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Performance of Traditional Arches and Domes in Recent Iranian Earthquakes

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SUMMARY

Arches and domes were the most important elements in Iranian buildings until the beginning of the 20th century. These forms are one of the main features of traditional buildings in small cities and villages in the neighborhood of the desert. The roofs in such buildings are very thick ones. Roofs with thickness up to tens of centimeters and sometimes over one meter are quite common in these areas. During previous earthquakes, wide damages to such traditional buildings were observed, especially those located in the vicinity of faults. The present paper investigates the general performance of arches and domes during recent earthquakes with certain emphasis on such behavior during three of these earthquakes, i.e. Ardekul (May 1997, Ms = 7.1), Avaj (June 2002, Ms= 6.5), and Bam (December 2003, Ms=6.6). The paper also discusses the suitability of these structures in earthquake hazard areas and reviews the main points of weakness of the current construction practices.

INTRODUCTION

By using the term "traditional buildings", we refer to those kinds of buildings that were commonly in use in Iran one century ago. This term may seem illusive, since it includes many types of building's systems that have no apparent similarity. The traditional buildings considered in this paper are those constructed along the traditional line and involve timber, stone, adobe or a combination of these traditional locally available materials. From structural point of view, these buildings can be classified into four main categories:

(1) A system that is based on some type of masonry bearing walls, mainly adobe made of unburned dried mud brick, with either flat or vaulted roofs. In this system, walls are so rigid that no deformation occurs in moderate earthquakes. Although most of the historical monuments have been constructed using such a system, this type of buildings has seized to exist. Mud brick with mud mortar are commonly used to build the traditional vaulted roofs. On the other hand, flat roofs were composed of

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wooden beams that were covered by wooden sheets and a thick layer of mud-straw materials. Vaulted roofs, as shown in Figure 1 are the main mark of vast areas in the neighborhood of the desert; i.e. the eastern, the southern and the central parts of Iran, while the flat roofs are spread all over the country. The majority of traditional buildings in mountainous areas of northern and western Iran have flat roofs. The thickness of these roofs is very large as much as tens of centimeters and sometimes over one meter. Such measurement is used because of the necessity for insulation against hot and cold climates. During previous earthquakes, heavy roofs caused high human casualties.

(2) A system similar to that in (1) but walls are thinner and the kinetic energy of the earthquake is absorbed by deformation. In this case a wooden ring beam is used to take the bending forces. During previous earthquakes, this system has proved its ability to resist earthquakes providing that suitable connections between walls, roofs and ring beams are provided. This system belongs mainly to mountainous areas, but can be also found in other parts of the country, especially in large cities

(3) A system similar to that in (2) but roofs are fixed to wooden columns within the wall. This system has some similarity to the confined masonry wall system, which consists of tie columns and beams. This system has proved its ability to resist earthquakes in the past. As shown in Figure 2, even by using thin irregular members, this system has prevented the collapse of the roof. However, and to have an ideal system, it is quite vital to provide suitable connection details. This system is mostly used in the mountainous areas and in some special buildings in large cities.

(4) A system that is based on a complete wooden frame. This system is mostly used in the mountainous areas of northern and western Iran, and has performed reasonably well in many earthquakes in the past. However, connections between the main members are seen to affect critically the seismic performance of this system.

In recent years and due to the relatively high cost of traditional construction, lack of proper construction material and the lack of qualified trained people, the quality of the newly constructed traditional buildings has been deteriorated. Accordingly, most of the existing buildings that considered as “traditional” ones have not met the minimum requirements for such buildings. Unfortunately, no official regulations exist for these buildings in Iran. Furthermore, the blame for high causalities in previous Iranian earthquakes was squarely laid at the door of these buildings. On the other hand, and due to the existence of new materials and systems that have been supported by relatively good codes of practice, most of traditional buildings have been replaced by new systems such as reinforced concrete frames, steel frames, confined masonry buildings, and semi-engineered brick buildings.

Figure 1: A typical village in eastern Iran with vaulted roofs.

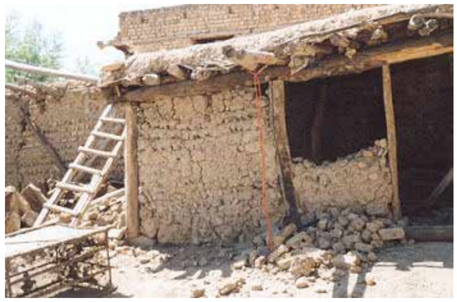

Figure 2: A typical traditional building with wooden beams and columns in western Iran after the 2002 Avaj's earthquake.

IMPORTANT EARTHQUAKES IN THE LAST DECADE

Iran is one of the highest countries of the world in its vulnerability to earthquakes. Table 1 shows some of the most destructive earthquakes that have occurred in Iran in the last decade. The majority of these earthquakes were shallow ones with focal depths around or less than 10 km. In Iran, and due to lack of a precise seismic network, specific numbers for focal depths have always been doubtful [1].

Table 1. General data on the most important earthquake in the last decade [2-4]

Date	Location	Latitude	Longitude	Mag. (Ms)	Deaths	Other Losses
23/2/1994	Sephidabeh, eastern Iran	30.81	60.57	6.1	6	The area is relatively unpopulated; thus, losses kept to a minimal.
1/3/1994	Firuzabad, southwestern Iran	29.10	52.62	6.1	2	50 injured
4/2/1997	Bojnoord, northeastern Iran	37.66	57.29	6.8	90	1984 injured; around 14400 houses experienced considerable damage
28/2/1997	Ardebil, northwestern Iran	38.08	48.05	6.1	965	2600 injured; 13500 houses were destroyed with 36000 people became homeless
10/5/1997	Ardekul, eastern Iran	32.55(1)	59.98(1)	7.3	1572	4460 injured; around 17600 houses experienced damages with 72000 people became homeless
14/3/1998	Golbaf, southeastern Iran	30.15	57.60	6.9	5	50 injured; 2000 houses were destroyed with 10000 people became homeless
4/3/1999	Southern Iran	28.34	57.19	6.7	1	Around 500 houses damaged
6/5/1999	Southwestern Iran	29.50	51.88	6.2	26	100 injured; 800 houses destroyed with 300 houses collapsed completely.
22/6/2002	Avaj, western Iran	35.67(2)	48.93(2)	6.5	261	1600 injured; around 15000 houses experienced considerable damage.
26/12/2003	Bam, southeastern Iran	29.01(3)	58.26(3)	6.6	More than 41000	50000 injured; 100000 homeless

1. According to USGS, the epicenter of this earthquake is 33.83 latitude and 59.81 longitude

2. According to USGS, the epicenter of this earthquake is 35.63 latitude and 49.05 longitude
3. According to USGS, the epicenter of this earthquake is 29.00 latitude and 58.33 longitude

THE 10TH MAY 1997 ARDEKUL EARTHQUAKE

The Earthquake

On May 10, 1997 at 7:57:29 GMT equal to 12:27:29 local time an earthquake with the magnitude of Ms7.1 occurred in the south region of Khorasan province in Iran. The earthquake maximum intensity was estimated to be in Ardekul as IX (MMI scale), which situated at 200-meter distance from the fault. It seems, however, that earthquake intensity in Ardekul village is also under the influence of site effect as it located over Clay and Marl sediments. The intensity of IX was also observed in Haji-Abad and Esfaragh villages. Generally, it was noted that the damage done in the southern part of the area along the surface fault was more severe than in the northern part [5]. The maximum acceleration recorded in this event was about 0.19g at the Ghasemabad station 88 km from Ardekul. There is no doubt that the acceleration in regions closer to the epicenter of the earthquake is much higher than that recorded one.

Buildings

For traditional buildings in the earthquake-stricken area, two kinds of roofs were observed, vaulted and flat roofs. In general, traditional houses experienced considerable damage throughout the region. Bearing walls of these houses were made of stone, adobe, brick and mud. The majority of such walls had thickness in the range of 40 to 50 cm. In the southern part of the area along the surface fault and especially in villages surrounding Ardekul inside a circle of 16 km radius, most of the traditional masonry houses were completely collapsed and flattened. However, the performance of some of adobe buildings with vaulted or flat roofs, even in places that had the highest earthquake intensities was better than other semi-engineered and engineered brick buildings. The apparent factors that account for the good performance of the survived adobe buildings was: the low height to thickness ratio of the adobe walls, the relatively few openings, and the relative good quality of adobe [6]. In addition to traditional houses, some engineered buildings were also present in the region. In 1979, some considerable part of the 1997 earthquake-affected area was the scene of two intense earthquakes. The predominant structural system used in the reconstruction process consisted of reinforced concrete frames with unreinforced masonry infills. The majority of these structures suffered considerably in the 1997 earthquake.

Vaulted Roofs

The two main types of vaulted roofs in the earthquake-stricken area were domes and barrel vaults. These roofs are shown in Figure 3. Adobe bricks and mud mortars with thickness not less than 25 cm were used to build the vaulted roofs. In some cases, and as has been reported by Hankuno [5], the thickness of some vaulted roofs were more than one meter. Burned bricks were also used for some vaulted roofs in the area. In a circle of 16 km radius around the village of Ardekul, where the earthquake had its highest intensity, adobe houses with vaulted roofs were also suffered heavy damages. Most of these failures were due to the weakness of wall-to-wall and wall-to-roof connections. However, and as reported by Hakuno [5], some of these buildings had remained stable and the vaulted roofs had not been collapsed. This phenomenon was also observed in other villages in the southern part of the earthquake-stricken area [5].

The main problem with a dome placed over a square plan is the transition from the square below to the circle above. In historical buildings of Iran, different solutions for this problem can be found [7, 8]. However, these solutions have not been implemented fully in constructing the small 2-3 meter diameter domes found in the area and used for small houses.

To have better understanding of the contribution of vaulted roofs and domes to the total stability of traditional buildings, the author has carried out elementary finite element analysis. By applying horizontal forces to a dome, all the points within the cross sectional area of the dome has remained in compression. However, minor tensile stresses at the intersection line of dome and the remaining part of the square plan were observed in this analysis. In addition to the wall-to-wall and roof-to-wall intersections, this line of intersection can be considered as another weakness point for this type of structures.

Some of rural houses in the area had barrel vault roofs. Such a vault is usually restricted to a relatively narrow width as shown in Figure 3. In traditional buildings, and due to the lack of ring beams between roofs and walls, walls carry all vertical and horizontal forces. As the finite element analysis shows, the failure of these types of structures is resulted when excessive displacements perpendicular to the vault generator occurred.

Figure 3: Typical adobe buildings with vaulted roofs in eastern Iran.

THE 22ND JUNE 2002 AVAJ EARTHQUAKE

The Earthquake

On June 22, 2002 at 2:58:20 GMT equal to 7:28:20 local time, an earthquake struck vast regions in the western part of Iran. The magnitude of this earthquake was Ms6.5. The earthquake maximum intensity was estimated to be in Ghangureh and Abdareh as VIII (MMI scale). The maximum acceleration recorded in this event was about 0.5g at the Avaj station that is situated 26km from the earthquake epicenter. There is no doubt that the acceleration in regions closer to the epicenter was much higher than that recorded, and this high acceleration may be regarded as one of the major reasons of destruction and collapse of rural buildings.

Buildings

During this earthquake, a large number of engineered as well as non-engineered buildings were severely damaged and collapsed. Across the earthquake-stricken area, adobe houses had suffered heavy damages; the damage level mainly depended on the distance from the rupture surface faulting. In Abdereh and Changureh, most adobe buildings were completely destroyed. The main cause of the destruction of these buildings was the poor quality of construction materials; i.e. adobe and mud mortars. Moreover, many steel frame structures in Changureh failed mainly due to the absence of bracings, soft stories, and bad connections.

Vaulted Roofs

Although most of the buildings in this mountainous area having flat roofs, the existence of masonry buildings with vaulted roofs had also been observed. As an example, Figure 4 shows a brick masonry storage building with vaulted roof that is situated three kilometers from the surface faulting. In this particular case, the lateral load direction was parallel to its generator (longitudinal direction) and the performance of this roof was excellent. Beside residential and storage buildings, the domes of many mosques, holy shrines, and towers were among the affected buildings by this earthquake.

The shrine of Imamzadeh Alaedin is one of the historical places in the region. The dome of the shrine was a double shell one. The exterior shell of the dome was damaged during previous earthquakes and had been repaired. The inner layer seemed intact and not reconstructed. In this earthquake, the outer shell was damaged again [9]. The arches surrounding the shrine had suffered some small damages as well. However, the vaulted entrance had shown good behavior. In the village of Mansour, the shrine of Imamzadeh Mansour is also damaged and a big crack had been noticed in its dome [9]. In this shrine, damages to arches and vaulted roofs were more severe than that observed at Imamzadeh Alaedin. In Hamadan's Province, the dome of the shrine of Imamzadeh Ismail was completely destroyed.

The most important monument in the earthquake-stricken region is the pair tower of Khargan. Their histories go back to the 11th century. Each of these towers is an octagonal one that has a height of 15 m and a diagonal length of 11 m. At the top of each tower, there is a double shell dome. It is believed that one of these domes is among the early double shell domes in Iran, if not the first. However, because of the special shape of these domes and due to the lack of maintenance, the outer shell of both domes was demolished, years before the earthquake. During the 2002 earthquake, one of the remaining inner shells was completely destroyed and many cracks appeared on the tower walls. The strengthening and renovation processes of these two towers are currently underway.

Adobe buildings with vaulted roofs had suffered heavy damages; the damage level mainly depended on the distance from the rupture surface faulting. A close study of these domes showed that use of weak mud mortars in the construction of domes has resulted in their lack of coherence. Further weakening of mortars due to time and weathering factors had increased the speed of disintegration of these domes and as shown in Khargan towers the shocks of the earthquake were merely the final stroke. On the other hand, a preliminary finite element analysis for double shell domes has shown that; and for most geometrical configurations and loading conditions, the outer shell of the dome is more vulnerable than the interior one.

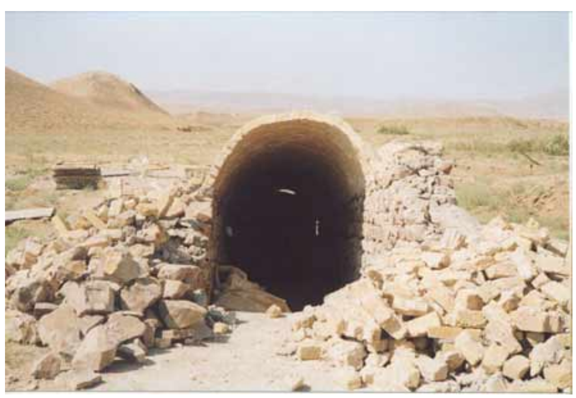

Figure 4: A masonry barrel vault, 3 km from Avaj's fault, western Iran

THE 26TH DECEMBER 2003 BAM EARTHQUAKE

The Earthquake

On December 26, 2003 at 01:56:56 GMT equal to 5:26:26 local time, an earthquake with magnitude of Ms6.6 hit the city of Bam in Kerman province, southeastern of Iran. The coordination of the epicenter of this earthquake has been determined by IIEES [10] at 29.01N and 58.26E around 10km to the south west of Bam. At a later stage and based on the surface evidences reported in [11], the epicenter is located closer to the city of Bam. According to this report, Bam's fault with a near north-south direction passes less that 1km distance to the east of Bam. The earthquake maximum intensity was estimated to be in Bam and Baravat IX (MMI scale). However, this intensity was confined to a small strip of 5 km wide and around 20 km Length. Generally, it was noted that the damage done was concentrated in very limited area and the intensity of earthquake decreased rapidly to VI at Darzine, a village at a distance of 27 km to the north west of Bam. The maximum horizontal recorded accelerations were 0.81g and 0.65g for the east-west horizontal and north-south horizontal components respectively, and 1.01g for the vertical peak acceleration [12]. The high value of the vertical peak ground acceleration with reference to the horizontal components values is indicative of the fact that accelerograms are recorded in the near field.

Buildings

Many buildings in Bam have been hit hard in this earthquake. Many villages around the city also underwent extensive damages. In this area, which had around 200000 inhabitants, the traditional buildings account for more than 30 percent of the total number. They are mostly made of sun-dried mud bricks. The most important ancient monument in this area is the citadel of Arg-e-Bam. It is situated at the northeastern skirt of the city at very short distance from the epicenter. The monument was constructed mainly from mud brick and clay. The total area of this adobe masonry fortress is more than 200000 square meters. Accordingly, this complex was the largest of its kind in the world. Its construction goes back to more than 2000 years and it was repaired many times in the past. This fortress had been used for residential and commercial purposes with some strong military facilities in the forms of towers and high walls. In modern times, its residential and commercial functions had diminished gradually and seized to exist around the beginning of the 19th century. However, a small barrack remained inside till 80 years ago. Other forms of structures including unreinforced masonry buildings, confined masonry structures and steel frame structures are also been noticed in the stricken area. The general performance of most of these buildings was not satisfactory.

Vaulted Roofs

Unlike the seismic-prone area of Avaj, the roofs of most residential buildings in this area are vaulted ones. Timber is rarely used in these buildings; however, the traditional method of increasing stability of masonry walls by using horizontal timber reinforcements is quite known in the area and has been used in some of the walls in Arg-e-Bam. In what follows, a general discussion on the performance of the structural elements of these roofs is carried out.

The Arch

The arch can have many architectural and structural functions. In the traditional Iranian architectural system, arches are used to face the central courtyard of the building, as shown in Figure 5. The small arches shown in this figure is merely a facade that is hiding the real structure behind it and merely worked as a shear wall. For the arches perpendicular to this direction, a complete separation between the facade wall and original structure had occurred, which led to partial failure of these walls as shown in Figure 6. As a structural component, and as shown in Figure 7, arches are used to transfer loads from a dome to its pillars. In this structure, arches of different sizes and shapes have been assembled to fulfill this function. It is clear from this figure that earthquake forces had led to serious sliding and opening of joints in the pillars. This partial failure was caused by the unbalanced thrust transmitted from the adjacent arches. This problem was observed in single-span vaulted roofs as well. To resist the horizontal seismic movement, the joint between the arch and the pillar must be inclined and the pillar must have enough width to keep the resultant forces within the central part. It is clear from Figure 7 that this later condition has not been met. Many of the buildings that survive the earthquake have successfully fulfilled these rules as shown in Figure 6.

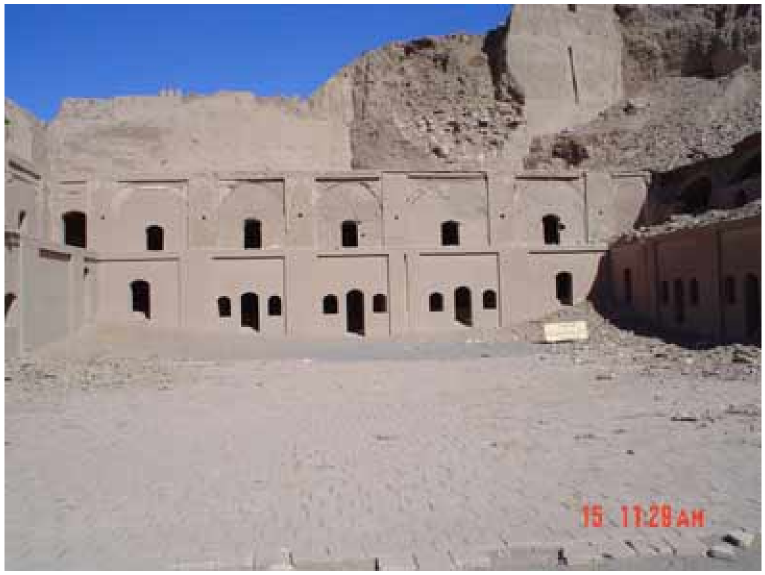

Figure 5: The east-west wall of the Military barrack in Arg-e-Bam.

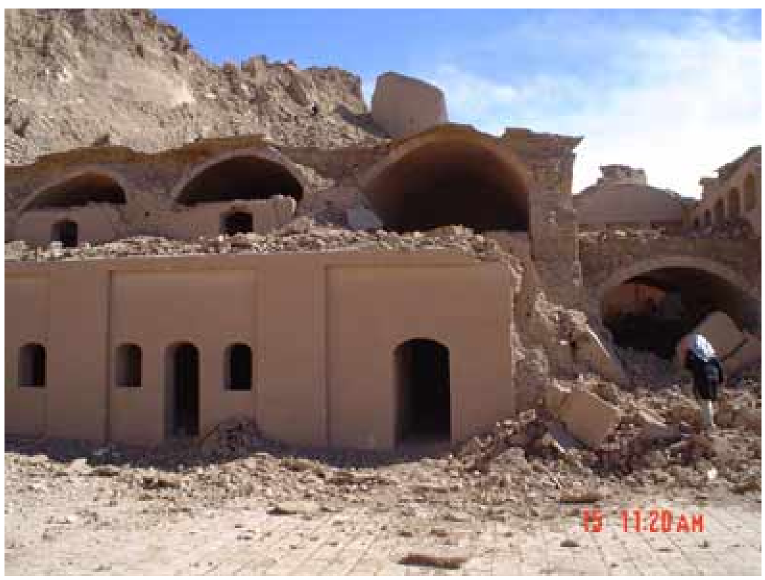

Figure 6: The north-south wall of the military barrack in Arg-e-Bam.

Figure 7: Arches *used* to transfer loads from a dome to its pillars.

The Barrel Vault

The number of shapes and forms of barrel vaults used in the Bam's area is quite large. As example, the types of those found in small and humble houses differ considerably from those found in large and luxuriance ones. The most common types used in residential buildings are in the form of long semi-cylindrical roofs with two plates or semi-spherical caps at their ends. Other types of barrel vaults similar to the old Sasanian ones are also used, as shown in Figure 6.

The surviving roofs can be seen all over the city and even at short distance from epicenter. In Arg-e-Bam, many barrel vaults were destroyed in the earthquake. However, others had shown good behavior even when the direction of the movement was perpendicular to their generators. Although it is very difficult to understand the reason of this good behavior, it has been noticed that the thickness of buildings' roofs inside Arg-e-Bam is much less than the corresponding ones inside the city. Other reasons like site effect may also be responsible for this behavior. Figure 8 shows another example of such roofs. It can be seen from this figure that bearing walls had minor cracks compared to those appeared in the roof. The pattern of cracks in the roof indicates clearly that some vertical forces were applied to it. That can be explained by the high vertical acceleration component of this earthquake. Furthermore, some new masonry buildings in the city of Bam had been constructed using barrel vaults as their roofs. These roofs were connected well with the wall by ring beams. With the exception of minor failures and some cracks, these roofs performed satisfactorily. The failures and cracks observed were mostly concentrated at regions in the neighborhood of the intersection line of the barrel vault with the end cap.

In most cases, complete destructions of adobe buildings including barrel vault roofs were observed. The sequence of such a failure usually starts with the separation of perpendicular walls and later on; and due to excessive deformations and lack of tie beams at the level of roofs, to the separation of walls and roofs. However, in some other cases, it had been noticed that the failure of these roofs had not followed walls' destructions. While walls remained relatively intact, a plane of failure formed few centimeters above the wall-roof intersection line. This phenomenon had been observed in many previous earthquakes as well. Reasons for such failure remain mostly within the classical causes of heavy roofs and weak connections. However, in Bam's earthquake the additional vertical forces had increased the possibilities of such a failure.

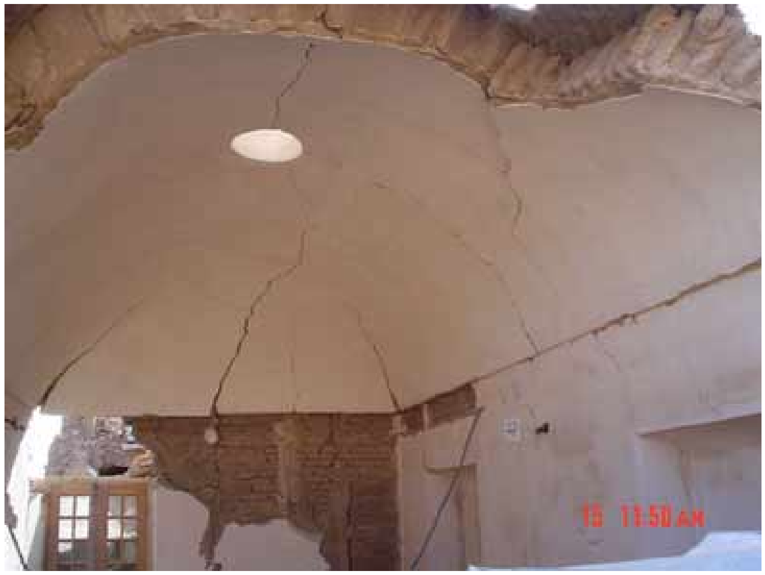

Figure 8: A barrel vault with cracks in Arg-e-Bam

The dome

Domes are one of the main features of the city of Bam. They can be seen in different sizes and shapes all around the city and inside the historical monument of Arg-e-Bam. The most noticeable type is the 2-3 m diameter commonly used in humble houses. However, larger domes have also been observed. The methods used to support these domes and transfer their loads to bearing walls are quite different from one place to another. The simplest method used to support small domes is by placing them directly on bearing walls. As it is well known, the existence of openings like doors and windows in these walls destabilizes the dome structure. To overcome this problem, early Iranian architects used arches to transfer stresses from the dome to either side of the opening as shown earlier in Figure 7. This was the start of development of the dome on four arches that later took more complicated forms.

In the majority of cases, a complete destruction of adobe buildings including their domes was observed. An example of such destruction is shown in Figure 9. This figure shows the stable courtyard inside Arg-e-Bam with many surrounding buildings that have a large number of domes, before and after the earthquake. The majority of domes shown in Figure 9a were destroyed completely as shown in Figure 9b. Supporting walls were also destroyed partially or completely. Although such walls had very small openings, it was the normal forces to the wall plane that had caused most damages. However, it is interesting to note that parts of these buildings that are located in the right corner of Figure 9 had survived the earthquake by taking advantage of their adjacency to two relatively rigid walls. In the author's opinion, the reaction applied by these two walls during the earthquake had increased the capacity of these parts to resist vertical forces applied by the vertical acceleration component. Prominent among the surviving domes in Figure 9, are those shown in Figures 10 and 11. The vaulted roof shown in Figure 11 has been used to support some of these domes. In this figure, additional arched panels had been added to this structure in order to relieve the bearing walls from parts of their loads. Accordingly, each dome is supported on two arches and two walls. In Bam's earthquake, the forces applied were perpendicular to the arched panels and parallel to the wall. Arches in this case had fulfilled the role of bracings in inactive walls and distributed the loads between active walls to prevent partial failure. The dome-arched panel system shown in Figure 11 is quite similar to that shown in Figure 10. The direction of movement during this earthquake was also parallel to the walls and perpendicular to the arch panels. As it is clear from Figure 11, one of the arches had suffered minor failures. This failure reflects the disability of the arch panel to transfer forces between active walls.

All surviving domes found in Arg-e-Bam and in the city had sustained some cracks. The typical pattern of the cracks observed in most cases is that of a meridian crack. Furthermore, it is clear that such cracks had been initiated at points closer to the intersection line of dome and flat roof.

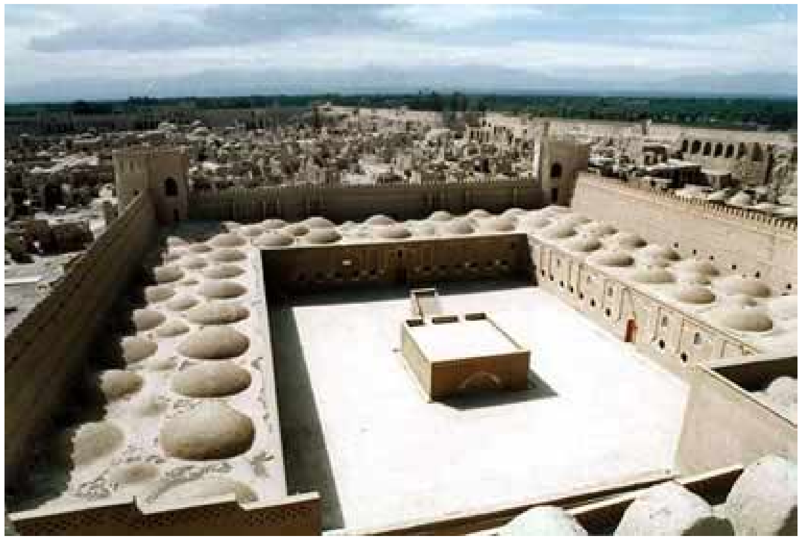

Figure 9a: A courtyard in Arg-e-Bam before earthquake.

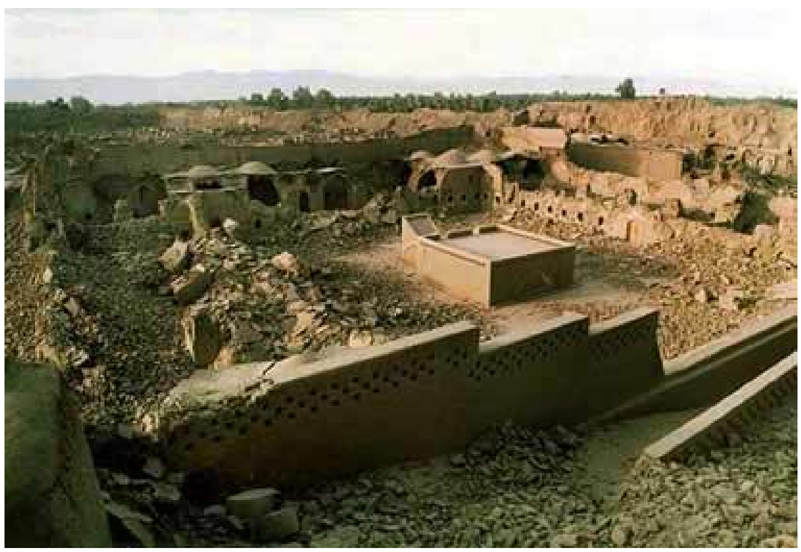

Figure 9b: A courtyard in Arg-e-Bam after earthquake.

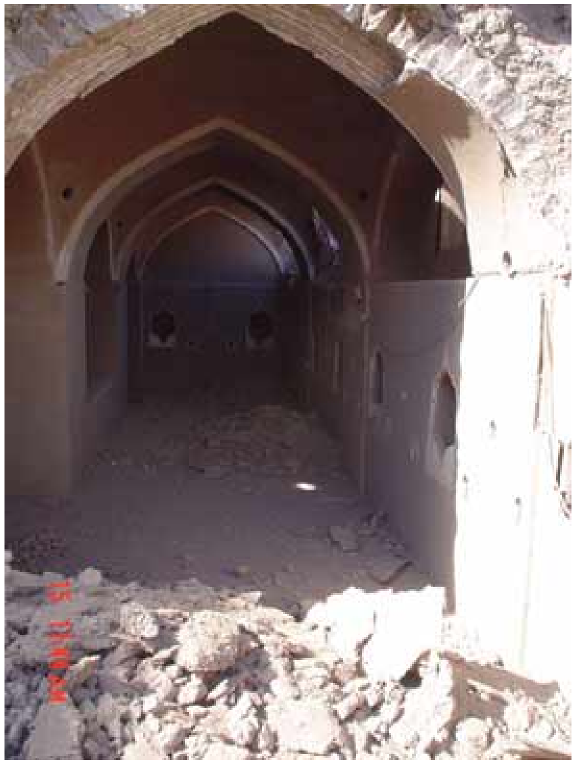

Figure 10: Vaulted roofs with arched panels

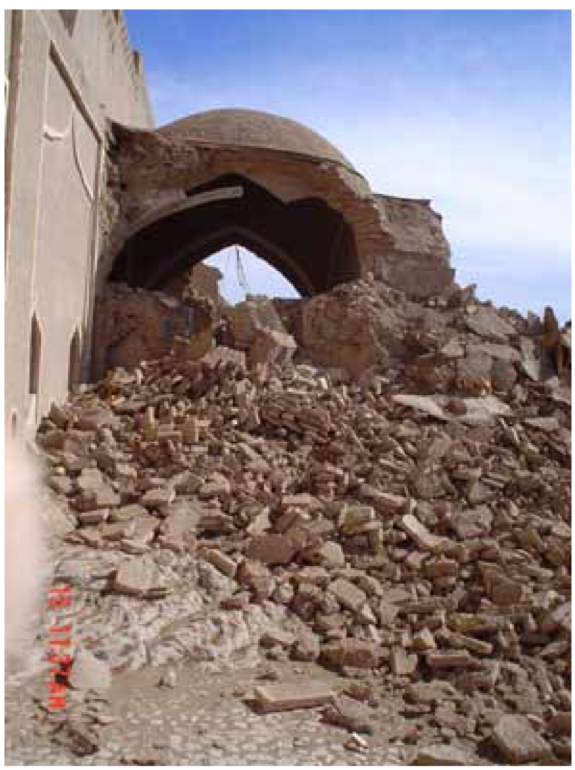

Figure 11: A dome supported by two walls and two arch panels.

STRENGTHENING MEASURES

Due to lack of bond between building units, the quality of most walls in traditional buildings is quite low. Generally, the appearance of cracks in mortar and the disintegration of these walls seem to start much earlier before the occurrence of an earthquake. Accordingly, traditional buildings have not sufficient stability against seismic shocks. The general rule for strengthening these buildings in general, and walls in particular has been reported in many references [13-15], and need no more repetitions. For traditional buildings with vaulted roofs, a simple and general strengthening method need to be defined. This method should be based on identifying the structural deficiencies and load path discontinuities and specifying measures to overcome these shortcomings. Although this needs a more careful and detailed survey, the present paper only outlines the main lines of the suggested scheme.

The Main Deficiencies

- Lack of suitable connections between walls and roofs.
- Lack of coherence of the vaulted roof.
- Weak sections in the vicinity of the intersection line of dome and the remaining flat part of the roof.

Load path

For vaulted roofs not supported directly on walls, the transition of loads from the vault to the four walls below is one of the most important problems. In classical shell books, a lot of information is available on the best geometrical shapes that can be used to have proper load path. However, most of these data are based on simple assumptions and only limited to vertical loads. To take horizontal loads in considerations, and to have general information on the continuity or discontinuity of load paths, a computer method similar to that suggested by Minke [16, 17] should be used.

Elementary Suggestions

Based on the observations made by the author and reported in this paper, the following elementary suggestions are made:

- Using lintel band and roofs bands made of wood can strengthen walls [15].
- Reducing the weight of the roof by using only 20 cm thickness of the earth [15] and using other measures to protect inhabitant against severe weather.
- Connecting walls and roofs in the same pattern used for ordinary adobe buildings.
- For vaulted roofs (including domes) that are not supported directly on walls, and to transfer the loads more efficiently from vaulted roofs to adjacent walls, extra facilities need to be added. These facilities may have simple or complicated forms. In all these cases, a tie beam under the shell needs to be included.
- To increase the stability of buildings with vaulted roofs, use of additional members that work as buttresses is always useful.
- To preserve the integrity of the vaulted roof, measures must be taken to increase its strength and ductility. Repairing or replacing old mortars, using small metal pieces to increase its connectivity, or using FRP members are among the measures suggested in this respect.

DISCUSSION

In previous earthquakes, most of the traditional masonry houses were completely collapsed and flattened. Those with vaulted roofs were moderately better. The present study has tried to investigate more closely the performance of these buildings and comparing their behaviors to those of other available systems.

Beside the many known weaknesses of these buildings, the present paper has tried to illuminate their unknown and good qualities as well.

The study of the response of traditional buildings during these earthquakes showed that the seismic performance of such buildings was a function of height to thickness ratio of the adobe wall, spans of internal subdivisions, size of openings, roof masses, nature of continuity with adjacent buildings, quality of construction, distance to fault, and topographical and site effects. In the survived adobe buildings, it was found that most of the factors mentioned above had been implemented in such a way that tensile forces in adobe were eliminated.

The roles of arches and domes in transferring horizontal forces have been discussed in this paper. As it is shown, the proper choice of structural elements capable of transferring these loads efficiently is quite important to the survival of these structures.

CONCLUSIONS

During previous earthquakes, it was common practice to put blame on traditional systems or local materials for the collapse of buildings. However, the responsibility of these catastrophes must be laid squarely on bad design and erecting practices. The failure of traditional arches and domes highlights the need for an approved code of practice to regulate the construction of these structures.

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