports the results from a survey carried out on 57 segmental adobe vaults in the city of Yazd, Iran, aiming at assessing the seismic behavior of adobe vaults, and performing a numerical parametric study. To this end, a reference vault is considered as representative of the sample.

Limit analysis theory implemented in Block2D software is employed to carry out the numerical analyses. Results indicate that variation in influential parameters such as span, rise and thickness of vault and also depth of infill over the vault affects the seismic performance of adobe vaults. In addition, physical properties of infill and mechanical properties of adobe have also a significant influence.

INTRODUCTION

For millennia, humans have used earth as a construction material in different forms. It is estimated that around 17% of the world's population lives in earthen buildings and among the several earth architecture techniques, the most common find worldwide is adobe, also called mud bricks or sundried earth blocks (Correia and Fernandes 2006). Adobe construction is a building solution that was and is often used to build houses in many regions of the world, such as Latin America, Africa, Indian subcontinent and other parts of Asia, Middle East and Southern Europe (Costa et al. 2013). In addition, adobe constructions are the most commonly found on UNESCO world earthen heritage sites (50%), mainly in the regions of Asia and the Pacific (68%) (Gandreau and Delboy 2012).

Adobe buildings are economical constructions, since earth is a low cost and easily available material. This construction typology is characterized by a simple building process, which allows self-construction and does not require skilled workmanship. In addition, adobe constructions have other advantages, such as good thermal and acoustic attributes (Blondet et al. 2011). Nevertheless, adobe has very low tensile strength, low compressive strength and brittle behavior. Due to these properties, adobe is known as a construction technique with poor seismic performance. Post-earthquake observations have shown that the poor seismic performance of adobe architecture has led to a significant loss of lives and high costs for strong or even moderate earthquakes. This aspect becomes even more important due to the fact that the majority of adobe architecture is located in regions with moderate and high seismic hazard (Blondet et al. 2011). From a structural point of view, the roof is one of the constructive elements of adobe architecture playing a significant role in their behavior under seismic actions. Most of the adobe architecture have pitched or flat roofs, but in some hot and dried regions adobe vernacular architecture have been built with adobe curved roofs (i.e. vault and domes) due to the lack of wood (NIKER 2012).

Adobe vault architecture have originated and developed in Middle East, one of the high seismic prone regions of the world, and dates back to more than 3000 years ago (Norton 1997). Among the Middle East countries, Iran has a vast vernacular adobe vaulted architecture, in particular in its Centre and Southern areas. Moreover, the country is located on the alp-Himalayan belt, one of the most seismically active areas of the world. For this reason, the paper comprises the study of 77 adobe houses in the city of Yazd, Iran with a rich collection of adobe-vaulted architecture.

In spite of adobe vaults vulnerability during past earthquakes, most of the researches in the field of masonry vaults are related to stone and brick vaults (Basílio 2007; Como 2012; Giardina 2006; Girardello 2013; NIKER 2012; Taranu et al. 2010) and researches on adobe vaults are limited. While their structural analysis and seismic safety assessment are greatly absent (Minke 2006; NIKER 2012; Norton 1997; Oliveira et al. 2012; Torrealva et al. 2006) . As a consequent, stability and safety of these vaults during earthquake are considerably unknown. For this reason, the main objective of this paper is to perform a numerical parametric study considering the main influential parameters on the seismic behavior of adobe-vaulted roofs to assess their safety against earthquake.

GEOMETRICAL STUDY

As stated before, this study focuses on old adobe houses from the city of Yazd, Iran, due to the existence of a vast number of traditional adobe houses with adobe vaults in this city, where most of them still remain in a good condition, see Figure 1(a) and Figure 1(b). Most of these houses date back to Qajar period (1785–1925) and a few of them have survived from Safavid period (1501–1736). An extensive field survey for a large number of adobe houses located in Yazd old fabric was carried out to collect architectural drawings and photos from their current situation. Using the results of this field survey as well as available documents in literature, a comprehensive study was carried out on the most important geometrical properties of 77 adobe houses to find typical combinations of vaults and adjacent walls. Most of the studied vaults have segmental shape and only a few of them have vaults with pointed shape, which often belong to the period before Qajar period; so they were not considered due to their reduced representativeness. As a result, 57 typical vaults and walls combinations with segmental vaults were selected.

(a) (b) (c)

Figure 1. (a) View of historical fabric of Yazd city; (b) Moayyed house, Yazd; (c) Structural model of a typical vaults and adjacent walls combination

Concerning entire combinations of vaults and adjacent walls, the relation between span (s) and rise to span ratio (r/s) of the main vault of each combination is depicted in see Figure 2. On the basis of the obtained results, it is possible to classify the main vaults of typical combinations of vaults and walls into three main groups based on the span length of them as follows:

- Short span vaults $s \leq 5m$

- Medium span vaults 5m < s < 6.5m
- Large span vaults s < 7m

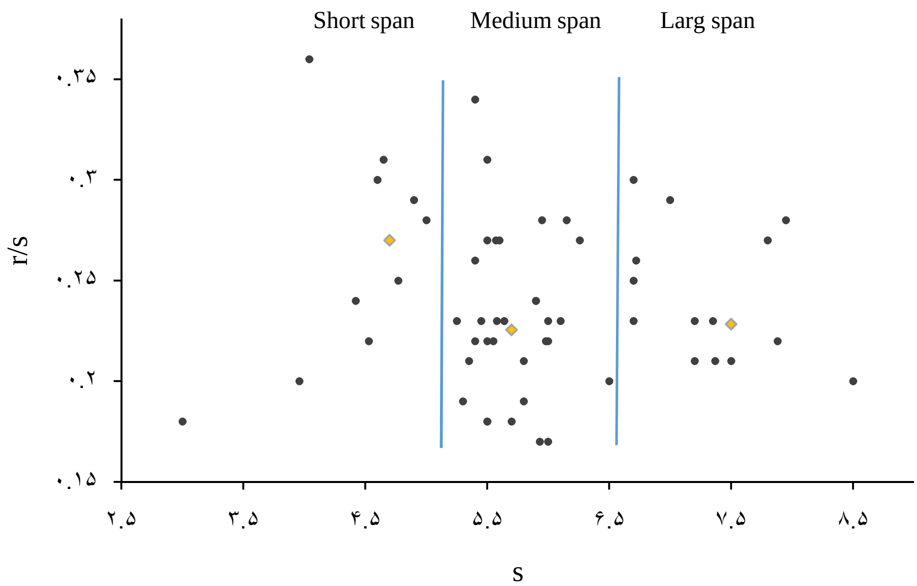
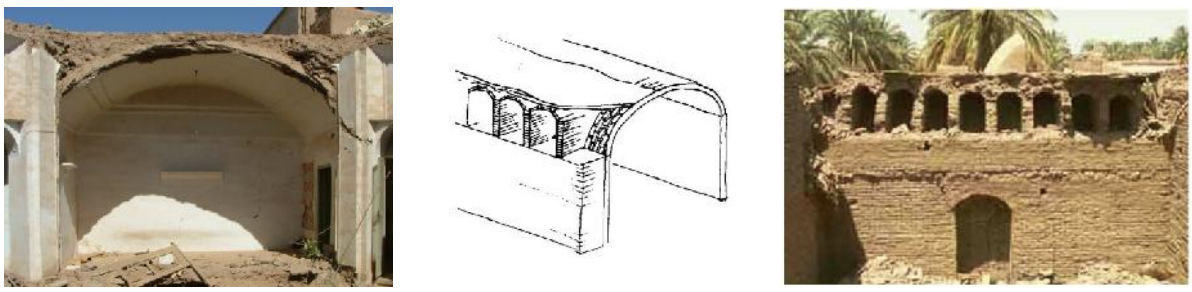


Figure 2. Relationship between span (s) and rise to span ratio (r/s) for 57 studied vaults (the reference vault of each group of vaults is also represented)

Comparing the obtained values for rise to span ratio, it can be stated that the values present a moderate scatter (i.e. 0.17 ≤ r/s ≤ 0.36). Moreover, it is concluded that 63% of vaults are classified as medium span vaults. Hence, this paper focuses on the second group of vaults with 5m < s < 6.5m. On the other hand, since the current paper is part of a PhD research, only the main vault (middle vault) in each combination of vaults and adjacent walls is considered for numerical analysis in this paper.

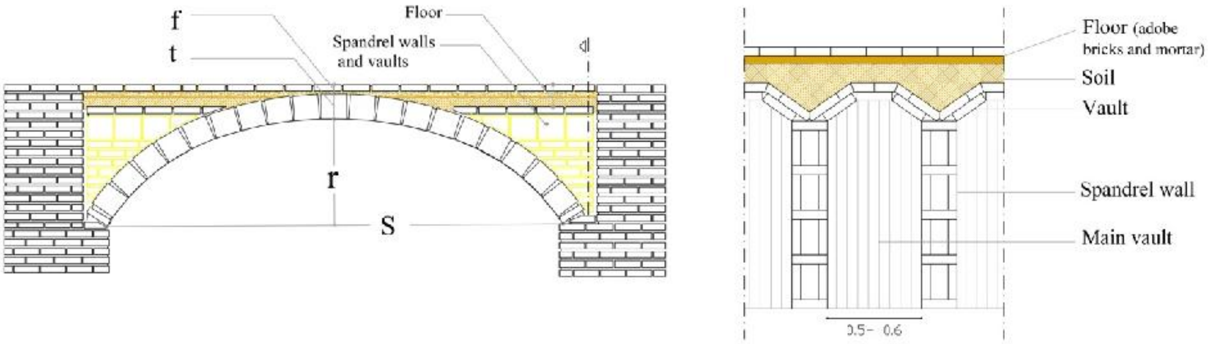
There is an interest to have houses with flat roofs in hot and dry regions. To this end, the space above the vault can be fully fill with soil or a system of spandrel walls and small vaults (known as “konou” in Persian architectural literature) can be used to create flat roofs. Filling over the adobe vault extrados was generally made of soil while “konou” is made of adobe as shown in Figure 3 and Figure 4. In most of the researches, the structural role of the infill and “konou” has usually been neglected, while they can have significant influence on vault stability and safety against earthquake. For this reason, the current study considers their influence on vault structural behavior.



(a) (b) (c)

Figure 3. (a) Full filling with soil. (b), (c) Spandrel walls and vaults (“konou”) over the main vault

Performing each parametric study needs to have a reference model, for comparison purposes. Based on the data provided in Figure 2, a reference vault is defined as being geometrically representative of the sample. Geometrical properties of medium span reference vault are following presented.



(a) (b)

Figure 4. (a)Section of adobe vault with “konou”. (b) Section of “konou”

NUMERICAL ANALYSES

Since strengthening weak adobe architecture before earthquake may reduce thefatalities, loss of cultural heritage and decrease the high costs of repairing damaged buildings after earthquake, the seismic behaviour of adobe vaulted architecture should be evaluated to distinguish the need and also the degree of intervention. To this end, herein a numerical parametric study aiming at assessing their seismic safety is performed using limit analysis theory implemented in Block2D software (Orduna 2003).

Limit analysis, a simplified yet powerful structural analysis tool, is aimed at obtaining the collapse load and failure mechanism for a given structure and loading conditions. Limit analysis is also an efficient structural analysis tool for traditional architecture due to a reduced number of material parameters necessary to perform the analysis (Orduna 2003). Limit analysis of masonry structures is based on the assumptions and hypothesis developed by Heyman (1997) as follows:

(1) Masonry has no tensile strength
(2) Masonry has an infinite compressive strength
(3) Sliding types of failure in between units cannot occur

These hypotheses together with the basic plasticity theory are applied to masonry structures. Here, the plastic theory is implying that the failure is due to the formation of a mechanism or plastic hinges (Heyman 1997). In order to provide a good representation for masonry structures, Block software assumes rigid blocks interacting through frictional interfaces. For the joints, the adopted constitutive model consists of the Coulomb criterion for shear stresses and a no-tension and limited compressive stress criterion for normal stresses (Orduna 2003). Block2D software is able to analyze the models under gravity loads (self-weight) and horizontal load (representative of earthquake load).

Reference vault

The material properties assumed for adobe material were based on available literature (Eslami et al. 2012; Kiyono and Kalantari 2004), as listed below, see also Figure 5.

- Compressive strength = 1120 kN/m2
- Volume weight = 17.5 kN/m3
- Friction coefficient = 0.62

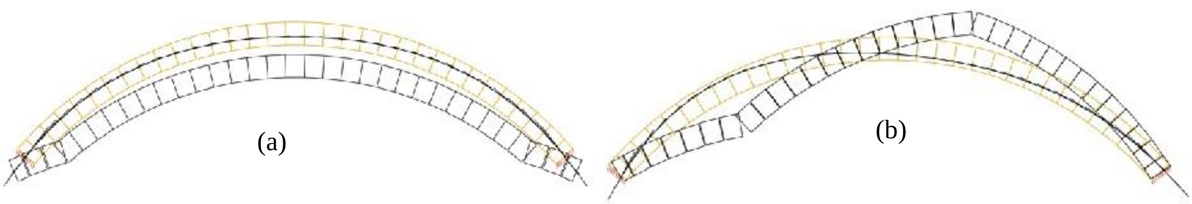


Figure 5. Failure mechanism and trust line of reference vault developed by Block2D software. a) Under gravity load. b) Under horizontal loading

As stated before, there are three available types for the infill of adobe vaults: vault without infill, vault fully filled with soil and vault with “konou”. In order to evaluate the effect of infill type on the load capacity of the reference vault, limit analyses were performed and corresponding safety factors were obtained as shown in Table 1. The results indicate that existence of fill above the vault considerably increases the safety factor of vaults under horizontal load while, for gravity load, vault without fill has higher safety factor comparing to two other vaults. Moreover, the resulted safety factors show that vaults with “konou” are slightly safer than vaults fully filled with soil. Results also show that stability of vaults is very different under gravity and seismic load, particularly for the vault without any infill.

Table 1. Safety factor of three kinds of adobe vaults with different fill types

	Without infill	Fully filled with soil	“konou”
Under gravity load	12.74	5.28	6.55
Under horizontal load	0.62	2.07	2.36

Results and discussion

The parametric analyses were performed on the reference vaults, in order to obtain a deep insight into the most significant parameters controlling the structural response. There are variables that influence the structural safety of adobe vaults such as shape, geometrical proportions, mechanical properties of materials and physical properties of the structures. The relevant variables considered within this current parametric study are presented below and the adopted values for each variable are provided in**Error! Reference source not found.**

- Geometry: span (s), rise (r) and thickness (t); infill depth at the crown (f).
- Infill: fully filled with soil and “konou”.
- Compressive strength of adobe (f_c)

Table 2. Values adopted for parametric analysis

Parameters	Unit	Lower values			Reference value	Upper values			
Vault span	m	5.25	5.4	5.55	5.7	5.97		6.23	6.5
Vault rise	m	0.97	1.07	1.18	1.3	1.39		1.49	1.6
Vault thickness	m	0.2			0.25	0.3			
Infill depth	m	0	.05		0.1	0.2	0.3	0.4	0.5
Compressive strength	MPa	0.33	0.55	0.8	1.12	1.3	1.5	2	2.5

Safety and stability was evaluated under gravity loads in a first step, and then under horizontal loads. For this reason, safety factors of vaults with variable properties have been obtained for both vertical and horizontal loading.

Vertical load

The results from the parametric analyses are illustrated in the next figures. The influence of vault span, vault rise and compressive strength of adobe on the safety factor of the vault under gravity load is shown in Figure 6. The analyses were performed on the vault with both types of infill. Assuming constant ratio between rise and span, increasing the span of vaultsdecreases the safety of two types of adobe vaults. Results obtained from analysis of vaults with same span but variable rise for vaults fully filled with soil, indicate that reference vault has the highest safety factor than the shallower or deeper vaults. But for vaults with “konou” the highest safety factor belongs to vaults with higher rise. Variation of compressive strength of adobe effects the safety of adobe vaults under vertical load more greatly. With increasing the compressive strength, the difference between safety factors of two kinds of vaults becomes larger.

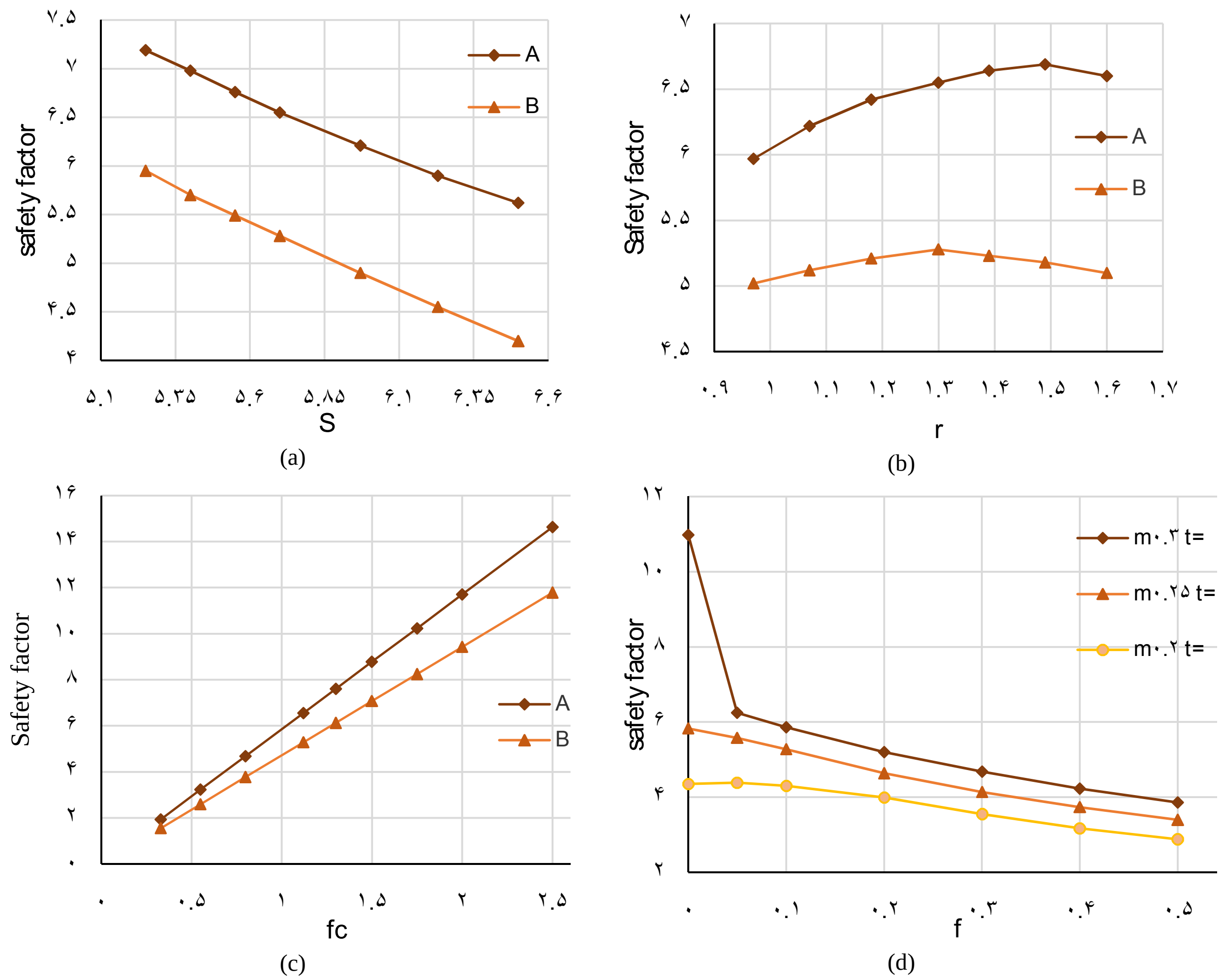


Figure 6. Relationship between safety factor under vertical load and (a) vault span; (b) vault rise; (c) adobe compressive strength. A: vaults with “konou”. B: vaults fully filled with soil. (d) Comparison of relation between safety factor and infill depth for vaults with different thickness.

Figure 6. (d) illustrates the effect of variation of vault thickness and fill depth coincidentally on the safety factor of adobe vaults under vertical load. It is clear that thicker vaults are safer but according to the results, increasing the fill depth over the vaults reduces the safety factor. Decreasing the fill depth causes more reduction in load on top of the crown compare with the load on the haunches (the sides) of the vaults that this distribution of loads helps the trust lines to be inside the vaults and makes them more stable.

Horizontal load

Figure 7 illustrates the influence of vault span, vault rise and compressive strength of adobe on safety factor of adobe vaults under horizontal load. These analyses are performed on vault with both kind of infill, to study their seismic safety. With constant ratio between rise and span, increasing the span of vaults causes reduction in the safety factor of two kinds of adobe vaults. Results obtained from analyzing vaults with same span and variable rise of vaults indicate that deep vaults are less safe than the shallow vaults. The difference between safety factor of vaults fully filled with soil and the vaults with “konou” reduces by increasing the rise. Variation of compressive strength of adobe has direct impact on the safety of adobe vaults. The effects of variation of vaults thickness and fill depth on safety factor of adobe vaults under horizontal load are illustrated in Figure 7. (d). It is clear that thicker vaults are safer but the results indicate that increasing the fill depth over the vaults first increases their safety factors but then a decrease is observed. Fill depth of the vault with maximum safety factor in vaults with different thickness is variable.

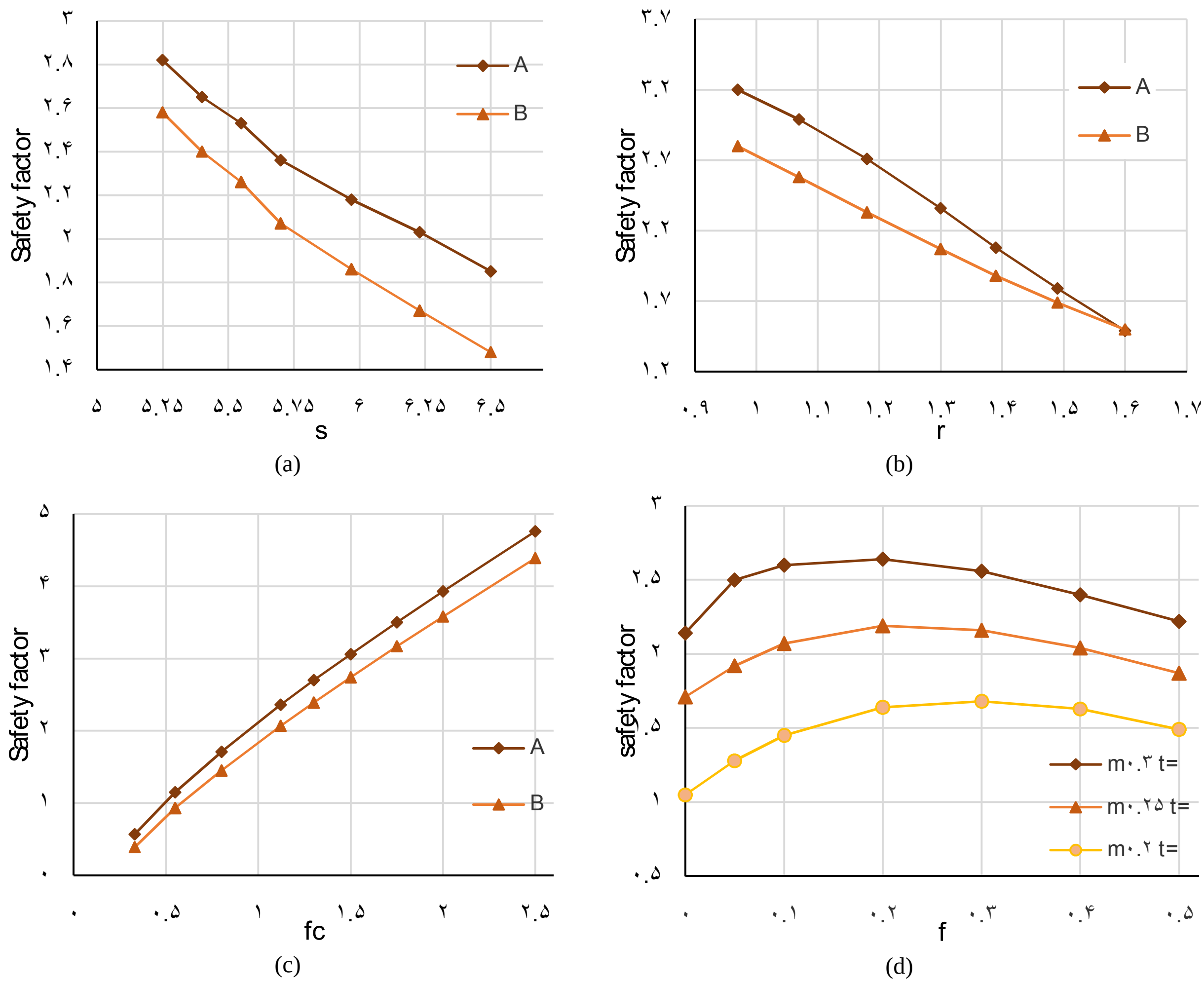


Figure 7. Relation between safety factor under horizontal load and (a) vault span; (b) vault rise; (c) adobe compressive strength (A: vaults with spandrel walls and vault. B: vaults with backfill full of soil.); (d) comparison of relation between safety factor and infill depth over the vault for vaults with different thickness.

Conclusion

In this paper, traditional adobe vaulted architecture located in the city of Yazd, Iran, was considered. A numerical parametric study using limit analysis approach implemented in Block2D software was performed on a reference vault derived from an extensive geometrical survey. A representative reference vault was analyzed under vertical and horizontal loads to evaluate its structural performance. The parametric analysis was performed on the reference vault to recognize the influence of important parameters such as geometry, mechanical properties of materials and physical properties of the structures on the structural safety of adobe vaults.

Results of the parametric study indicate that increasing adobe compressive strength results in a higher safety factor for adobe vaults (with different types of infill) under both vertical and horizontal loads. Variation in span of vault and fill depth over the vault causes change in the safety factor of adobe vaults more than variation in vault rise. While vault span and rise are more influential parameters on seismic safety than fill depth. Vault with more thickness have more safety and stability against both gravity and seismic loads.

Finally this work shows that studying the effect of influential parameters on adobe vaults can provide a deep insight into the safety and stability of traditional adobe vaulted architecture, which are at risk of earthquake. It is evident that numerical analysis results can also be applied in conservation of vaulted architecture.

Ongoing works

It is clear that an adobe vault belongs to an entire structure and should be considered as such. Walls have also a significant role in the safety and stability of the structure. Hence, ongoing works will address evaluating safety and stability of a combination of main adobe vaults with adjacent walls and vaults (see Figure 1. (c)). In future studies based on parametric studies, analytical equations will be developed, allowing to estimate seismic safety factors of the vast number of adobe vaulted construction based on their influential parameters. These equations can be used as a simple tool, applicable for safety assessment of a large number of adobe-vaulted architecture, which is the primary step within a conservation process.

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