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Local seismic culture in Iranian vernacular architecture: evidence from Yazd earthen architecture

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Abstract

Iran, located in one of the most earthquake-prone regions of the world, has experienced a very large number of destructive earthquakes that brought about considerable loss of human life and economic consequences. The country possesses a vast number of monumental and vernacular built heritages that are constantly threatened by earthquakes. As vernacular techniques for dwellings comply with the needs, comfort, utility, and functionality of people, it is expected that endemic earthquake-resistant techniques make an essential contribution to Iranian vernacular architecture. The city of Yazd presents a unique and rich vernacular for earthen construction within Iranian architectural heritage, which has resulted in the recognition of the historic fabric of the city as a World Heritage Site since 2017. Considering the importance of exploring different local seismic cultures worldwide, this paper introduces an essential part of Iranian local seismic culture by recognising and classifying the vernacular earthquake-resistant techniques used in the earthen architecture of the city of Yazd. The techniques were collected by surveying the historic fabric, using data available in the literature, and interviewing traditional builders and local conservators. Next, the seismic influence of each technique was evaluated using examples from the performance of adobe constructions during the 2003 Bam earthquake.

Keywords: Local seismic culture, Vernacular earthen architecture, adobe, Yazd, Iran

1 Introduction

In general, vernacular architecture is designed and built by people to meet their needs for comfort, utility, and functionality in their dwellings. Vernacular architecture, inspired by its environment, is mainly characterised by the use of local building materials and construction techniques, resulting in its continued success and sustainability (Haji Sadeghi 2018; May and Reid 2010). Earthen material was used to create constructions with valuable architectural heritage since prehistory due to its availability throughout the world. Different earthen construction techniques have been developed by humans, such as adobe, cob, rammed earth, compressed earth block, and wattle and daub (Houben and Guillaud 1994). Although many monuments have been built in earthen, the availability of earthen materials and ease of application techniques have enabled the construction of more earthen vernacular buildings.

Earthquakes have led to enormous destruction in terms of loss of life and property to humankind since the beginning of civilisation. Most vulnerable constructions that can be subjected to earthquakes are categorised as unreinforced masonry (URM) buildings due to their heavyweight, low strength, nonductile behaviour, and inappropriate connection between structural elements.

Types of vernacular architecture made of unreinforced masonry are in general particularly vulnerable to earthquakes due to the use of poor materials and constructive details, the shortage of resources in poverty-stricken communities, and inadequate maintenance (Varum et al.

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2015). However, vernacular constructions have been continuously adapted to climate conditions, excessive loadings, changes in functionality, and available materials to achieve the desired performance (Cañas and Martin 2004). Therefore, inhabitants of earthquake-prone regions eventually learn how to minimise seismic risk by either implementing an active response, i.e., developing preventive strengthening measures to reduce future losses due to earthquakes, or adopting a reactive response, e.g., taking temporary post-earthquake measures and then abandoning them (Correia and Merten 2001).

For both cases, the local construction practices improve gradually to better protect people against earthquakes. This results in the development of local seismic culture, i.e., a collection of seismic-resistant measures, practices, and techniques in earthquake-prone regions. The local seismic culture develops based on the local knowledge of inhabitants, enriches the vernacular architecture of a region, modifies construction practices, and incorporates earthquake-resistant elements in vernacular constructions. Exploring the local seismic culture in a region requires a comprehensive study of the performance of the vernacular architecture during past earthquakes as well as a detailed survey of its construction practices and technical features.

The Alpine–Himalayan earthquake belt, one of the most seismically active regions of the world, includes several ancient countries with valuable monumental and vernacular architectural heritage. In the country of Iran, more than 90% of the area located in earthquake-prone regions, and there have been a notable number of casualties and economic losses from a long series of catastrophic earthquakes. Notwithstanding the seismic hazard, earthen architecture, mainly adobe constructions in the centre and southern areas of the country, account for a substantial proportion of its architectural heritage. In the middle of the Iranian Plateau, site of a vast desert with a prevailing hot and dry climate, the city of Yazd boasts a precious earthen architectural heritage from ancient cultures and civilisations from various historical periods. The city of Yazd is the site of many adobe monumental and vernacular constructions, while a local version of the cob technique has been used in the city for centuries.

The historic fabric of Yazd (see Fig. 1), including traditional districts, the qanat system, traditional adobe houses, bazaars, hammams, mosques, synagogues, Zoroastrian temples, and the historic garden of Dolat-abad, are still in use and in good condition. This means that the city's vernacular construction practices and knowledge have survived for centuries. Moreover, the unique roofing system, which consists of different kinds of vaults and domes, is the main feature of the earthen architecture of Yazd and distinguishes it from both architectural and structural points of view. These characteristic features have made the historic fabric of the city worthy of recognition as a World Heritage Site by UNSECO since 2017.

The seismicity of Yazd, with a probable peak ground acceleration of 0.25 g (return period of 475 years), along with the seismic vulnerability of adobe buildings and less known behaviour of vaulted adobe constructions under seismic actions, motivate an urgent need for evaluating their earthquake risk. According to the nomination dossier for Yazd as a World Heritage Site, the International Council on Monuments and Sites (ICOMOS (2017) considers earthquakes to be one of the main threats to property. Moreover, ICOMOS (2017) recommends

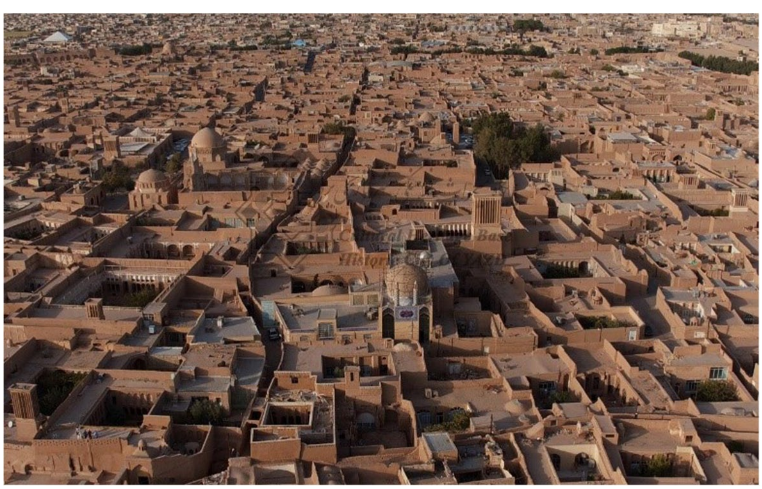


Fig. 1 Aerial view of the historic fabric of Yazd (Source: S.H. Rashedi)

research on seismic risk preparedness for the city historic fabric. Given the necessity of using traditional materials and techniques for conservation projects in Yazd, it is important to investigate the structural features of the earthen constructions in more detail and provide support through specialised technical studies. To this end, a recommendation has been made for further collaboration between the Iranian Cultural Heritage, Handicrafts and Tourism Organisation (ICHHTO) and Yazd University that is to include the education and training of local communities and specialists (ICOMOS 2017).

Local seismic cultures in many regions around the world have been recognised as prone to frequent earthquakes, such as Latin America, the Mediterranean region, Central and Eastern Asia, and the Middle East (for more information, see (Correia, Lourenco, and Varum 2015)). A few research contributions on the local seismic culture in Iran can be found in the literature, e.g., description of an endemic method in (Naderzadeh 2009) and a short review of several techniques in (Golabchi and Javani Dizaji, 2016) and (Zomarshidi 2016).

However, research on finding, exploring, and classifying vernacular earthquake-resistant techniques in Yazd earthen architecture is very limited in the literature. The authors of this paper found that this subject was addressed in two studies conducted by Moles et al. (2017) and ICHHTO (2016), that present a limited number of techniques without addressing the vulnerable attributes of Yazd vernacular architecture. Concerning the seismic behaviour of the vaulted adobe houses in Yazd, Haji Sadeghi et al. (2018) used a numerical approach to evaluate their structural safety. Moreover, an experimental assessment of a typical adobe vault strengthened with a textile-reinforced mortar (TRM)-based compatible composite was performed by Haji Sadeghi et al. (2020).

Therefore, the objective of this paper is to identify and classify earthquake-resistant vernacular practices used in the earthen architecture of Yazd as an important part of Iranian vernacular architecture. The results can be used for projects to strengthen and partially reconstruct vaulted adobe structures in the city. The findings also can make a major contribution to guidelines for the use, maintenance and conservation of historic adobe buildings. Providing such guidelines constitutes an essential part of the conservation plan for seismic risk mitigation that has been proposed by ICOMOS (2017) to the Iranian government. Moreover, the construction practices identified in this study may be considered an important contribution to local seismic culture studies in Iran. The techniques used in Yazd are like those of other regions of the country, particularly central and southern Iran.

To achieve this objective, first, data on vernacular techniques were gathered by surveying the city's historic fabric, interviewing traditional builders and specialists in local conservation, and using data available in the literature. The influence of the earthquake-resistant techniques on the seismic behaviour of buildings was then discussed using scientific principles and some instances from the 2003 Bam earthquake.

The Bam earthquake of 26 December 2003 with a magnitude of Mw = 6.5 and maximum horizontal and vertical peak ground accelerations (PGAs) of 0.80 g and 0.99 g, respectively, affected the city and its vicinity. This earthquake, which caused more than 25,000 deaths, was one of the most catastrophic natural events that occurred in Iran. The Bam Citadel (known as Arg-e-Bam), built between 2000 and 2500 years ago, suffered severe damage during this earthquake. Prior to the earthquake, Arg-e-Bam was considered one of the best surviving (and largest) adobe building complexes in the world (Nadim et al. 2004; Eshghi et al. 2003). Despite being one of the more catastrophic natural events in Iran, the effects of the Bam earthquake became a notable focus of research. For instance, Iranian scholars published a total of 36 papers (Torkzaban 2017), which mainly focused on studies of Arg-e Bam, at the Terra 2021 international conference (e.g., see (Mehraeen 2012; Porta and Maria Santoro 2012; Ravankhah 2012)). Because similar adobe construction practices were used in Arg-e-Bam and Yazd, and several post-earthquake reports (e.g., (Mahdi 2004; Langenbach 2004; Maïni and Davis 2020; Maheri, Naeim, and Mehrain 2005; Mostafaei and Kabeyasawa 2004; Sanada et al. 2004)) are available, the Bam earthquake is appropriate for use in the current study.

2 The city of Yazd: earthen architecture and earthquake

Adobe masonry refers to an earthen construction typology where sun-dried mud blocks, namely, adobe (known in Persian as "Khesht"), are used as masonry units, and mud mortar is often used for head and bed joints. Adobe material is appropriate for use in hot and arid climates due to its high power of cooling and heating energy storage. Located in the central region of Iran, the city of Yazd, as the administrative centre of Yazd province, is surrounded by vast deserts with a particular climate condition. As the driest major city in Iran, the climate of Yazd is characterised by the following features: a hot desert summer (maximum temperature of 45 °C, 12% relative humidity and high evaporation rate); a cold winter (minimum temperature of -14 °C); 3188 sunny hours per year; and approximate annual precipitation of 64 mm (Ayatollahi 2012).

These environmental factors, along with the local availability of high-quality soil for producing adobe units, have made adobe architecture the predominant construction type in the historic fabric of Yazd. The adobe architecture of Yazd, which still is in good condition, comprises religious buildings, defensive fortifications, schools, palaces, gardens, and traditional houses dating back to the Islamic Era from the 6th and 7th centuries onwards. The research performed by Aqasafari et al. (2011) indicates that in 2006, there were approximately 4,200 surviving adobe houses with more than 60 years old in the historic fabric of Yazd. Most of them belong to the Qajar (1785–1925) and Pahlavi (1925–1979) periods, while only a few have survived from the Safavid period (1501–1736) and earlier (Abouei 2006).

The vernacular form of Yazd adobe houses was developed for centuries in response to the desert climate of the city. The houses face a central courtyard around which the residential spaces are organised. The spaces surrounding the courtyard are often roofed by consecutive adobe barrel vaults. The houses are mainly characterised by a pool in the centre of the courtyard and gardens on its sides, as well as by high solid walls around the building. These walls, which were built for security, privacy, and protection from the sun and hot winds, present the only opening to the street via the entrance door (Memarian 1998). These vernacular adobe dwellings are also known as year-round houses because the residential spaces placed around the courtyard are dedicated for use at different seasons of the year. For instance, the "Talar," a three-sided room located on the southwest side of the house, is always shaded and usually used during the summer. The majority of Yazd adobe houses have a wind-catcher, a vernacular Iranian architectural element that provides natural air ventilation and is often located on the south-facing side of the house (Noghsan-Mohammadi 2001). Figure 2 shows a typical adobe house in Yazd.

Notwithstanding the dominant use of adobe material, bricks (baked adobe), floor tiles, wooden elements, gypsum, and plaster of clay with straw have also been used in Yazd adobe constructions. Moreover, the city earthen architecture presents another endemic technique, called "Chineh" (a Persian word). The Chineh technique was used in Iran until almost 100 years ago for erecting long, high, and thick wall-like fences around cities and gardens. The walls were erected following a construction process very similar to the cob technique. The Iranian vernacular builders constructed the Chineh walls from a series of mud bands with a height of approximately 50 cm laid along the wall from one end to the other. The top of each band was smoothed and levelled before proceeding to the next band.

According to the Iranian seismic design code (Standard No. 2800) (BHRC 2015), the city of Yazd is categorised within the "intermediate level of relative seismic hazard" with a probable PGA of 0.25 g for a return period of 475 years (see Fig. 3a). Moreover, the probable PGA of 0.27 g for a return period of 75 years was determined by Ariamanesh (2017). In this regard, Asadi, Neshat, and Barkhordari (2014) obtained probable PGAs of 0.25 g and 0.35 g for return periods of 475 and 2475 years, respectively. For years, Yazd Province has been prone to ground shaking. Earthquake epicentres and important faults of the province and neighbouring areas are depicted in Fig. 3b.

Prior to 1900, the province experienced nine major historical earthquakes with an approximate magnitude greater than 4 (see Table 1). The most important ones (that are known) occurred in 1824, 1844, and 1853. However, there are no relevant reports for the severe damage they caused (Ambraseys and Melville 2005; ICHHTO 2016; Asadi et al., 2014). Thirteen seismic events with a magnitude greater than 4.5 and a distance less than 150 km from the city of Yazd occurred since 1900 (USGS 2021), and no notable damage to buildings was reported (see Table 2).

Although the city of Yazd is prone to relatively low to moderate shocks (nondestructive earthquakes), the presence of eleven active faults around the city and its vicinity (see Fig. 3b) implies a considerable potential seismic hazard. This arises from a well-accepted seismologic phenomenon, namely, destructive earthquakes are caused by active faults after centuries of seismic inactivity. This phenomenon applies to two devasting seismic events that occurred in Iran, and both were felt in the city of Yazd, namely, the 2003 Bam and 1978 Tabas earthquakes. The oldest mosque in Tabas and Arg-e-Bam survived for approximately 700 and at least 2000 years, respectively, before the earthquakes. This confirms that the lack of past seismic activities may result in major shocks with very long return periods (Nadim et al. 2004; Mohajer-Ashjai and Nowroozi 1979).

3 Vernacular aseismic techniques in the earthen architecture of Yazd

The main feature of vernacular architecture, making it different from monumental architecture, is that traditional construction practices must adopt affordable and locally available materials and techniques. Therefore, local seismic cultures usually consist of techniques to prevent building collapse. This means that vernacular solutions improve the building capacity to prevent global collapse, suffering some deformations, cracks, and local damage (Ortega et al. 2017).

The quality of vernacular aseismic constructions and their behaviour against real earthquakes depend directly on the frequency of appearance of earthquakes in a region. The seismic performance of the empirically devised solutions can be evaluated during frequent earthquakes. In other words, if a region has at least one

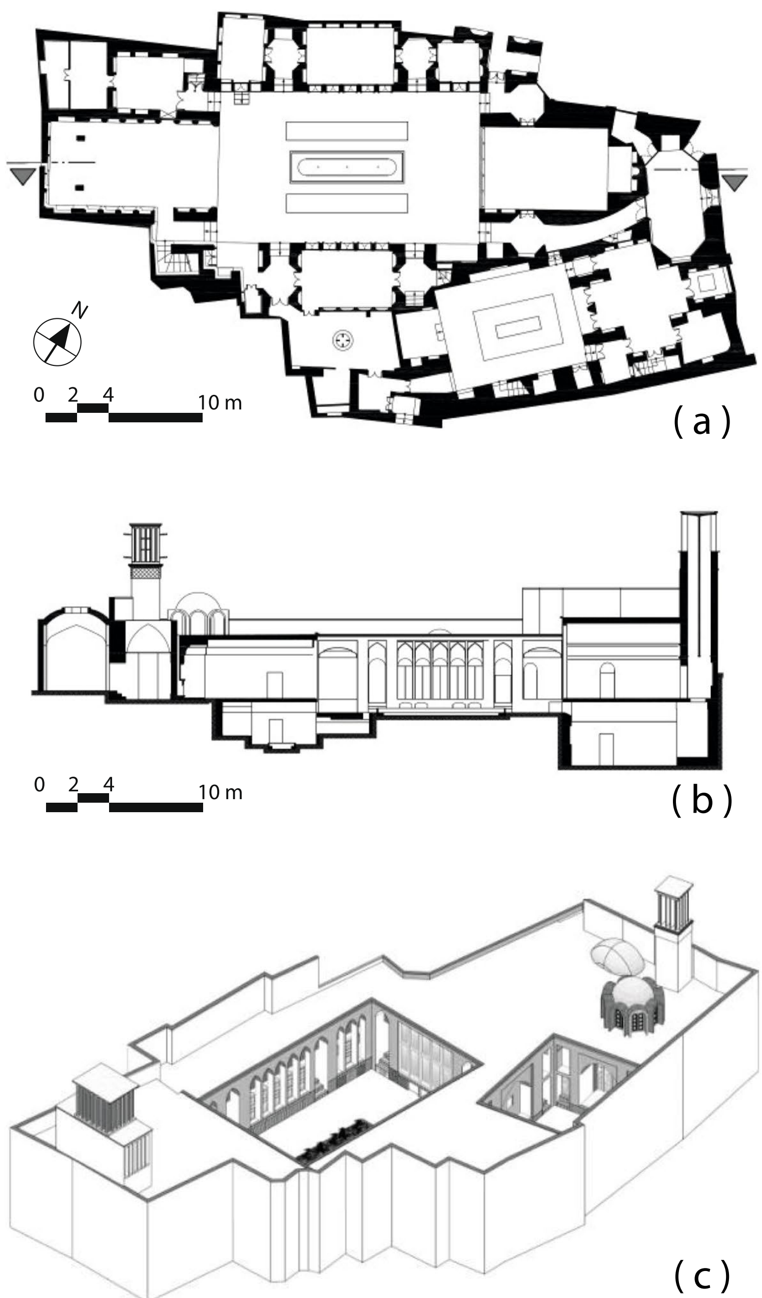
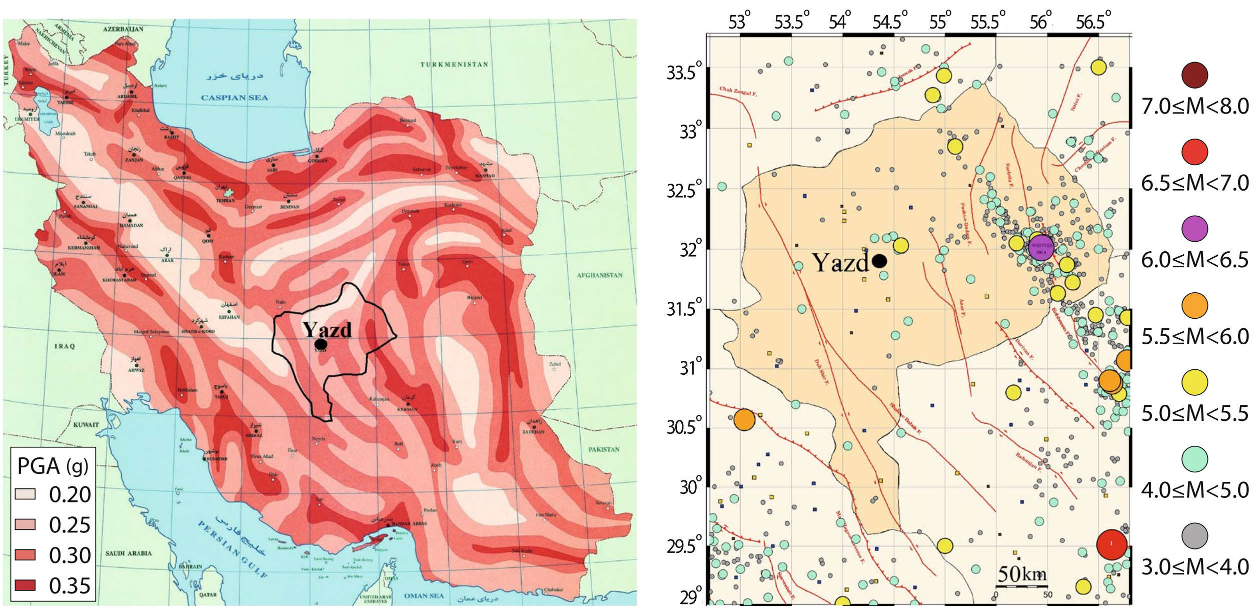


Fig. 2 A typical vaulted adobe house in Yazd: (**a**) plan view, (**b**) cross-sectional elevation view, and (**c**) perspective view of the Aghayee house (Source: Shamseh Consultant Engineering Company)

important seismic event during the average generation lifetime (approximately 70 years), the collective memory of past earthquakes enhances the quality of vernacular aseismic practices, resulting in a complex of different reliable vernacular techniques that is referred to as seismic prevention culture. In contrast, if a region occasionally experiences important earthquakes, i.e., an earthquake occurrence period longer than approximately 70 years, then the efficiency of the vernacular solutions developed after an earthquake are forgotten and gradually abandoned, resulting in a culture of repairs and eventual erosion of seismic culture (Ortega et al. 2017; Touliatos 1992).

As stated in Section 2, seismologic data show that the city of Yazd has not experienced frequent earthquakes with considerable damage to buildings. Therefore, it can



(a) (b)

Fig. 3 Seismicity of Yazd province: **a** seismic hazard zonation map of Iran (Source: IIEES 2017), with the limits of Yazd province, highlighted in black; **b** earthquake epicentres and major faults of Yazd province and neighbouring areas (Source: Dezvareh et al. 2017)

Table 1 Historical earthquakes near Yazd province (Source: Ambraseys and Melville 2005)

No.	Year	Magnitude (M_s)
1	1344	5.7
2	1459	6.6
3	1591	5.9
4	1752	5
5	1765	4
6	1784	4
7	1824	6.4
8	1844	6.4
9	1853	6.5

be concluded that the seismic culture of repairs rather than the prevention culture is dominant in the city. However, Iran has experienced 14 earthquakes of magnitude approximately 7.0 (i.e., one every seven years) and 51 earthquakes of magnitudes in the range of 6.0–6.9 (one every two years). There were approximately 126,000 deaths since 1900, most of them occurring within the 20th century. During this period, nine cities were demolished (one city every ten years) (Berberian 1997; Gholipour et al. 2008).

Living in a country with this history of earthquakes frequently reminds inhabitants and traditional builders of the importance of earthquake-resistant construction.

Table 2 Recent earthquakes near the city of Yazd (Source: USGS 2021)

No.	Year	Magnitude	Distance (km)
1	1958	5.7 M_w	122
2	1973	5 M_b	17
3	1974	5.2 M_b	121
4	1978	4.5 M_b	18
5	1979	4.6 M_b	86
6	1981	4.5 M_b	140
7	1982	4.8 M_b	128
8	1995	4.8 M_b	112
9	2001	4.5 M_b	149
10	2005	4.5 M_b	56
11	2007	5 M_{wc}	147
12	2012	4.5 M_b	64
13	2017	5 M_b	97

This means that the loss of collective memory of past earthquakes hardly happens in seismic-prone countries such as Iran, even in regions where there has not been a destructive earthquake. Hence, the vernacular architecture of the city of Yazd is affected by the experience of destructive earthquakes in neighbouring regions, implying that the architecture presents a seismic prevention culture. Table 3 presents some instances of such earthquakes that caused considerable economic and human losses.

Table 3 Main destructive earthquakes that occurred in regions neighbouring the city of Yazd (Source: Nikouhemat 1979; Ambraseys and Melville 2005; Eshghi et al. 2003)

No.	Year	Magnitude (M_s)	Distance from Yazd (km)	Epicentre location
1	1574	6	360	Kashan
2	1788	6.2	360	Kashan
3	1864	6	280	Chatroud
4	1875	6	200	Kuhbanan
5	1911	6.2	320	Ravar
6	1933	6.4	190	Bahabad
7	1978	7.6	360	Tabas

Evidence from the local seismic culture of the vernacular earthen architecture in the city of Yazd is classified into three main groups:

1) Techniques for reducing the seismic vulnerability of an entire building by enhancing its global capacity in terms of displacement, strength, and stiffness and, or decreasing its earthquake demand;
2) Techniques for stabilising constitutive components of a building to improve the mechanical properties of masonry material (masonry units and mortar) as well as the seismic capacity of masonry elements (walls, roofs, and floors);
3) Techniques for using new structural elements to counteract and absorb horizontal seismic forces generated in a building under earthquake loading, resulting in an increase in the lateral resistance of the building;

3.1 Techniques for reducing the seismic vulnerability of an entire building

Adobe houses, as the major representative of the earthen architecture of the city of Yazd, possess some characteristic architectural features that guarantee their acceptable structural behaviour under both gravity and seismic loads. In this section, these features that improve the seismic behaviour and stability of the whole building, are presented and discussed.

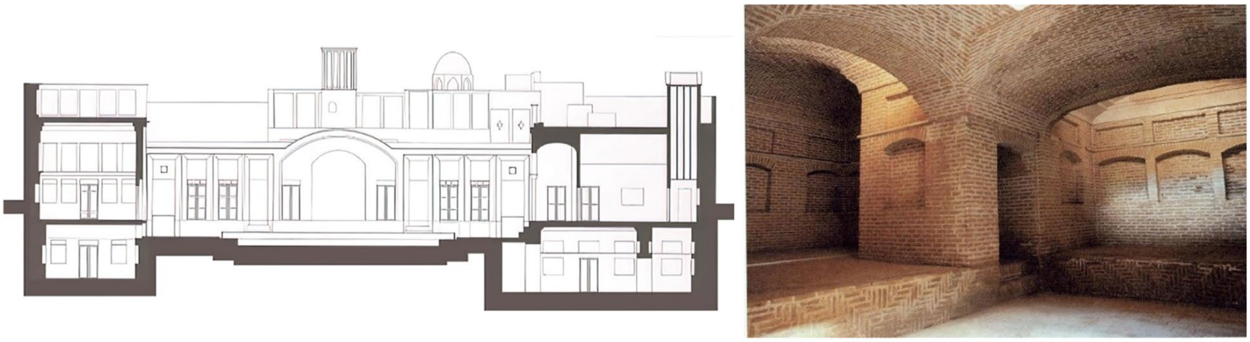
According to archaeological surveys, the old part of the city of Yazd was based on the initial bed made of solid virgin soil, which is locally called Chillow. Traditional builders erected adobe houses on this firm soil (ICHHTO 2016). This vernacular measure not only prevents the settlement of houses under gravitational loads but also improves their seismic performance, reducing the earthquake demand.

As stated in Section 2, in a typical adobe house, the surrounding spaces of the courtyard are covered by consecutive barrel vaults. From a structural point of view, the arrangement of these spaces is often such that the gravity-bearing walls (main walls) are perpendicular to each edge of the rectangular courtyard. However, the gravity nonbearing walls, or gable walls, are parallel to each edge. Such a typical wall layout enables the houses to resist in-plane seismic actions, providing a considerable capacity (the cross-sectional areas of the main walls) in both horizontal directions. This implies a relatively uniform distribution of the main walls in both directions of the houses.

Haji Sadeghi et al. (2018) evaluated the sufficiency of the in-plane seismic capacity of Yazd adobe houses by applying an index-based assessment method to a collection of 60 traditional vaulted adobe houses. The method involved three indices, namely, the ratio between the area of the earthquake-resistant walls and the total in-plan area of the building; the ratio between the earthquake-resistant wall area and the total weight of the building; and the ratio between the shear strength of the structure, which is provided by earthquake-resistant walls and the total base shear for seismic loading. The results indicated that the indices obtained for both horizontal directions of most of the studied adobe houses were within the threshold values for the in-plane safety of the houses.

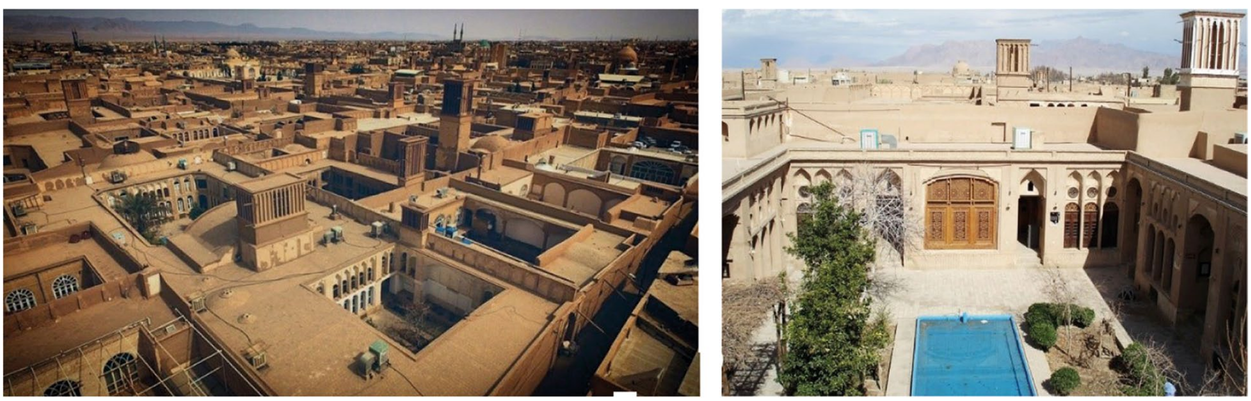
To obtain in situ soils for producing adobe units, traditional builders in Yazd considered cellars beneath almost all the spaces around the courtyard (see Fig. 4a). Furthermore, these cellars provided desirable residential spaces for house inhabitants during the City's hot summers (see Fig. 4b). Meanwhile, constructing a major part of the building below the ground substantially reduces the earthquake demand, benefiting from ground stiffness. A maximum of two stories above the cellar is another important architectural feature of Yazd adobe houses, as shown in Fig. 5a, an aerial view. Statistical analysis indicates that 67% of the houses in the historic fabric of the city of Yazd have one story above the courtyard level (Aqasafari et al. 2011) (for instance, see Fig. 5b). This results in a limited height for the houses, thus improving their seismic performance and decreasing the earthquake demand.

As shown in Fig. 6, Yazd adobe houses often have a relatively symmetric plan and symmetric arrangement of openings along an elevation. Like other types of buildings, the symmetry of buildings has a significant role in their seismic performance and enhances the distributions of seismic actions among structural elements. In the case of masonry buildings, the load-bearing walls develop cracks with different severities during earthquakes, which leads to repeated changes in the centres of mass and rigidity of the building. This causes the in-plan and



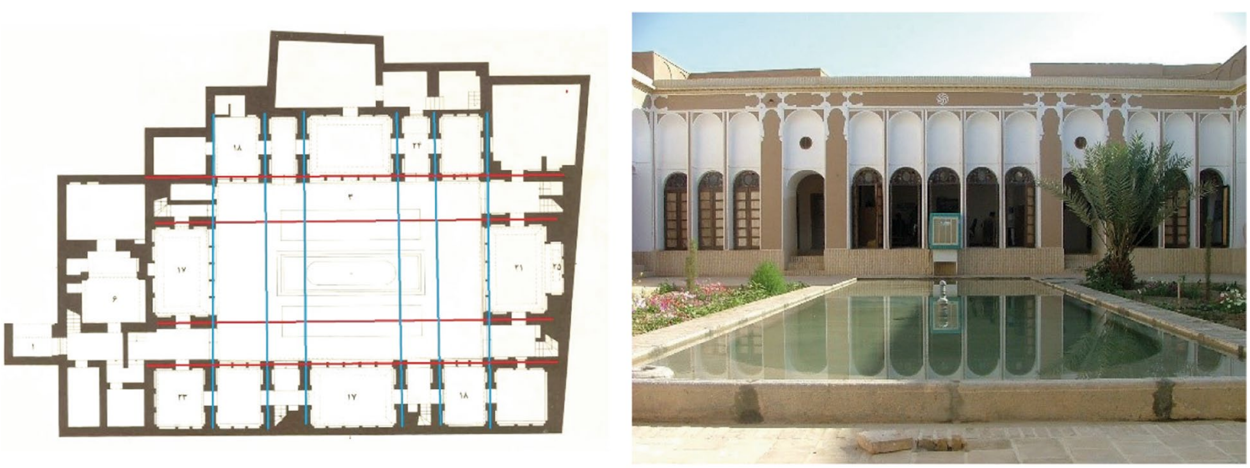
(a) (b)

Fig. 4 Cellar in the Akhavan-sigari house, Yazd: (**a**) cross-sectional elevation view and (**b**) view of southwestern cellar (Source: Haji-Qassemi and Khoei 2004)



(a) (b)

Fig. 5 Low-rise adobe buildings in Yazd: (**a**) view of the city's historic fabric (Source: Hoseini) and the (**b**) Lariha house (Source: the authors)



(a) (b)

Fig. 6 The rather symmetric plan and elevation of Yazd adobe houses: (**a**) plan of the Shafipoor house (Source: Haji-Qassemi and Khoei 2004) and (**b**) view of the Shokoohi house (Source: the authors) in-elevation asymmetries of masonry structures to be more crucial and unpredictable in comparison with those of framed structures (for more information, see (Azizi-Bondarabadi, Mendes, and Lourenço 2019)).

Lowering the centres of gravity of buildings is another vernacular measure used in Yazd adobe houses. This measure improves the global stability of a building against seismic shear actions and thus results in less damage to the building. For instance, due to climate issues, some of the adobe houses in Yazd, known as "Godal-baghcheh," were totally excavated from flat terrain based on the main concept of the central courtyard (see Fig. 7), which lowered the centre of gravity of the partially buried buildings. In addition, underground spaces profit from ground stiffness (Moles et al. 2017).

In this regard, there is also a traditional construction practice applied to vaulted adobe roofs/floors to create a flat surface without increasing their weight. For this purpose, there are a variety of construction details in Iranian architecture (for more information, see (Houshyar, Heydari, and Hemmat Zadeh 2020)). The most common one consists of thin adobe walls with small vaults on top (spandrel walls and vaults known as "Konou" in Persian architectural literature) built upon the vault transversal direction (see Fig. 8a and b).

The empty spaces over the adobe vault extrados not only exhibit excellent thermal performance but also shift the building gravity centre towards a lower level. Moreover, thick spandrel walls and vaults can function as transversal stiffeners and enhance the vault lateral capacity during earthquakes (see Fig. 8c). Notably, the spandrel walls and vaults are sometimes built in the vault longitudinal direction with the same effects of lightening the weight and lowering the centre of gravity of the building (see Fig. 8d).

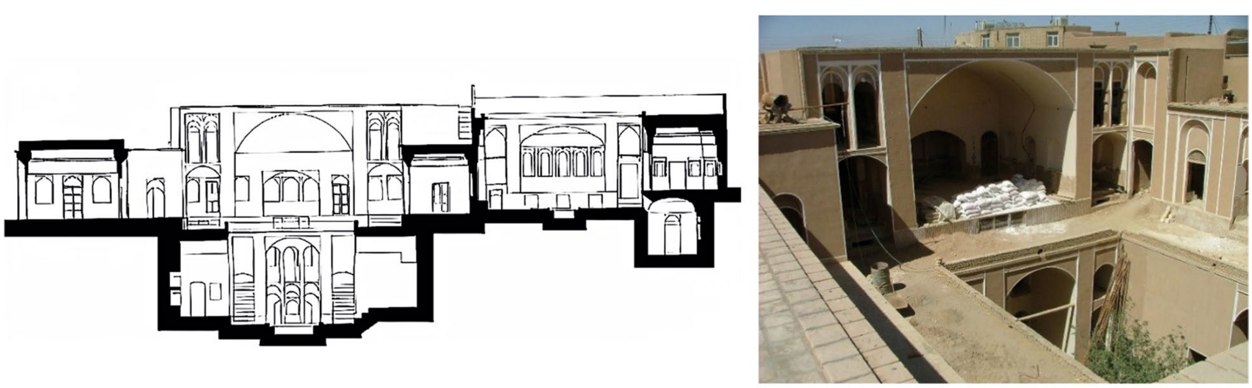
Traditional builders in Yazd also used a particular type of brickwork, Sandoghe-chini, to build much lighter spandrel walls in Konou (see Fig. 8e). Moreover, this type of brickwork is sometimes used upon the topmost course of high perimeter adobe walls (see Fig. 8f). Although the technique might have been devised for security purposes, it can reduce the weight of the upper parts of the walls and consequently lower their centres of gravity.

3.2 Techniques stabilising the constitutive components of a building

3.2.1 Adobe units

One of the main influential parameters on the stiffness, strength, and ductility of a masonry structural element is the mechanical properties of its constitutive components, i.e., units, mortar, and unit-mortar interfaces. The soil grain size distribution, water content, and type of clay play a vital role in the mechanical properties of the adobe unit, particularly its compressive strength. The appropriate soil used for producing adobe units should have enough sand and clay to achieve higher compressive strength with minimum shrinkage and sufficient binding forces, respectively (Minke 2012; Haji Sadeghi 2018). For this reason, a traditional adobe producer (in Persian, Kheshtmal) produced high-quality adobe units using appropriate soil from locally available sources. In this process, the water content was controlled so that both workability and strength requirements were satisfied. Additionally, some natural additive materials, such as straw, ash, cottonseed oil, and goat hair were used to improve the mechanical properties of the adobe.

However, the use of straw in adobe is not so usual in the city of Yazd due to the widespread presence of termites in the city's historic fabric. Moreover, there is special attention to the curing of adobe units in the vernacular



(a) (b)

Fig. 7 Godal-baghcheh in the Olumiha house, Yazd: (**a**) a cross-sectional elevation view (Source: Haji-Qassemi and Khoei 2004) and (**b**) a view in the large courtyard (Source: the authors)

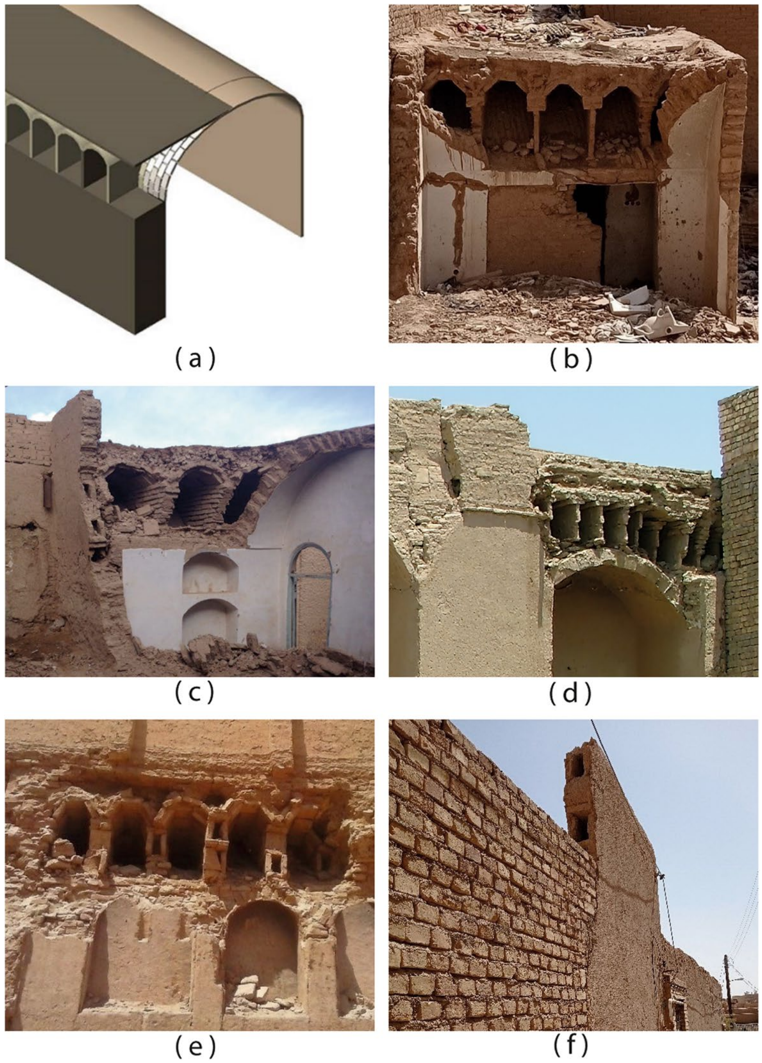


Fig. 8 Techniques used to lightening the building weight and lowering its centre of gravity: (**a**) a schematic view of Konou (Source: Fakhar Tehrani 1998), (**b**) Konou in the vault transversal direction, (**c**) thick Konou in the vault transversal direction, (**d**) Konou in the vault longitudinal direction, (**e**) combination of Konou and Sandoghe-chini, and (**f**) Sandoghe-chini upon the fence walls (Source of b-f: the authors)

architecture of Yazd, such as considering the weather condition and temperature, maintaining the quality of kneading and compacting the mud by hand, allowing the soil to absorb enough water to have a complete reaction between water and clay, and putting wet adobe units in a particular form to improve the drying process. Figure 9a shows the process of adobe production in a local workshop.

To improve the mechanical properties of the unit-mortar interface, there is an innovative vernacular technique called the adobe keyway. In this technique, the labourers use their fingers to scratch the adobe surface (see Fig. 9b) to enhance the shear strength of the unit-mortar interface, which increases the frictional force between the adobe unit and mortar. The adobe units produced by this technique, called Khesht-e-Abmal in Persian architectural literature, present acceptable mechanical properties. For instance, within an experimental study performed by Eslami et al. (2012) on such adobe units sampled from a historic building in Yazd, the mean values of 6 and 1.12 MPa were obtained as the compressive strength of the adobe unit and prism (an assemblage of units and mud mortar), respectively.

3.2.2 Walls

One of the most common vernacular earthquake-resistant techniques around the world is to subdivide the height of masonry walls by continuous horizontal bands

(a) (b)

Fig. 9 Traditional adobe production in Yazd: (**a**) curing of adobe units and (**b**) adobe units with keyway (Source: Ehsan Raad)

(see, e.g., (Inan 2014) and (Langenbach 2007) for the application of timber and brick bands in Turkey, respectively). This technique is also common in Yazd earthen architecture for improving the structural behaviour of walls. The technique consists of the use of brick courses that extend through the wall cross section. These brick masonry bands are repeated regularly along the wall height (see Fig. 10a) and sometimes at the wall base (see Fig. 10b). Adobe walls with brick bands better resist gravity actions due to the much higher compressive strength of brick than adobe. Under seismic actions, the brick courses interrupt the structural homogeneity of the wall, causing relative displacement of the subdivided parts and thus absorbing substantial amounts of energy. In addition to the fused interface action of the brick courses, they prevent vertical crack propagation and the out-of-plane global mechanism of the wall.

For the same reason, the Chineh walls, with no maintenance over 150 years, suffered very little damage during the Bam earthquake (Langenbach 2004), as shown in Fig. 11a. In a Chineh wall made of layered mud bands (see Section 2), the horizontal interfaces between the mud bands interrupt the cracks that tend to develop vertically under static conditions. Meanwhile, under seismic actions, the horizontal interfaces and existing vertical cracks (under gravity loads) provide ductile behaviour for the wall, causing lateral slip between large blocks of the wall. Notably, some traditional builders used adobe units on each mud layer, as shown in Fig. 11b, to improve the structural behaviour described herein.

One of the characteristic features of the main walls of Yazd adobe houses relates to the arrangement of their openings. As shown in Fig. 12a, these walls usually present only a relatively small door at the middle of their length. Openings with a limited area, sufficient distances from the edges, and a symmetric layout make walls less vulnerable to earthquakes by preventing a greater reduction in their shear capacity. Gable walls, which are located along the courtyard edges, usually contain large wooden doors and accessible windows that enable the

(a) (b)

Fig. 10 Application of brick courses in adobe walls in the Yazd historic fabric: (**a**) along the wall height (Source: the authors) and (**b**) at the wall base (Source: Ehsan Raad) inhabitants to escape in case of earthquake occurrence (see Fig. 12b).

Another vernacular practice for stabilising high and thick adobe walls is to insert discharging arches at the base of the walls (see Fig. 13a) and above the openings (see Fig. 13b). The arches undergo a large amount of compressive stress and thus are often made of brick. The discharging arches, which are usually combined with timber lintels above the openings, undergo vertical loading to lighten and better transmit the load on the underlying elements.

(a) (b)

Fig. 11 The vernacular technique of Chineh: (**a**) an example of acceptable performance during the Bam earthquake (Source: Langenbach 2004) and (**b**) wall stabilisation by brick courses, Abarkuh, Yazd (Source: the authors)

(a) (b)

Fig. 12 Openings in Yazd adobe houses: (**a**) main walls of the Zargar house (Source: Haji-Qassemi and Khoei 2004) and (**b**) gable walls of the Mortaz house (Source: the authors)

(a) (b)

Fig. 13 Discharging vaults in Yazd earthen architecture: (**a**) in the base of adobe walls (Source: Ehsan Raad) and (**b**) in combination with a timber lintel above the opening (Source: the authors)

3.2.3 Vaults and domes

Since there are no forests in many parts of the Middle East, the timber needed for flat ceilings is scarce. Hence, both vernacular and monumental adobe architectures are characterised by the use of adobe domes and vaults for covering adobe buildings as not only practical and economical but also a highly ideal endemic technique in regions close to the vast deserts of Iran or along the Nile valley in Egypt, in contrast to other regions of the world. Moreover, the extreme shortage of wood gave rise to the development of the innovative Nubian vernacular technique, dating back to approximately three thousand years ago, for constructing curved roofs, which enables the construction of roofs without any supporting formwork (Haji Sadeghi 2018; Van Beek 1987).

The earthen architecture of Yazd, like a considerable part of Iranian architecture, presents a wide variety of geometrical shapes and construction techniques for curved roofs/floors (vaults and domes) mainly made of adobe. Traditional builders in Yazd used three main vernacular techniques for vault construction:

1) The Roomi technique, in which masonry units are laid with courses parallel to the length of the vault, is used to construct vaults that can cover long-span spaces. The arrangement of masonry units enables the vault to transmit trust lines by undergoing compressive forces perpendicular to the mortar joints (see Fig. 14a). This means that the masonry compressive strength supports the imposed loads. However, the application of this technique requires formwork, making its use less common than other techniques in Yazd.
2) The Par technique, in which masonry units are laid vertical to the circumferential courses. This vernacular building practice, which is very common in the adobe architecture of Yazd, is the local version of the Nubian technique. Like the Nubian technique, several inclined arches are laid together to construct a vault. The degree of inclination of the arches, which makes an essential contribution in the construction process, is less than the optimum degree in the Nubian technique (between 65° and 70° according to (Minke 2012)). In this technique, the trust lines pass within the vault thickness, suffering compressive stresses due to the shear strength of masonry (arising from the unit-mortar interface) rather than the compressive strength. Traditional builders were aware of this structural phenomenon and used some construction practices based on their vernacular knowledge. They used different adobe units for roofing and walls. These special adobe units, which usually are found in the keyway (Khesht-e-Abmal, see Section 3.2.1), should have a much more concave surface than those used in walls to improve the masonry shear strength. Therefore, the Par technique was usually used for roofing spaces with a shorter span than in the case of the Roomi technique. However,

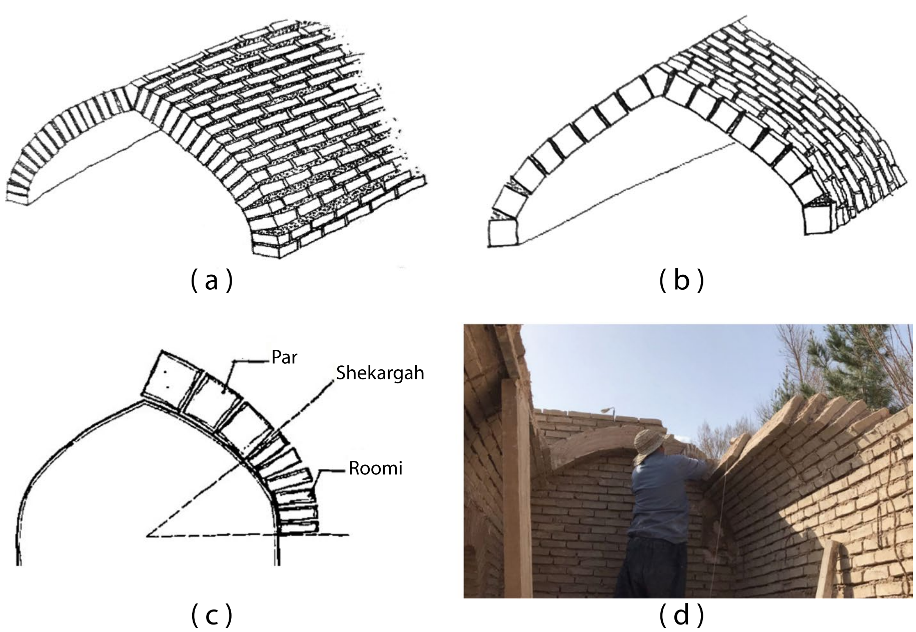


Fig. 14 Different vernacular practices for vault construction in Yazd: (**a**) Roomi, (**b**) Par, (**c**) hybrid techniques (Source of a-c: adapted from Golabchi and Dizaji, 2016) and (**d**) application of the hybrid method in the Green guesthouse in Yazd University (Source: Arman Sedighian)

the vaults built by the Par technique present more shear resistance to horizontal forces parallel to the vault length than vaults built by the Roomi method. As shown in Fig. 14b, the Par technique provides an indirect means to transmit imposed shear forces, unlike the straight load paths of the Roomi technique (Golabchi and Javani Dizaji, 2016).

3) Aware of the vault failure mechanism, traditional builders devised a hybrid technique without supporting formwork. They developed an innovative construction practice in which the brickwork of the Roomi technique extends from the vault impost to the approximate location where a plastic hinge forms (see Fig. 14c and d). This location, Shekargah in Persian architectural literature, is at an angle of 22.5° to the horizon. This is done on both sides of the vault. In the middle part, the vault is built using the Par technique in which the vaulted brickwork starts at the back gable wall.

To the best of our knowledge, there is no reliable range of values for the span of the vaults built by the Par, Roomi and hybrid techniques. In general, quantitative criteria are less common for different aspects of Yazd adobe architecture, such as a vernacular architecture, which was mainly based on the experiential knowledge of builders. Traditional builders selected the appropriate vault construction technique by considering the loading and load-bearing capacity of the vault built by each of the techniques, the type of adobe and mortar (mud, gypsum, etc.), the availability of necessary equipment such as massive and resistant wooden formwork, and the geometrical shape and proportions of the vault (Fakhar Tehrani and Koosheshgaran 2003). Due to the scarcity of wood and ease of execution, the two prevailing vault construction practices in the city of Yazd were the Par and hybrid techniques.

Both of the abovementioned techniques presented acceptable seismic behaviour during the Bam earthquake (Maïni and Davis 2020), as shown in Fig. 15a and b. In addition to construction techniques, the geometrical dimensions and shapes of vaults play an important role in their seismic behaviour. Post-earthquake observations indicate that flat adobe vaults collapse very quickly, while vaults with a high rise-to-span ratio, such as catenary vaults, have better resistance, as presented in Fig. 15b (Haji Sadeghi 2018). Concerning the shapes of adobe vaults, as reported in (ICHHTO 2016) and investigated in (Vali Beig 2003), a special domelike vault, Kolombu (see Fig. 16), is known as the most earthquake-resistant. The Kolombu vault, which is constructed between arches with square bases in most cases, presents good seismic behaviour. This arises from the special brickwork of the vault, which provides structural integrity and leads to its global in-plane seismic behaviour.

The mastery of traditional builders over the knowledge of the structural analysis of vaults appeared in another vernacular technique, which was used to create a flat surface upon a vault. The technique has a much more substantial effect on the structural behaviour of the vault than those already described in Section 3.1.

In this technique, a thin adobe vault is built along the longitudinal direction of the main vaults such that the main vault extrados is the thin vault impost, as shown in Fig. 17a. Once a plastic hinge is formed at the approximate position of Shekargah, the lower part of Shekargah tends to move outward, while its upper part moves inward (see Fig. 17b). Knowing this principle, traditional builders constructed the thin vault within the lower part to prevent outward movement. In this way, the thin vault

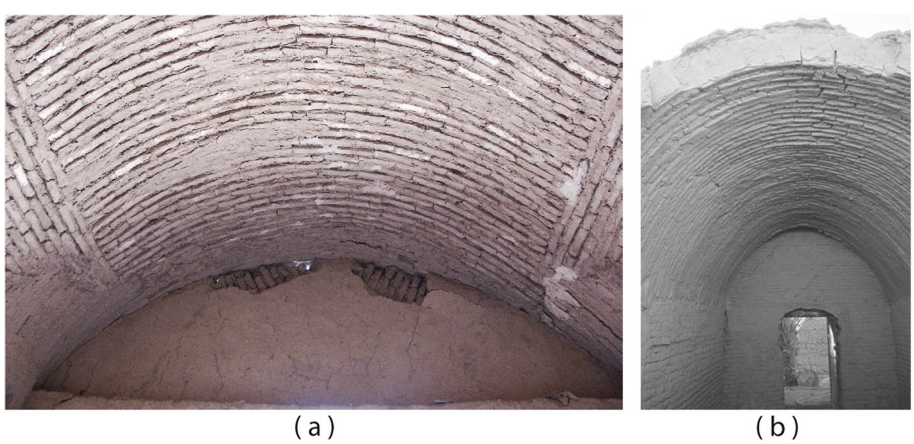


Fig. 15 Acceptable behaviour of curved roofs in the Bam earthquake: (**a**) an adobe vault built by the hybrid technique (Source: Maïni and Davis 2020) and (**b**) an adobe catenary vault built by the Par technique (Source: Minke 2012)

counteracts the horizontal thrust exerted by the main vault, which improves the structural behaviour of the main vault under gravity and seismic loads (Pirnya 1994; Houshyar, Heydari, and Hemmat Zadeh 2020).

Using brick courses that are extended along the vault axis and repeated in its longitudinal direction constitutes another common technique for improving the resistance of adobe vaults in Yazd architecture (see Fig. 18a and b). For the reasons explained in Section 3.2.2 for walls, vaults strengthened by this technique present much better behaviour than other vaults under gravity and seismic loads. However, in an adobe vault, the greater compressive strength of brick vs. adobe makes the brick courses more appropriate to better transmit the actual trust forces of the vault to the load-bearing walls.

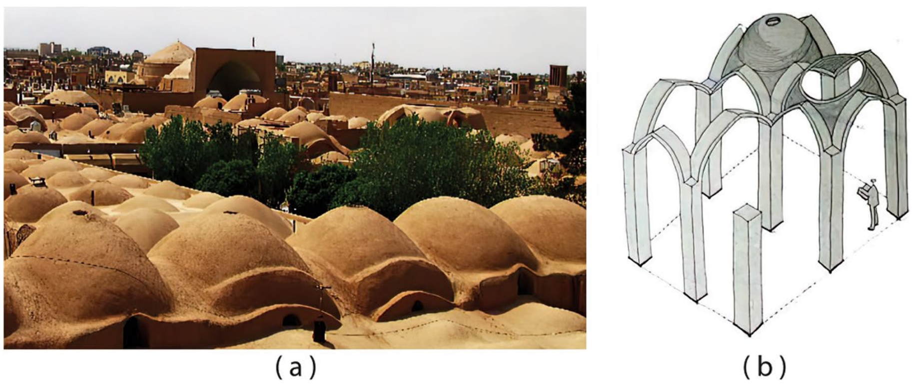


Fig. 16 Kolombo vaults in Yazd adobe architecture: (**a**) the rooftop of the bazaar of Khan Square of Yazd and (**b**) construction technique of the vault (Source: ICHHTO 2016)

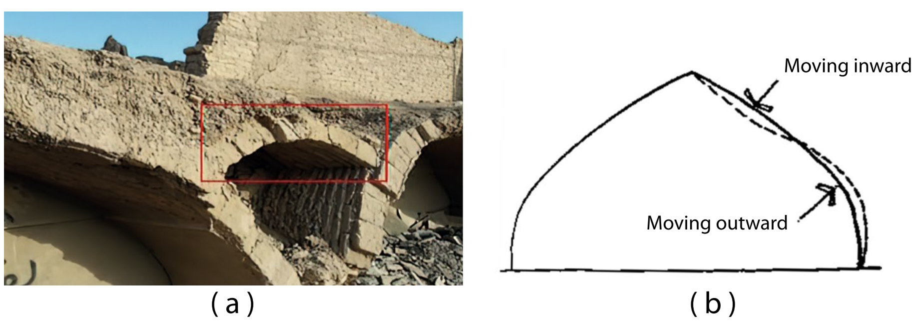


Fig. 17 Using thin vaults on the main vaults to create flat surfaces: (**a**) an instance from Yazd architecture (Source: Houshyar, Heydari, and Hemmat Zadeh 2020) and (**b**) the main vault mechanism around the Shekargah point (Source: Golabchi and Dizaji, 2016)

Fig. 18 Application of brick courses in adobe vaults: (**a**) a barrel vault in the Sadrololama house, Yazd (Source: the authors) and (**b**) an arch from Yazd adobe architecture (Source: Ehsan Raad)

Adobe domes, in particular semi spherical domes with bidirectional load-bearing capacity, presented acceptable performance in the 2003 Bam (Maheri, Naeim, and Mehrain 2005; Mahdi 2004; Maïni and Davis 2020) and 1978 Tabas (Mohajer-Ashjai and Nowroozi 1979) earthquakes. Because domes carry the entire load in compression, horizontal seismic loads do not create sufficient flexural stresses in the dome to result in net tensile stress. Thus, adobe domes generally show better seismic behaviour than adobe vaults (see Fig. 19a and b).

Figures 15 and 19 also indicate that the walls-vault/dome connection remains rather intact under earthquake excitations so that the overall stability of the structure is very likely. As one of the most-used details for wall-barrel vault connection, a timber element is first placed upon the wall. Next, the first courses of the vault are laid, leaning on the timber element and creating an inclined base surface for continuing the vault brickwork (see Fig. 20a). In the vault impost, brick units (fired adobe) are commonly used rather than adobe units due to their greater compressive strength. Gypsum mortar is then applied on the timber and bricks to bond them (see Fig. 20b). By providing a smooth and continuous thrust line, such details better transmit the exerted thrust to the wall underneath the vault. After finishing the vault brickwork, gypsum grout is usually applied on its exterior surface as a vernacular solution to improve the integrity of the vault.

3.3 Techniques for counteracting lateral loads

As the first vernacular technique in this category, the use of horizontal timber elements or metal tie-rods installed between two load-bearing walls at the level of the vault impost is addressed (see Fig. 21a). Considering the horizontal thrust generated by the vault, these elements produce counterthrust and absorb the exerted tension. This technique, commonly used in long-span and low-rise vaults under gravity loads, also presents good structural behaviour under lateral seismic loads. Figure 21b shows a vault at the end of a series of vaults that withstood the

Fig. 19 Acceptable behaviour of curved roofs during the Bam earthquake: (**a**) an adobe dome that was damaged but did not collapse (Source: Langenbach 2010) and (**b**) an adobe dome without damage (Source: Mahdi 2004)

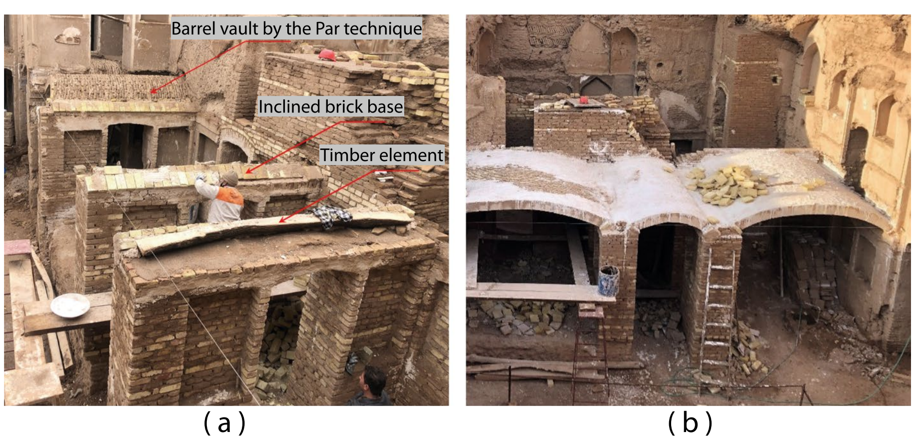


Fig. 20 Wall-barrel vault connection details in Yazd adobe architecture: (**a**) using timber element and brick course at the vault impost and (**b**) finishing by the application of gypsum grout (Source: Ehsan Raad, during reconstruction work on the Mortaz house)

Fig. 21 Application of in-span elements in vaulted adobe buildings: (**a**) the main vault of the Taghdiri house, Ardakan, Yazd (Source: the authors) and (**b**) an undamaged vault after the Bam earthquake (Source: Maïni and Davis 2020)

Bam earthquake and enabled the side vaults to remain intact. This performance is due to the application of two tie-rods along the vault length (Maïni and Davis 2020). The method for the installation of these elements in adobe buildings is very important, as Ginell and Tolles (2000) emphasise their proper anchorage to both walls. Otherwise, localised stress concentrations may occur, causing local compressive cracks.

In Yazd earthen vernacular architecture, masonry buttresses were used to resist out-of-plane movement and overturning of massive, high, and long adobe façades (see Fig. 22a). The local seismic cultures of several regions of the world indicate that buttresses can be considered earthquake-resistant elements that counteract earthquake-induced horizontal forces by their sheer mass to prevent wall rotation. However, a sound connection between the buttress and wall is needed due to the cyclic inherent to seismic loads.Otherwise, without a sound connection, the load path from the wall to the buttress is interrupted. This results in their independent movement and even the tendency of the buttress to rock against the wall when the wall moves away from the buttress during

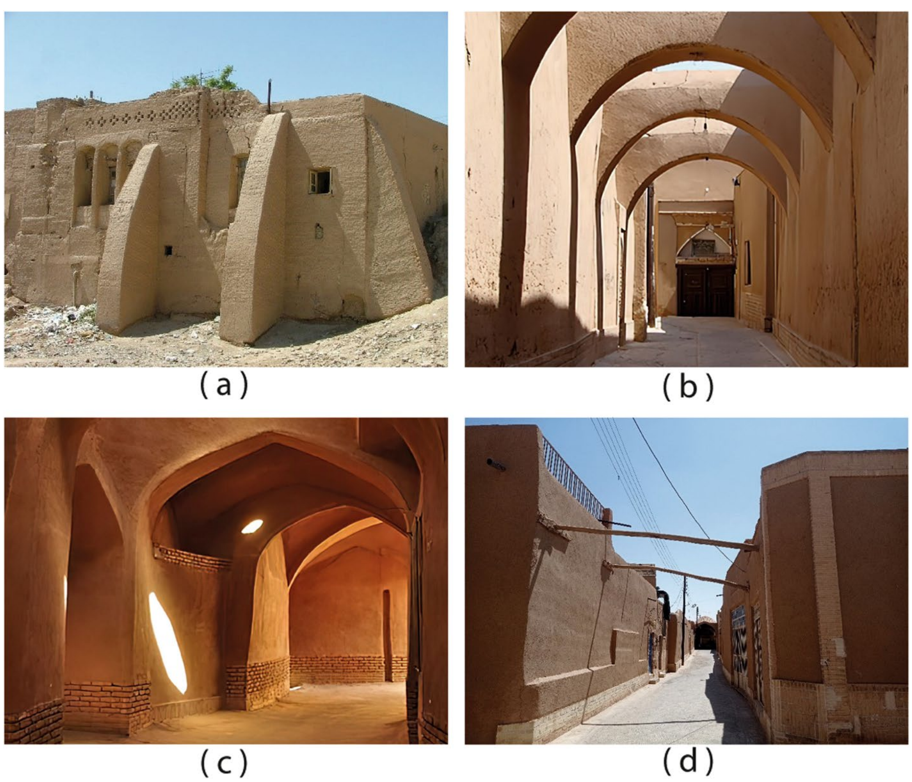


Fig. 22 Different techniques for counteracting lateral loads in Yazd: (**a**) masonry buttresses (Source: Asgharian Jedi and Owlia 2013), (**b**) masonry arches, (**c**) Sabat, and (**d**) timber elements. (Source of b-d: the authors)

an earthquake (Ortega et al. 2017; Michiels 2015). Thus, existing buttresses in Yazd can function as seismic-resistant elements provided that their connections to walls are sufficient.

Concerning the vernacular aseismic measures in urban environments, one of the most common techniques applied in different countries is the use of reinforcing masonry arches, also known as buttressing arches. These arches are used to transmit horizontal forces from one building to another and prevent out-of-plane overturning of the attached façades (Ortega et al. 2017; Moles et al. 2017). Based on the same concept, different vernacular measures have been devised in the historic fabric of the city of Yazd to join facing buildings by spanning arcades with adobe or brick arches (Fig. 22b) and covering arcades with adobe curved roofs (Sabat in Persian architectural literature, see Fig. 22c). Sabat has made a considerable contribution to the betterment of the urban living environment by providing protection against intense sunlight and hot temperatures during summers. Notably, timber elements have been used between facing buildings to prevent local out-of-plane overturning of façades, counteracting lateral loads (Fig. 22d). However, due to their small cross-sectional dimensions, they are not expected to present the same performance as reinforcing arches.

The collaborative action of neighbouring constructions (Ortega et al. 2017) is the main feature of the built-up areas, in particular the Yazd historic fabric, in which almost the entire fabric can be considered a very large block (see Fig. 1). Within this integrated fabric, consisting of several joined buildings, seismic demand (forces and displacement) redistribution occurs among the structural elements of the buildings. This leads to more minor earthquake damage in comparison with similar but stand-alone buildings. Hence, for strengthening or partial reconstruction projects in Yazd, special attention should be given to maintaining the joining elements, not only due to earthquakes but also under static gravitational loads. Most of the time, the thrust exerted by a vaulted structure in a building should be transmitted to another in a neighbouring building, and elimination of the joining elements in arcades interrupts the thrust path.

It is worth noting that the collaborative action of neighbouring constructions is also presented within each of the adobe houses in Yazd. As stated before, in a typical adobe house, the surrounding spaces of the courtyard are usually roofed by consecutive adobe barrel vaults such that the vaults often end to the domes in the house corners (marked with red circles in Fig. 23a). This layout of curved roofs counteracts the horizontal thrust exerted by one vault through the adjacent vault until the terminal dome, which has greater resistance than the other vaults. Prior earthquakes confirmed the crucial role of adjacent vaults in their stability and failure modes, as illustrated in Fig. 23b.

4 Discussion

After evaluating different earthquake-resistant vernacular techniques in this paper, it can be concluded that, in general, the techniques are able to enhance the seismic performance of Yazd adobe vaulted constructions. However, vaulted adobe houses of the city of Yazd present some features that decrease their safety during severe earthquakes. Addressing these features provides a deep insight into the seismic vulnerability of the Yazd earthen architecture, as follows.

One of the main failure modes of adobe buildings during past earthquakes was the out-of-plane overturning of gable walls due to insufficient connection between these walls and vault as well as orthogonal walls (see Fig. 24a). The rear gable wall, which is erected before vault construction, uses only a frictional connection to support the first courses of the vault. Meanwhile, the front gable wall, built after finishing the vault construction, has no connection to the ending section of the vault.

However, the Bam earthquake showed that, in some cases, gable walls underwent severe damage and even collapsed, but the entire vaulted structure remained standing (see Fig. 24b). This means that the main walls and their connection to the vault provided overall stability for the building under seismic excitations, as already discussed in Section 3.2.3. Such conditions saved the lives of residents, while the out-of-plane collapse of gable walls compromised evacuation conditions by blocking streets.

Notwithstanding the overall seismic stability of adobe vaults and domes as mentioned above, the Bam earthquake indicated that using mud mortar with low shear strength, as well as not applying vernacular construction measures such as those addressed in Section 3.2.3, led to local out-of-plane failures of adobe vaults and domes.

Despite this vulnerability, surveying the vernacular adobe architecture of Yazd indicates that the architecture lacks vernacular measures to prevent the out-of-plane failure modes of walls, such as improving connections between structural elements. In this regard, reference can only be made to two techniques, namely, using a timber beam upon the main walls at the vault impost (see Fig. 25a) and implementing wooden ties to connect some of the parallel walls in a house (see Fig. 25b). Engineers can apply both techniques to develop effective strengthening practices using compatible connecting elements to improve the global behaviour (box behaviour) of buildings. However, it should be noted that wooden elements in Yazd and other cities of Iran with similar climate conditions are constantly

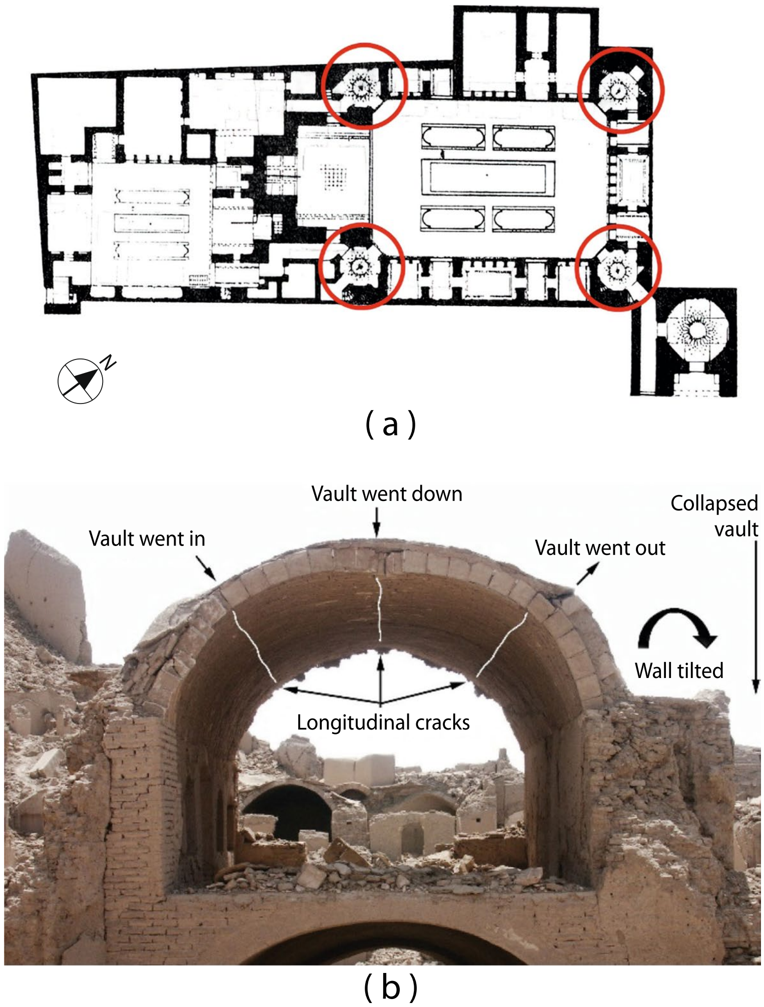


Fig. 23 Collaborative action of neighbouring constructions: (**a**) the layout of curved roofs in the Mortaz house, Yazd (domes marked by red circles) (Source: Haji-Qassemi and Khoei 2004) and (**b**) a vault that lacked collaborative action and was damaged in the Bam earthquake (Source: Maïni and Davis 2020)

Fig. 24 Out-of-plane failure modes of adobe vaults during the Bam earthquake: (**a**) tilting and splitting of a front façade and (**b**) overturning of both gable walls, although the vault remained standing (Source: Maïni and Davis 2020)

(a) (b)

Fig. 25 Vernacular techniques for improving the connections between structural elements with (**a**) timber beams at the vault impost, Zargar house, Yazd (Source: the authors) and (**b**) wooden ties (Source: Asgharian Jedi and Owlia 2013)

subjected to the risk of termites. Using the wood of ash trees and sealing timber elements with gypsum are two common anti-termite vernacular solutions that are recommended for use in strengthening projects.

Concerning the performance of vaults and domes, it should be noted that good ductile in-plane behaviour under severe seismic actions is certain only in the case of strengthened adobe vaults and domes (e.g., externally bonded with low-cost textile-reinforced mortar, see (Haji Sadeghi et al. 2020) for more information), which missing from Yazd vernacular adobe architecture.

As addressed in Section 2, wind-catchers, one of the main symbols of Yazd vernacular architecture, present extraordinary architectural character, special structural features and unparalleled function for regulating environmental conditions. However, their seismic vulnerability is a matter of concern. This vulnerability arises from their height, aspect ratio (ratio of the height and

(a) (b)

Fig. 26 Using timber elements in wind-catchers in Yazd: (**a**) upon the external walls, the Lariha house (Source: the authors) and (**b**) upon the internal walls (Source: Ehasn Raad, during reconstruction work on the Navab-vakil house) the planar dimensions) and construction details (e.g., thin adobe walls and connectivity), which may compromise acceptable seismic performance. As a vernacular solution to mitigate the vulnerability of wind-catchers to lateral movements, wooden tie beams are used at different height levels on both external (Fig. 26a) and internal walls (Fig. 26b). However, it is necessary to further study the effect of this vernacular measure on improving the structural behaviour under moderate and severe earthquakes. The interaction between a wind-catcher damaged by earthquake excitations and the building that supports it is another concern that requires a detailed evaluation.

5 Conclusions

Within the conservation projects defined in Arg-e-Bam before the 2003 earthquake, the majority of the restoration projects did not address the structural integrity of the buildings or their original materials and construction practices. As a result of the earthquake, most of the restored adobe buildings experienced severe damage and collapsed. However, buildings that had not been restored survived the earthquake and suffered far less damage (Langenbach 2004; Maïni and Davis 2020). This indicates the importance of recognising the local seismic culture in a region before earthquakes occur. This recognition allows local conservators to learn effective vernacular techniques and apply them in their restoration projects. These techniques, which use compatible materials and earthquake-resistant elements, can meet requirements imposed by conservation rules.

Considering this important finding, the current paper introduced some evidence from the local seismic culture in Iran, a country with rich architectural heritage and high earthquake risk. To this end, the earthen vernacular architecture of the city of Yazd was selected. First, the vernacular earthquake-resistant practices mainly used in the adobe houses of Yazd were identified and classified. Next, the effectiveness of each technique against earthquakes was evaluated using instances from the 2003 Bam earthquake. As a result, the vernacular techniques introduced in this paper were shown to reduce the seismic vulnerability of adobe constructions not only in Yazd but also in other regions of the country with similar architecture. However, it is necessary to conduct both experimental and numerical research studies to further evaluate the effectiveness of each of the techniques.

Notwithstanding the existence of these vernacular effective techniques, due to the scarcity of vernacular techniques dedicated to connecting structural elements in Yazd adobe constructions, which led to much damage by out-of-plane actions, the current vulnerability of these constructions to severe earthquakes is a matter of concern. The likely local out-of-plane failures of adobe vaults and domes and the vulnerability of wind-catchers under severe seismic actions are other concerns.

Abbreviations
URM: Unreinforced Masonry; PGA: Peak Ground Acceleration.

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Authors' contributions
All the information presented arises from the research done by the authors. All authors read and approved the final manuscript.

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