SEISMIC PERFORMANCE OF ADOBE CONSTRUCTION DURING RECENT IRANIAN EARTHQUAKES

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ABSTRACT
Adobe, in the form of sun-dried bricks and clay or lime/clay mortar, has traditionally been the prime construction material in Iran. Presently, this type of construction still constitutes a notable portion of the buildings in the urban areas and a majority of the buildings in the rural areas. The performance of traditional adobe construction during numerous Iranian earthquakes has generally been poor. Low material strength, poor workmanship, lack of proper connections between building elements and the excessive weight of the building, resulting from the thick walls and massive roofs, are but a few shortcomings contributing to the general weakness of these buildings under earthquake loading. In this paper, the performances of different types of the Iranian adobe construction during a number of recent earthquakes are discussed and their points of weakness and strength are highlighted. The current rehabilitation trends for this type of construction in Iran are also discussed.

INTRODUCTION
The earthquake destruction in Iran has a reported history as long as the history of the country itself [1]. In the last century alone, over 100,000 people lost their lives during about 30 destructive earthquakes [2]. Another 30,000 people died as a result of the Bam earthquake of December 2003. Save for the recent Bam earthquake, almost all the earthquakes in the last 100 years occurred in the less densely populated rural areas of the country, affecting mainly scattered villages and small towns and a large portion of the fatalities were caused by the collapse of the adobe buildings.

Over 80 percent of rural houses in Iran are of adobe or stone masonry types, constructed using strictly local materials and workmanship. Materials are mainly common earth with varying degrees of clay, silt, sand and gravel content. Depending on the region, different types of roofs are, however, constructed. In the Western and Southern parts of the country, where timber is more readily available, flat roofs, made up of wooden beams and mud, are mainly constructed whereas, in the more arid Central and Eastern parts, the roof is primarily of the adobe dome or vault type. Curved or flat roofs, thick adobe walls and relatively small openings are characteristics of the local traditional architecture, dictated by climate conditions, availability of materials and village life. Where foundations are provided for the buildings, it is of rubble stone with mud or lime mortar. Adobe bricks are laid in the wall using mud mortar or in some cases, mud-lime or gypsum mortar. To prevent water erosion, a few bottom layers of the wall are often constructed with rubble stone or fired bricks and lime mortar.

The dome and vault roofs are normally constructed using one layer of adobe bricks, 20cm to 30cm thick. A 5cm to 7cm thick layer of mud plaster, reinforced with straw, known locally as ‘kahgel’ is then applied to the top of the roof as well as the outer faces of the exterior walls for water proofing. Every year or so, a new layer of kahgel is added to the roof and the roof

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becomes progressively heavier as it grows older. In some constructions, the dome consists of an inner layer of bricks, a substantial amount of straw and leaves and another layer of bricks coated with a layer of kahgel resulting in a minimum roof thickness of 70cm.

Adobe flat roofs, on the other hand, consist of tree trunks or logs placed directly on top of the walls with spacing of between 30cm to 50cm. The wooden beams are covered with branches, foliage or a type of mat made of flattened bamboo on which a thick layer of mud is placed to act as a hold down weight and insulating material. A layer of kahgel plaster is then added to provide water proofing.

Besides the adobe dwelling construction described above, there are a large number of historic and monumental adobe buildings of more complex architecture and better construction which have survived the adverse effects of earthquakes and time to present day. The seismic performance of these buildings is beyond the scope of this paper. A study of the seismic vulnerability of some adobe monumental buildings in Iran conducted by the author is reported elsewhere [1].

GENERAL WEAKNESSES OF ADOBE CONSTRUCTION
The poor performance of the traditional adobe buildings, observed in a number of past Iranian earthquakes, is well reported [2-10]. The fate of the majority of these buildings during medium to large earthquakes was to disintegrate into a heap of dried mud brick rubble. The main points of weakness of the adobe construction contributing to their poor seismic response can be summarized as follows;

1. Poor quality of adobe units, being simply sun-dried local mud.
2. Poor quality of mortar, resulting in the lack of proper bond between adobe units.
3. Weak bond in adobe masonry, including uneven laying of units and lack of proper overlap between layers. The latter causes vertical joints in two or more successive layers to coincide.
4. Improper structural layout, with low wall density, great height and long unsupported length of the walls.
5. The non-homogeneous roof is not capable of diaphragm action and can not provide the necessary restriction for the out-of-plane vibration and movement of the supporting walls.
6. Lack of proper connections between the perpendicular walls resulting in separation of walls from each other, failure in the walls and subsequently the collapse of the roof.
7. Heavy roof, causing an increase in the earthquake-induced inertia force on the building.
8. Lack of proper foundation and in many instances the absence of foundation.
9. Presence of large openings such as windows and doors, reducing the effective length of the wall and dividing the supporting walls into a series of adobe columns or pillars. This causes drastic reductions in both the out-of-plane and in-plane stiffness and load carrying capacity of the wall. In such a wall flexural and shear failures can easily occur.
10. Proximity of windows to the end of the walls. This makes the end of the wall to act as an adobe column and reduces the fixity of the perpendicular walls.
11. In flat adobe roofs, placing of the wooden beams directly on the adobe brick resulting in local failures due to the development of high local stresses.
12. In curved adobe roofs, the presence of a roof-induced horizontal force on top of the supporting wall, results in a pre-earthquake outward thrust being imposed on the wall.
13. Vault roofs have specifically poor seismic response due to their small support ratio and a one-directional support system.
14. Age and repairs; In most cases adobe houses were found to have undergone extensive repairs before the earthquake. The main defect of these buildings is the deterioration of their walls near the ground.
15. Addition of kahgel plaster water proof course every year or so without removing the half-washed existing layer.
16. Embedment of piping in the adobe walls. Although this is not common, these vertical openings reduce the strength of the wall.
17. Cluster type construction; Most villages are built and expanded by simply adjoining new adobe houses to the existing ones. This produces weak units and the resistance of the cluster tends to become that of its weakest unit.
18. Degradation of the building due to the adverse effects of rain or moisture changes.
19. Narrow and crooked alleys; Narrow streets and alleys contribute in different ways to the extent of damage and the increase in the number of casualties in an earthquake. The narrowly spaced houses collapse on each other resulting in secondary damage. It also makes the rescue work harder.

OBSERVED MODES OF FAILURE OF ADOBE CONSTRUCTION
The earthquake performance of an adobe building depends on the type of roof constructed for that building. Due to the differences in materials, load carrying mechanisms and support systems, the seismic behaviour of the flat roof adobe is somewhat different to that of the curved roofs such as domes and vaults. In the following, the two types of buildings are discussed separately.

Flat Roof Buildings
The seismic performance of this type of construction is reported from a number of earthquakes including Lar (1960) [3], Buyin Zahra (1962) [4, 5], Qir (1972) [7] and Manjil (1990) [11]. The modes of failure of flat roof adobe buildings under earthquake shaking is observed to vary according to the architectural form of the building, the quality of materials and workmanship. However, by studying more closely the types of failure incurred by different elements of the buildings in a number of earthquakes, a general trend can be constructed as follows;

Under very low to low intensity ground shaking the building behaves primarily as a rigid box, owing to its inherent stiffness. When the intensity of the shaking increases, flexural and shear cracks form at locations of high stress concentration. These locations include; top of the adobe load bearing walls under the wooden roof beams, the intersections of perpendicular walls and at locations where the rigidity of the wall changes suddenly due to the presence of openings, that is in the narrow walls or adobe columns separating the openings and in the intersection of spandrels and vertical wall elements. The formation of these cracks in turn makes the building more flexible. The increased flexibility of the building may cause an increase in the seismic load as the fundamental frequency of the stiff building moves towards the range of strong earthquake frequencies. As the earthquake shaking continues, this increase in flexibility and amount of structural deformation causes the structure to cease acting as a rigid box and results in the different elements of the building to move apart and act as individual semi-connected elements. The non-homogeneous roof is not capable of providing sufficient support for the top of the walls and the lack of proper connections between the intersecting walls also means that a wall can not be supported at its vertical ends. Therefore, at this stage, the walls act as separate free standing vertical and horizontal elements failing easily in different shear and...
flexural modes. With increased ground shaking and depending on the prevailing mode of failure, the wall elements start to collapse and bring the unsupported parts of the roof down with themselves.

The primary failure modes of the roofs are due to one of three types of failings. These include: (i) separation of the roof beams from the moving supporting wall due to insufficient bearing length, (ii) relative movements of the roof wooden beams form each other and from their location on the supporting wall. This can easily happen as the beams are not anchored in position and will invariably result in failure, disintegration and collapse of the overlaying mud and (iii) total or partial collapse of the supporting walls as outlined above.

![Fig. 1 Flat roof adobe construction](image)

**Curved Roof Buildings**

The modes of failure of the dome and vault roof adobe buildings were observed in a number of recent destructive Iranian earthquakes. Some earthquakes of note in this respect include; the Buyin Zahra (1962) [4, 5], Dashte Bayaz (1968) [6], Tabas (1978), Sirch (1981) [8], Golbaf (1998) [9] and Bam (2003) [10]. A general conclusion drawn from these observations is that the dome type adobe roofs have shown better seismic performances than both the vault type curved roofs and the flat wood supported roofs. The resilience of the semi-spherical domes stems from their bi-directional load bearing capacity and support system. A dome carries its load primarily in compression and it is noted that the horizontal seismic loads do not also create sufficient flexural stresses in the dome to result in a net tensile stress. As a result, the dome is required to carry the load in compression and adobe is capable of transferring compressive stresses. Numerous surviving domes showed that as long as the supporting walls of the dome roof remained in place and intact, the roof also remained in place. However, similar to the case of the flat roofs, the dome is also not capable of binding the top of the walls and the adobe walls supporting the dome are as susceptible to earthquake forces as the walls of the flat roofed buildings. In fact they have an added diverse effect of imposing pre-earthquake permanent outward thrusts on top of the walls. This horizontal thrust has forced the traditional builder to construct thicker and therefore heavier walls (Fig. 2). Heavy weight is one of the major contributors to the poor seismic performance of domed
buildings. The other major contributor is the inability of the supporting walls to sustain themselves under earthquake loading (Fig. 3).

Fig. 2 Thick walls are characteristics of curved roof adobe construction (Golbaf, 1998)

The earthquake performance of vault type curved roofs, as observed during the recent earthquakes in Iran, is very poor. Unlike a dome, a vault is a uni-directional element supported only by uni-directional, parallel walls. This makes the vault susceptible to horizontal forces perpendicular to the direction of supporting walls. The end, non-load bearing walls are effectively tall free standing walls normally with large openings. They are the first elements of the building to collapse due to overturning (Fig. 4). After the collapse of these transverse walls, the shear resistance of the building in that direction reduces to a minimum as the vault is not capable of transferring any loads in that direction. If the vault is an end vault, the exterior supporting wall will, at this stage, be pushed outwards, bringing the vault down with itself. The central vaults fair relatively better as the horizontal thrusts from the vaults at two sides of the wall balance each other out. However with increased earthquake loading, the horizontal thrust in one direction prevails and the out-of-plane movement of the supporting wall and the resulting bending stresses in the vaults result in the failure (Fig. 5) and the subsequent collapse of the vaults.

Fig. 3 The partial collapse of the dome is due to the collapse of the supporting wall
The fact that the majority of the earlier earthquakes in Iran occurred in the rural areas with scattered villages and little economic significance, caused the government to assume the level of destruction as a direct result of the way of life. At worst it ignored the event and allowed the villagers to rebuild their homes in the same old ways and at best attempted to introduce building materials and types which were not compatible with their way of life. The first serious attempt to address the issue was however the rehabilitation program carried out after the destructive Sirch earthquake of 1981 in the town of Golbaf [8]. This small town in Kerman province, not far from the recently devastated town of Bam, was almost totally ruined in that earthquake and over 2000 people perished. The primarily adobe construction in the town succumbed to the 6.1 Magnitude earthquake. Following that earthquake a number of housing complexes were constructed using different types of small, low cost units. All units
had either RC or steel horizontal ring beams supported by vertical elements and most had pre-
cast RC flat roofs. However housing units of one particular complex had dome roofs of adobe
bricks supported by the said ring beams (Fig. 6). Some load bearing walls were also made of
adobe bricks. Seventeen years after the first earthquake, the town was again subjected to
another, more powerful earthquake, centered much closer to the town than the earlier event. In
the 1998 event, only five people died and that was due to the collapse of the remaining adobe
buildings left from the previous event. None of the low cast units described above, suffered
any damage save for some minor cracking in the ring beams [9]. The domes all stayed in
place and no failure could be seen in the supporting walls. This experience highlights the fact
that provision of some elements, in the form of ring beams to bind the walls together and
provide a uniform support for the roof, can greatly enhance the seismic performance of the
adobe and unreinforced brick masonry buildings.

Today, the prevailing trend is to attempt to preserve so far as possible, the rural adobe
construction as it has undeniable social, economical as well as technical advantages including
its architectural functionality and its suitability for environments with sharply changing
temperatures. In the recently drafted Iranian National Building Regulations, a section is
devoted to the adobe construction for seismic areas. The said binding elements made of wood,
concrete or steel with recommendations to remove material and workmanship weaknesses
listed in the previous sections, are prominent features of the new regulations.

Fig. 6 Excellent performance of ring beam supported adobe houses during Golbaf earthquake
of 1998

CONCLUSIONS
The poor seismic response of both the flat roof and curved roof adobe construction in Iran is
apparent from their performances in the numerous Iranian earthquakes of the last 100 years.
Massive weight, low material quality and lack of proper connections between the main load
carrying elements of the building are some of the major shortcomings of this type of
construction. Practical lessons learnt from recent rehabilitation programs however indicate
that the traditional adobe construction can be preserved with little effort directed at providing
an overall binding system in the form of wood, steel or reinforced concrete ring beams
supported by vertical elements. Education of the local builders to improve workmanship will
also greatly help the improvement of this construction type.
REFERENCES


