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PERFORMANCE OF TRADITIONAL ARCHES, VAULTS AND DOMES IN THE 2003 BAM EARTHQUAKE

T. Mahdi*
Department of Structual Engineering, Building and Housing Resarch Center, Tehran, Iran

SUMMARY

Arches, vaults 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 present paper investigates the general performance of arches and domes during the Bam earthquake (December 2003, Ms=6.6). In this earthquake, wide damages to such traditional buildings were observed, especially those located in the vicinity of the fault. The paper reviews the main reasons of failures of such buildings. It 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. They involve a system that is based on some type of masonry bearing walls, mainly adobe made of unburned dried mud brick. 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. Sun-dried adobe bricks and mud mortars were used to build the walls and roofs of these buildings. Domes and vaults, 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. 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.

THE EARTHQUAKE

On December 26, 2003 at 01:56:56 UTC 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. USGS [1]

* E-mail address of the corresponding author: mahdi@bhrc.ac.ir

reported that magnitude of this earthquake was Mw 6.6 and its hypocenter was located at 29.00N, 58.34E with 10 kmdepth. On the other hand, IIEES [2] reported that its hypocenter was 29.08N and 58.38E with 13.2 km. depth, while BHRC [3] located the hypocenter at 29.12N and 58.35E with 7 km. depth. At first, it was supposed that the main shock had occurred in the geological Bam fault, which was well known before. However, and according to the seismological investigations carried out by Nakamura et.al. [4], it has been found that most of epicenters of aftershocks are not located on the geological Bam fault itself but are distributed along a line parallel and about 3.5 km. to the west of the fault. Accordingly, the main shock hypocenter was estimated at 29.05N and 58.37E and 7 km. deep [4]. The distance from the assumed hypocenter of the main shock is estimated to be about 9 km., which is more consistent with that measured by BHRC. According to this report, Bam's newly founded fault has a nearly north-south direction with three branching fault sections at its northern part. It has been noticed that most of the heavy damages were concentrated in the densely populated eastern part of the city of Bam. Comparing the heavily damaged area with the projection of the new fault, it has been found that these areas are located just or nearly on the three fault branches at the northern part of the fault [4]. 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 [3]. 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.

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

PERFORMANCE OF DIFFERENT TYPES OF 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 are the most dominant ones. 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 hypocenter. The monument composed mainly of unfired earth construction. 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.

Figure 2. The east-west wall of the Military citadel in Arg-e-Bam.

Generally, adobe buildings with domes and vaults had suffered heavy damages; the damage level mainly depended on the distance from the rupture surface faulting. Most of these failures were due to the weakness of the wall-to-wall and the wall-to-roof connections. Other factors like the use of weak mud mortars, weathering factors, lack of maintenance, and the large thickness of roofs had also played important roles in the disintegration of these buildings. However, some of these buildings had remained stable with minimum cracks. In what follows, a general discussion on the performance of the structural elements of these roofs; i.e. arches, barrel vaults, and domes, is carried out.

THE ARCHES

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 2. The small arches shown in this figure is merely a facade that is hiding the main 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 3. As a structural component, and as shown in Figure 4, 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 4 that this later condition has not been met. Many of the buildings that survive the earthquake have successfully fulfilled these rules as shown in Figure3.

Figure 3. The north-south wall of the military citadel in Arg-e-Bam.

THE VAULTS

The number of shapes and forms of vaults used in the Bam's area is quite large. 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. This type of roofs is called locally a "Tharby" roof. Other type of vaults that also widely used is called "Kalil". The later type covers only part of the roof, as shown in Figure 5. In traditional buildings, and due to the lack of ring beams between roofs and walls, walls carry all vertical and horizontal forces.

The failure of these types of structures is resulted when excessive displacements perpendicular to the vault generator occurred. However, when the displacement is relatively small as shown in Figure 6, only minor cracks occurs at the intersection of the roof with the end plates.

Figure 4. Arches used to transfer loads from a dome to its pillars.

Figure 5. The two types of vaults that are commonly used in Bam, Tharbi and Kalil

Figure 6. Cracks at the intersection line of the vault with the end plate

Figure 7. A vault with cracks in Arg-e-Bam

The surviving roofs can be seen all over the cities of Bam, Paravat and even at Arg-e-bam at short distance from hypocenter. In Arg-e-Bam, many vaults were destroyed in the earthquake. However, others had escaped with minor cracks. 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 elsewhere. Furthermore, it has been noticed that some of the buildings that survived the quake are located on rock. Figure 7 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.

In most cases, complete destructions of adobe buildings including vaults were observed. The sequence of such a failure usually starts with the separation of perpendicular walls and the opening of cracks at the corners. Later on, and due to excessive deformations and lack of tie beams at the level of the roofs, walls and roofs are separated from each other's. 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. Generally, it has been observed that such failures occurred more with the "kalil" type of vaults more than the "Tharby" type.

Based on the traditional form, some new masonry buildings in the city of Bam had been constructed using burned brick for both walls and vaults. 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 DOMES

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 4. 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. However, example of good performance of domes can be also seen as shown in Figure 8. The building shown in the figure is located at Konari neighborhood in Arg-e-Bam and it has two domes. With the exception of some cracks at the Intersection of perpendicular walls, no other failure has been observed. On the other hand, many examples of massive and wide destruction had been observed few meters from the structure of Figure 8. As an example, the stable courtyard inside Arg-e-Bam is shown in Figure 9. Around the courtyard, many surrounding buildings are shown 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. For walls situated parallel to the earthquake direction, and due to the presence of vertical forces, the ability of these walls to resist shear forces has been reduced considerably. However, for walls perpendicular to the earthquake direction, it is believed that the combination of the normal forces to the wall plane and the vertical acceleration forces had caused their failures. However, it is interesting to note that some 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 the stable courtyard, are those shown in Figures 10. The vaulted roof shown in Figure 10 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, two arches and two walls support each dome. In Bam's earthquake, the forces applied were perpendicular to the plane of 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. As it is clear from Figure 10, one of the arches had suffered minor failures. This failure reflects the disability of the arch panel to transfer forces between active walls.

Figure 8. Domes located in Konari neighborhood in Arg-e-Bam

In general, 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 [5,6]. However, these solutions have not been implemented fully in constructing the domes found in the earthquake-stricken area. As a result, approximately all surviving domes had sustained some cracks. The typical pattern of the cracks observed in most cases is that of a meridian crack, as shown in Figure 11. In most cases, such cracks had been initiated at points closer to the intersection line of dome and flat roof. Accordingly it can be safely stated that in addition to the wall-to-wall and roof-to-wall intersections, this line of intersection can be considered as another weakness point of these structures.

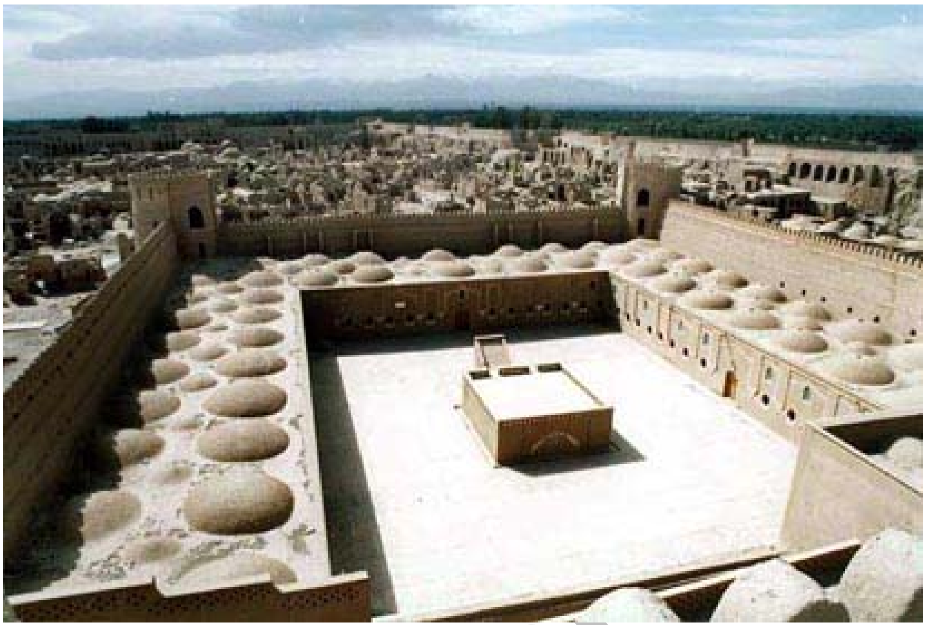

Figure 9a. A courtyard in Arg-e-Bam before earthquake.

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

Figure 10. A dome supported by two walls and two arch panels.

Figure 11. A meridian cracks in the dome

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 lack the required resistance against seismic shocks. The general rule for strengthening these buildings in general, and walls in particular has been reported in many references [7-9], and need no more repetitions. For traditional buildings with vaults or domes, 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 vaults or domes 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 [10, 11] should be used.

Elementary Suggestions

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

- At lintel and roof levels, using ring beams made of wood can strengthen walls [9].
- Reducing the weight of the roof by using only 20 cm thickness of the earth [9] and using other measures to protect inhabitant against severe weather.
- Making proper Connection details for intersecting walls and at the wall-roof intersection levels similar to that suggested in References [7, 11].
- For vaults and 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. Arches and domes can be used to transfer horizontal forces, as has been discussed in this paper. However, without providing coherence between the old and new parts of structures, such transfer would not take place.
- To increase the stability of buildings with vaults or domes, use of additional members that work as buttresses is always useful. Coherence between the walls and new buttresses need to be provided.
- To preserve the integrity of vaults and domes, measures must be taken to increase their 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

The present study has tried to investigate more closely the performance of traditional buildings having arches, vaults and domes 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.

It has been noticed that the performance of some of adobe traditional buildings with vaults or domes was better than other semi-engineered and engineered buildings. The apparent factors that account for this good performance was: the low height to thickness ratio of the adobe walls, the relatively few openings, small spans of internal subdivisions, light roofs, continuity with adjacent buildings, and the relative good quality of adobe. 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 confined to local regions.

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, vaults and domes highlights the need for an approved code of practice to regulate the construction of these structures.

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