

NUMERICAL STUDY ON THE SEISMIC PERFORMANCE OF ADOBE VAULTED ARCHITECTURE: A CASE STUDY FROM IRAN

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Abstract

Past earthquakes prove that adobe vaults, as traditional roofing systems for adobe architecture located in hot and dry areas, play a significant role in the seismic behaviour of adobe buildings. This paper reports the results from a geometrical survey carried out on 60 traditional adobe vaulted houses from the city of Yazd, Iran, followed by a simplified seismic assessment. To this end, a reference vault combination 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 parameters such as vault span, vault rise, supporting wall thickness and mechanical properties of adobe masonry have significant influence on the safety factor.

1. Introduction

Iran, with a vast number of historical adobe constructions, is located on the Alpine-Himalayan earthquake belt, one of the most seismically active areas of the world. Historically, the city of Yazd, with a large number of adobe monuments and vernacular architecture, possesses a great built heritage legated by ancient cultures and civilizations from various historical periods. Yazd has a vast number of traditional adobe houses with adobe vaults, where most of them still exhibit a good condition and are in everyday use. The relatively high seismic hazard of Yazd, with a peak ground acceleration of 0.25g, in addition to the seismic vulnerability of the adobe vaulted houses, gives rise to an urgent need for evaluating their behaviour under seismic actions.

Based on literature, most of the seismic studies on adobe constructions have focused on adobe case studies [1-3], mechanical behaviour of adobe units and prism [4-6], adobe walls [7, 8] and scaled adobe structures with wooden pitched or flat roofs [9-12]. In spite of adobe vaults vulnerability during past earthquakes, only a limited number of studies on seismic behaviour

of adobe vaulted structures can be found in literature. In PUCP, Peru, two vaulted models, one unreinforced and the other fully reinforced, were subjected to seismic simulation tests and the results showed that the unreinforced adobe vault was very vulnerable, but the fully reinforced vaults, on the contrary, performed well [13]. Sathiparan and Meguro [14] also evaluated the seismic behaviour of models of adobe vaulted houses using different retrofitting methods. There is also a few number of field surveys based on case studies such as adobe vaulted buildings performance in Bam earthquake [15, 16].

Aiming at assessing the seismic safety of adobe vaulted houses located in Yazd, 60 houses were initially chosen as representative of existing adobe houses. A typological and geometric characterization of the vaulted constructions under study was performed in order to define the reference vaults combinations as representative of the samples. Afterwards, a numerical parametric study was conducted adopting the limit analysis theory implemented in Block2D software [17].

2. Geometrical study

The majority of adobe vaulted houses of Yazd dates back to the Qajar period (1785–1925). One of the most important features of adobe historical houses in Yazd is related to their shape, which is inward looking centralized by a courtyard and all the openings are organized around it. The plan of houses is geometrical and nearly symmetrical. Most of the adobe buildings in the city of Yazd had been vaulted with adobe roofs. Most of the studied vaults have segmental shape and only a few of them have pointed shapes so the latter were not considered due to their reduced representativeness. Different constructive solutions can be found over the vaults. In order to create the flat roofs in vaulted architecture, the space above the vaults can be fully filled with soil or present spandrel walls with small vaults on top, made of adobes, which is named “konou” in Persian architectural literature. Different constructive solutions over the vaults are illustrated in Fig 1. In order to better understand vaulted adobe houses of Yazd, vaults of “Talar” were chosen for a detailed geometric study. Aiming at assessing the in-plane behaviour of critical elevation of studied houses, the elevations consisting of “Talar” and its adjacency have been selected for further studies.

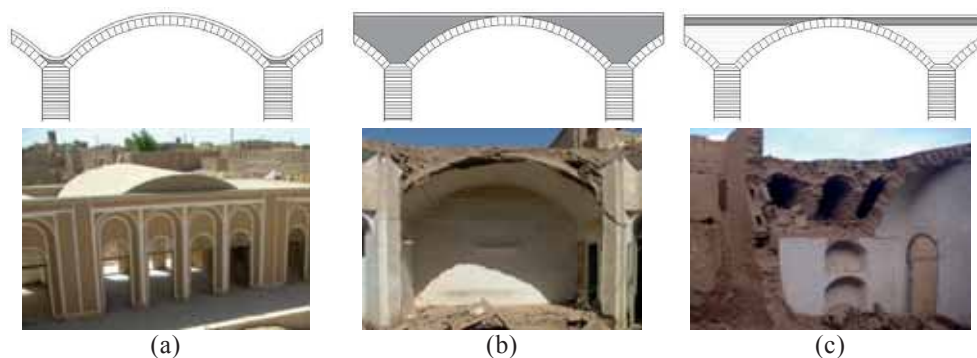


Figure 1. Different types of fill over the adobe vaults: (a) vault without fill, (b) vault full of soil, (c) spandrel walls and vaults over the main vault (“konou”).

2.1 Typological characterization of vaulted structures

In order to provide a more detailed geometrical analysis, vaults of “Talar” were chosen due to its presence in most of the traditional houses of Yazd. These vaults have the largest span among all the house’s vaults. From the carefully analysis of the “Talar” elevation view of each of the constructions present in the sample under study, it was possible to derive eight major typical configurations, as schematically shown in Fig 2, and organized according to the number of stories and the number and arrangement of vaults.



Figure 2. Typologies adopted for vaulted adobe structures.

One-story vaulted constructions, classified here as typology T1.*n*, represent about 45% of the sample, while 55% of the studied adobe houses have two stories or at least one part of the house consists of two floors (T2.*n*). For the sake of simplicity in geometrical and numerical studies, adjacent vaults have been considered fully parallel to the main vault and it was also assumed that existing thick adobe walls, staircases, perpendicular vaults or domes provide very stiff boundary conditions at each side. According to a statistical analysis carried out about the elevation view typologies, typologies T1.1 and T2.1 are clearly dominant in the sample, with 24% and 40% of elevation views; see Fig 3(a). These results allow to consider typology T2.1 as the most representative one, thus further studies will considered it in first place. Fig 3(b) illustrates the dominant typology of elevation view, T2.1, which is a combination of five vaults and supporting walls.

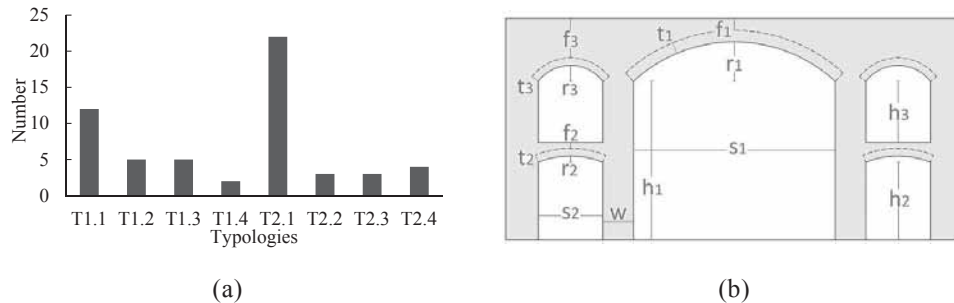


Figure 3. (a) Statistical analysis of the elevation view typologies, (b) Dominant typology regarding the elevation view (typology T2.1).

2.2 Reference vaults combination

The relation between span s_1 and rise to span ratio r_1/s_1 of the main vaults (“Talar” vault) is depicted in Fig 4 for one-story and two-story structures, respectively. The main vaults of reference vaults combination are also represented. Also, a proposal is done to classify the combinations of vaults into three main groups based on the span length of their main vault as follows:

- Short span vaults $s_1 \leq 5\text{m}$
- Medium span vaults $5\text{m} < s_1 < 6.5\text{m}$
- Large span vaults $s_1 > 6.5\text{m}$

According to the results obtained, it is concluded that 59% of the main vaults are classified as medium span vaults, 15% as short span and 26% as large span vaults. In order to study each group of vaults, it is convenient to define reference vaults combination as representatives of each group established above. The majority of short span vaults belong to one-story houses, while most of the large span vaults pertain to two-story houses or two-story part of the houses. Medium span vaults exist in both one-story and two-story constructions. Based on the statistical study of the sample, it can be stated that the two-story medium span group (MS2) constitutes a considerable proportion (33%) of the sample, thus it has been chosen here for further studies.

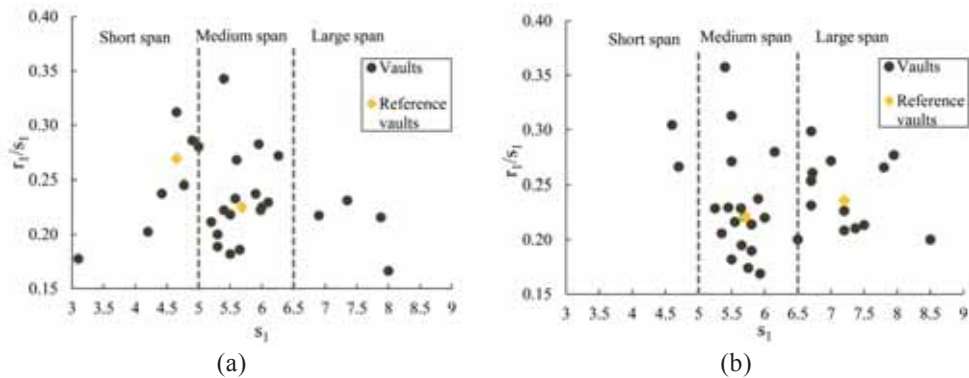


Figure 4. Relationship between span (s_1) and rise to span ratio (r_1/s_1) for the main vault (Talar): (a) one-story structures; (b) two-story structures.

Table 1 presents the geometrical features of the reference vaults of all the four groups considered. Parameter influencing structural response, such as effective vault thickness, is not measurable due to the existence of mud or gypsum plaster which covers the adobe vault. In addition the value of adobe vault thickness was not available in the literature survey. Therefore, in order to characterize the vault thickness, some of the half-ruined adobe vaulted houses were investigated and finally conservative values have been adopted for each group of vaults.

Table 1: Geometrical features of references of the vaults combination groups.

Groups	s_1	r_1	h_1	t_1	f_1	w	s_2	r_2	h_2	t_2	r_3	
Short span (SS1)	4.60	1.20	3.26	0.20	0.10	0.80	1.7	0.35	2.52	0.10	0.55	
Medium span	One-story (MS1)	5.70	1.30	3.10	0.25	0.10	0.84	1.6	2.34	0.10	0.25	0.60
	Two-story (MS2)	5.70	1.30	4.30	0.25	0.10	0.84	1.9	1.98	0.20	0.34	0.45
Large span (LS2)	7.20	1.75	4.40	0.30	0.10	0.97	2.7	0.52	2.13	0.20	0.64	

3. Numerical analysis of vaulted structures

Seismic safety of adobe vaulted architecture should be evaluated to distinguish the need and also the degree of possible intervention. The numerical safety assessment of historical masonry structures requires practical computational tools. Therefore it can be claimed that advanced non-linear analysis or other sophisticated models are more suitable for the assessment of remarkable monuments because they are very time and cost consuming, while simplified approaches like limit analysis are more appropriate for smaller buildings [18]. To this end, a numerical study using limit analysis theory implemented in Block2D software [17] has been performed to assess the seismic behavior of vaulted constructions. The vaults are assumed as assemblages of rigid blocks interacting through frictional interfaces for which calculations are carried out by means of the Block2D software, able to analyze the models under gravity and horizontal loading (earthquake load). The main result is a safety factor indicating the ratio between the collapse load and the structure weight [17, 19]. The collapse mode is also given.

As material properties, it was assumed a compressive strength equal to 1120 kN/m^2 [6], volume weight equal to 17.5 kN/m^3 [6] and friction coefficient equal to 0.62 [20]. According to the geometrical study of case studies, reference vaults combination MS2 as the dominant typology has been chosen. In order to gain a better understanding of structural behaviour of the reference vaults combination, three types of fill cases were considered under both vertical and horizontal loading.

Table 2 presents the load factors reached. A given load factor represents the multiple of the initial load applied that causes structural failure. Results indicate that load factors of vaults combination without fill are the lowest and vaults combination with “konou” has the highest vertical and horizontal load factors. Fig 5 illustrates the failure mechanisms of reference vaults combination with “konou”, under vertical and horizontal loading. Both mechanisms show global failure, involving mainly the central vault and the adjacent walls.

Table 2: Vertical and horizontal load factors of reference vaults combination (MS2) with different types of fill.

	Without fill	Full fill	“konou”
Under gravity load	2.20	5.26	6.05
Under horizontal load	0.06	0.19	0.20

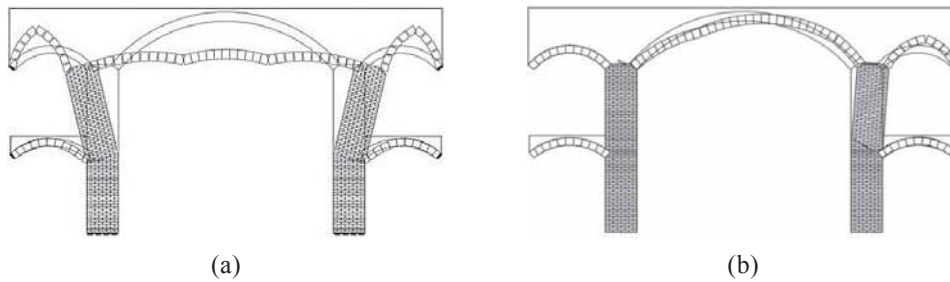


Figure 5. Failure mechanism of reference vaults combination (MS2): (a) under vertical loading; (b) under horizontal loading.

3.1 Parametric analysis

The parametric analyses were performed to reach a profound understanding of the most effective parameters on the structural response of vaults combinations. There are variables that influence the structural safety such as main vaults span and rise, adjacent vault span, supporting walls thickness and also compressive strength of adobe. The relevant variables considered within this current parametric study and the corresponding adopted values for each variable are provided in Table 3. For parametric analyses of reference vaults combination, the “konou” option was chosen as this fill type is predominant in the vernacular adobe houses of Yazd. Load factors of vaults combination with variable properties have been obtained considering both vertical and horizontal loading, as described above.

3.1.1 Vertical loading

The results of parametric analyses of vaults combinations under gravity load are illustrated in Fig 6. Increasing the span of main vault in the case of constant rise (main vault rise = 1.3 m) leads to reduction in vertical load factors of vaults combinations. Based on the obtained results, it can be claimed that vaults combinations have a higher vertical load factor when

Table 3: Values adopted for parametric analysis of vaults from group MS2.

Parameters	Unit	Lower values		Reference value	Upper values		
Main vault span	(m)	5.00	5.35	5.70	6.05	6.40	
Main vault rise	(m)	1.10	1.20	1.30	1.40	1.50	
Adjacent vault span	(m)	1.15	1.50	1.65	1.90	2.15	2.40
Wall thickness	(m)	0.63	0.74	0.84	0.95	1.05	
Compressive strength	(kN/m ²)	550	850	1120	1500	2000	

their main vault has higher rise. Geometrical properties of adjacent vaults influence the structural behaviour of the structure. When two vaults converge in a wall, the horizontal components of the thrust are neutralized in the case of identical vaults [21]. In this current study, increasing the span of adjacent vaults helps the whole structure to improve its equilibrium and thus increases the vertical load factor. Thickness of walls is also one of the effective parameters on the improvement of the structural load factor under vertical loading. Fig 6(e) shows that the variation of compressive strength of adobe considerably affects the safety of adobe vaults combination under vertical loading.

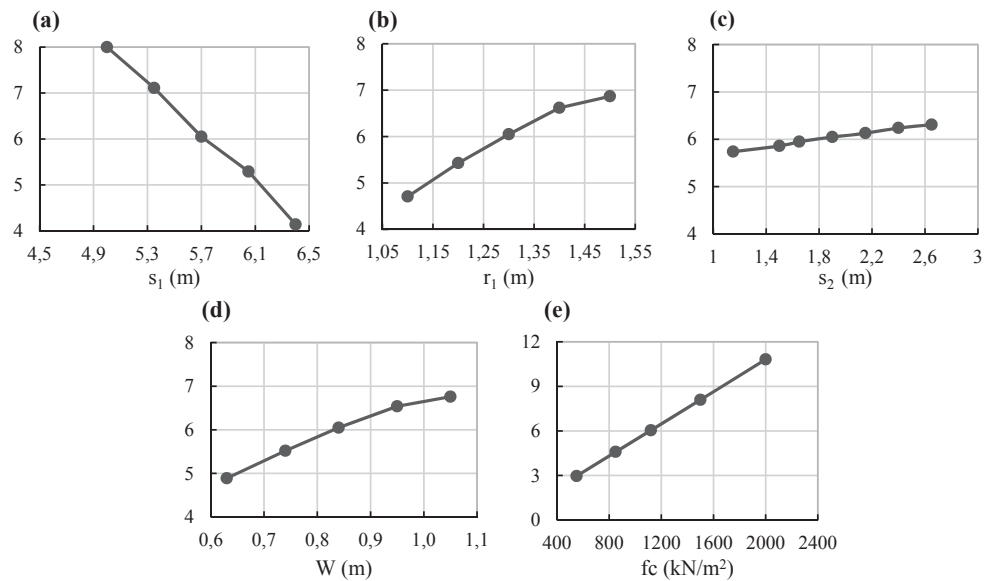


Figure 6. Relationship between vertical load factor and: (a) main vault span (s_1); (b) main vault rise (r_1); (c) adjacent vault span(s_2); (d) wall thickness (w); (e) compressive strength of adobe (f_c).

3.1.2 Horizontal loading

Fig 7 illustrates the results of parametric analyses of vaults combination under horizontal loading. Assuming a constant value for the rise, increasing the span of vaults causes reduction in the load factor values. The existence of main vaults with higher rise leads to an improvement of the horizontal load factor value of the whole structure. Also, increasing the adjacent vaults span slightly changes the horizontal load factor of vaults combination. After a small reduction, no changes were observed neither in load factor values nor on failure modes. The results from the analyses of vaults combinations with different walls thickness indicate that increasing the thickness of walls first increase the horizontal load factor of structure, but then no changes are observed. This fact shows that the wall thickness of about 0.95m is efficient for placing the thrust line inside the wall and further increases of the wall thickness cannot improve the structural safety. According to the parametric analyses results, graph of

compressive strength of adobe versus horizontal load factors of vaults combinations displays ascending order.

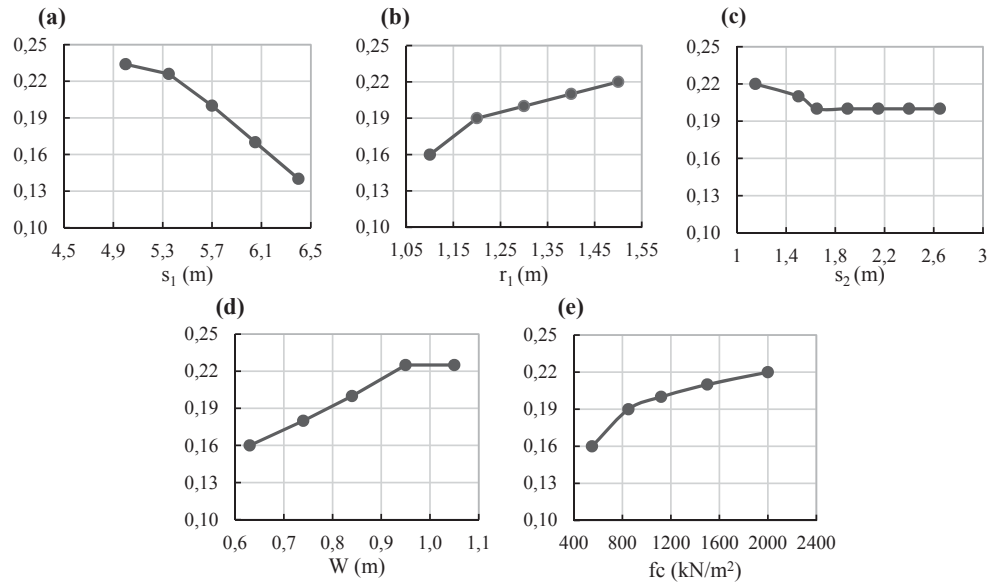


Figure 7. Relationship between horizontal load factor and: (a) main vault span (s_1); (b) main vault rise (r_1); (c) adjacent vault span (s_2); (d) wall thickness (w); (e) compressive strength of adobe (f_c).

3.2 Discussion

The parametric study results indicate that under vertical loading a larger variation of load capacity has been observed when compared to the horizontal loading. Fig 8 illustrates a non-dimensional relationship between loads factors and studied variables. The most influencing parameter under the vertical load is main vault span. Main vault rise, compressive strength of adobe, wall thickness and adjacent vault span are the parameters that influence the structural behaviour of adobe vaults under gravity loads in decreasing order of importance. On the other hand, the variation in main vault span also affects the horizontal loads factor (e.g. during an earthquake) more than other parameters studied. Other parameters such as, main vault rise, wall thickness, compressive strength of adobe and adjacent vault span have influence on the seismic behaviour of adobe vaults in decreasing order of importance.

4. Main conclusions

In this paper, 60 traditional adobe vaulted vernacular buildings located in Yazd, Iran, were considered. A numerical parametric analysis using limit analysis approach was performed on a reference vault derived from a detailed geometrical study. A representative reference vault combination was analyzed under vertical and horizontal loads to evaluate its structural performance. The parametric analysis was performed to recognize the influence of important

parameters such as geometry and mechanical properties of materials on the structural safety of adobe vaulted structures.

For the studied adobe vaults combination, the vertical load factor obtained is always higher than one, indicating their safety under gravitational loads. However, horizontal load factors of all vaults combinations are less than 0.25g (i.e. the PGA value at Yazd), so most of the adobe vaulted structures under study may be not safe for a future earthquake in the area.

Finally this work shows that studying the effect of influential parameters on adobe vaults combinations can provide a deep insight into the safety and stability of traditional adobe vaulted houses, which may be at risk.

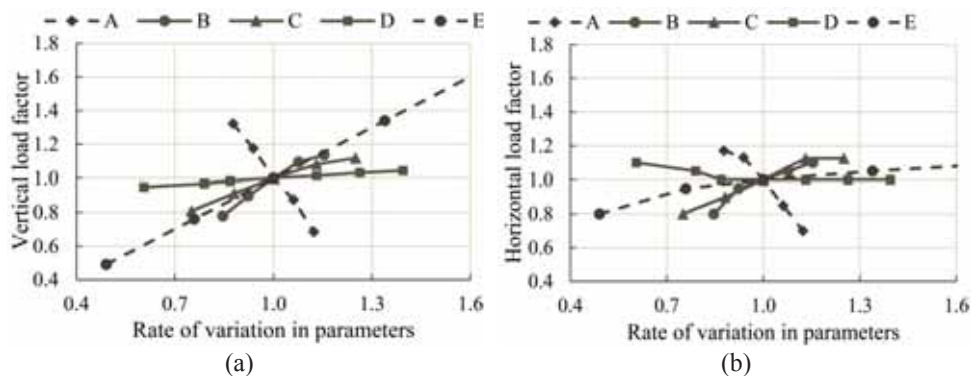


Figure 8. Non-dimensional relationship between variables and loads factors: (a) vertical loading; (b) horizontal loading (A: Main vault span, B: Main vault rise, C: Wall thickness, D: Adjacent vault span, E: Compressive strength of adobe).

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