Performance of Roofs and Floor Slabs During Bam, Earthquake of 26 December 2003

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ABSTRACT: *Collapse of non-engineered roofs and floor slabs during the Bam earthquake of December 2003 was the single major contributor to the large fatalities during that earthquake. Different floor systems of buildings in the city of Bam can be categorised into three types namely; the traditional masonry dome or vault, the steel I-beam jack arch system and the concrete beam-hollow block system. In this paper the seismic performance of each type of flooring as observed after the Bam earthquake is discussed and their points of weakness and strength are highlighted. Also the poor seismic performance of the traditional dome and vault roofs and the unanchored jack arch slabs are noted and the seismic merits of the anchored jack arch slabs and concrete beam-hollow block slabs are discussed.*

Keywords: Bam earthquake; Seismic response; Domes and vaults; Jack arch slabs; Concrete beam-block slab

1. Introduction

The Bam earthquake of 2003 caused widespread devastation in the city of Bam. Despite the relatively low magnitude of the earthquake, the shallow depth of the event resulted in very high and localised ground accelerations both in horizontal and vertical directions. The recorded accelerations of 0.8*g* in the horizontal direction and 1.0g in the vertical direction were amongst the highest accelerations ever recorded for an earthquake. As a result of the high global ground accelerations, various modes of failure could be observed in structural systems and elements. The most important of the structural elements, so far as their effect on the level of earthquake fatalities is concerned, are floor and roofs.

Majority of buildings in the city of Bam at the time of the earthquake were unreinforced masonry buildings with load bearing walls or low rise steel-framed buildings. The former buildings were roofed by either the traditional masonry domes or vaults or non-engineered, unanchored, jack arch flooring system, whereas the latter buildings were mainly floored by anchored jack arch slabs. In some of the more recently constructed buildings, the floors consisted of concrete beam-hollow block slabs.

A large number of the buildings in the older quarters of Bam were traditional masonry types having masonry dome or vault roofs. These buildings are generally characterised by weak, brittle materials, weak element connections and excessive weight. The construction materials and techniques used for this type of construction have remained unchanged throughout the history for thousands of years. From around the middle of 20^{th} century a new type of floor construction in the form of steel beam jack arch slab was introduced into Iran from Europe. The new flooring system, considered as a non-engineered construction, became very popular in Iran such that the majority of existing buildings in provincial towns and villages and a vast number of buildings in Tehran are floored with this type of construction. In this flooring method a number of parallel steel I-beams are placed directly on the load bearing walls at between 80*cm* to 1.0*m* spacing and spanning from one wall to the other. The space between the two adjacent I-beams is then filled with a series of shallow brick arches, see Figure (1). The process is repeated until the whole slab area is covered. A layer of lime-clay mortar or concrete is then placed on the brick arches to create a flat surface. The slab is subsequently plastered underneath to create a flat

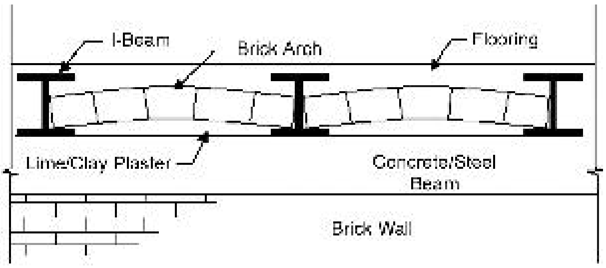

Figure 1. Steel beam, jack arch flooring system.

ceiling. Due to a number of advantages including ease of construction, speed of construction and low cost, the jack arch system is still popular in Iran. In Figure (2) the jack arch construction as a percentage of the total construction in provincial towns and cities is shown for recent years. This figure highlights the importance of studying the seismic performance and dealing with seismic design and retrofitting of this flooring type.

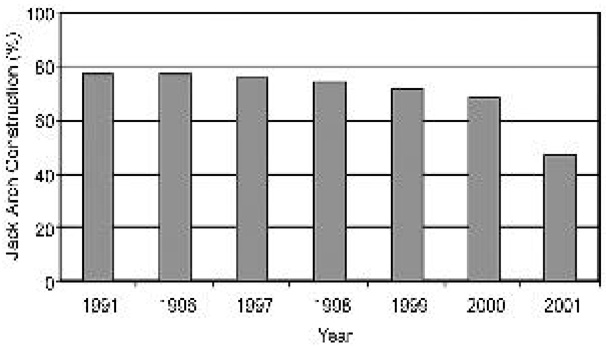

Figure 2. The trend of jack arch construction in recent years in Iran (as a percentage of total floor construction).

The steel I-beam jack arch systems are stable under normal static conditions as the brick arches transfer the gravity loads, mainly in compression. However, reports of slab damage and collapse in recent earthquakes in Eastern Europe and Iran [1-3] reflect the weakness of the unanchored slab under dynamic loading. To overcome this problem, it is suggested that the slab beams be joined together at their ends by either transverse beams or by steel tie bars [4]. This form of anchored jack arch slab has a better seismic response as the relative movements of the slab beams are somewhat prevented.

In recent years, there has been a notable trend away from the jack arch construction in favour of the more robust concrete beam-hollow block floors. This flooring system is similar in principle to the steel beam jack arch system but uses different materials and construction techniques. In this method, the steel *I*-beams are replaced by small section pre-cast reinforced concrete beams. The concrete beams are, however, placed more closely to each other at about 40*cm* intervals. The gaps between the adjacent concrete beams are filled with purpose-cast hollow concrete or earthenware blocks. The beams are inverted *T*-shaped in cross-section so that the hollow blocks can be supported on the bottom flanges as seen in Figure (3). The resulting beam-block slab is then reinforced by the addition of a 5 to 10*cm* thick reinforced concrete slab. In this way a relatively light and insulated reinforced concrete composite flat slab is constructed without using scaffoldings.

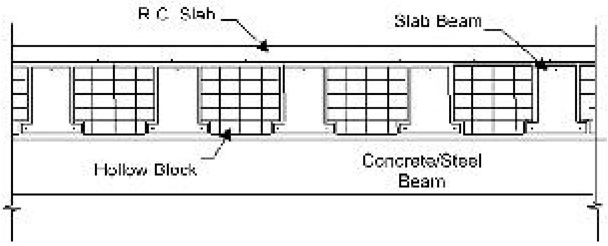

Figure 3. Concrete beam, hollow block flooring system.

2. Masonry Buildings Roofed with Domes and Faults

The poor behaviour of this type of construction under earthquake forces, observed in numerous past Iranian earthquakes, is well documented [3, 5]. Low material strength, poor workmanship, weak mortar, brittleness of sun-dried or traditionally fired bricks, lack of proper connections between perpendicular walls and between walls and the roof and non-homogeneous roofs are but a few parameters contributing to the general weakness of the structures. Added to these weaknesses, the excessive weight of the structure resulting from the thick walls and massive roofs causes an increased seismic load on the structure. The fate of the majority of these buildings in the Bam earthquake was to disintegrate into a heap of mud and brick rubble causing many casualties.

Many of the roofs of these types of buildings were vaults spanning between shared parallel load bearing walls. The typical mode of failure was the partial or total failure and collapse of the weak and heavy load bearing walls followed by the local or global collapse of the roof. These types of non-homogeneous, brittle roofs are not capable of restraining the top of their supporting walls. However, a number of vaulted and domed roofs survived the earthquake. These were in buildings where the supporting walls had remained in place under earthquake loading, see Figure (4).

Figure 4. Survival of masonry vault roof during the earthquake.

3. Performance of Masonry Jack Arch Slabs

Many of the residential and commercial buildings in Bam were roofed with the masonry jack arch slabs. As was discussed, these slabs may be divided into two groups namely; the unanchored jack arch slabs and the anchored jack arch slabs.

3.1. Unanchored Jack Arch Slabs

Depending on the response of the load bearing walls and the construction details of the slab, in buildings floored with this type of slab, different modes of failure, stemming from certain points of weakness could be observed. A discussion on these will follow.

i) Short bearing length of the slab beams: In many instances it was noted that the bearing length of slab beams over the load bearing walls were minimal, in some cases the ends of the beams were simply resting on the edge of the walls, see Figure (5). This short supported length of beams caused increased concentration of stresses in regions of the walls already highly stressed. At the onset of ground shaking, local support failures under the slab beams resulted in the movement of the beams causing the subsequent collapse of the masonry arches. Also as the unrestrained load bearing walls moved away from the slab under ground shaking, the beams simply separated from their supporting walls and collapsed as seen in Figure (5).

ii) Use of end walls to support end brick arches: To reduce the construction cost, it appeared common practice to omit the slab beam over the end walls and to use the end walls to support the end jack arches. Since there are no proper connections between the perpendicular walls, separation of the end walls from the load bearing walls was a common mode of failure resulting in the collapse of the end masonry arches as seen in Figure (6).

Figure 5. Collapse of jack arch steel beams as a result of small bearing length.

Figure 6. Collapse of masonry arches due to the movement of end support wall.

iii) Inability of the slab to act as a diaphragm: The ill-connected composite form of the unanchored slab does not allow for a diaphragm action as is required for good seismic performance. It was observed that when a part of the load bearing wall or supporting beam failed under earthquake loading, the unsupported section of the slab had also failed. This can be seen in Figure (7) where the collapse of load bearing walls has caused the collapse and disintegration of the composite, non-homogeneous slabs.

Figure 7. Collapse and disintegration of unanchored jack arch slabs.

Figure 9. Failure of masonry arch as a result of out-of-plane bending loads.

iv) Failure of the masonry arches due to the earthquake induced in-plane forces: In the traditional one-way slabs, the in-plane axial and shear loads are transferred mainly by the brick arches. The brick arches are however ill-suited to transfer these forces. An example of the failure of a masonry arch due to in-plane loads in the direction perpendicular to the main beams can be seen in Figure (8).

Figure 8. Failure of masonry arch due to in-plane transverse loading.

v) Failure of the masonry arches caused by the out-of-plane forces: Bam earthquake was associated with very large vertical accelerations. The vertical component of the quake had caused large out-of-plane dynamic loading on the slabs. The geometry of the brick arches makes them far stiffer than the steel beams in vertical vibration. Therefore, the vibration-induced stresses tend to concentrate in the stiff brick arches rather than the more flexible and ductile steel beams, resulting in the failure of the former, see Figure (9).

vi) Weak slab materials: The type of brick and mortar used for construction of arches is of prime importance for good seismic response. The bricks used in construction of the arches were traditionally fired, heavy solid bricks with low strength to weight ratios. Using this type of bricks, not only does not increase the strength of the arch but results in a heavy slab, increasing the gravity and seismic loads.

vii) Poor workmanship: Poor workmanship was another shortcoming of the older unanchored jack arch slabs. The ability of the brick arch to transfer the load in compression depends on the rise of the arch. As it was noted in Bam, the masons tend to reduce the rise of arch as much as possible to almost a flat brick slab so that the amount of plaster required to make a flat surface is reduced to a minimum. This will change the load-carrying behaviour of the brick arch into one of a flat brick infill, susceptible to flexural failure under small loads.

3.2. Anchored Jack Arch Slabs

The above general points of weakness, as was observed repeatedly in the response of buildings in the Bam earthquake, make the unanchored traditional jack arch system unsuitable for earthquake prone areas. Considering the apparent popularity of the jack arch system, Iranian seismic code [6] proposes to anchor the ends of the slab beams to their supporting walls through concrete or steel ring beams and to join the parallel beams together by diagonal steel bars. Although observations made during recent earthquakes including the Bam earthquake of 2003 have shown the inadequacy of the code recommendations, a better seismic performance for the anchored slabs was noted. In fact some observed performances of the anchored jack arch slabs reinforce previous numerical and experimental findings of the author regarding the seismic capabilities and resilience of the anchored slab. A good example of the resilience of anchored jack arch slab can be seen in Figure (10). This figure shows the collapse of the second floor jack arch slab of a two storey steel-framed building due to the failure of the main beam/column connections on one line of support. The slab beams are joined together by transverse beams acting as girders. The confined brick arches survived both the earthquake shaking and the collapse of the slab. Also it is noted in the same figure that the first floor jack arch slab of the building had also survived the earthquake loads and the massive shock caused by the collapse of the upper floor slab.

Figure 10. Integrity of the anchored jack arch slab under earthquake loading and after collapse.

Another example of the ability of the anchored jack arch slab to act as a diaphragm can be seen in Figure (11). The failure of the supporting columns of this building, caused by the excessive sway has resulted in the collapse of the jack arch floor slab. However, the slab has managed to retain its integrity and act as a diaphragm.

The jack arch slabs have been considered to be non-ductile, brittle composite systems. However, the behaviour of a large number of jack arch slabs during the Bam earthquake showed a different response. It was noted that the masonry arches, when confined, underwent large deformations along with their supporting steel beams and remained intact. An example of this behaviour can be seen in Figure (12) in which the masonry arch shows large deformations compatible with plastic deformations of the supporting steel beams.

Perhaps the best example of the strength and ductility of the anchored jack arch system is the masonry building shown in Figure (13). The roof of this three-bayed, single-storey building consists of continuous steel beams spanning over the supporting masonry walls and resting on purposely placed concrete blocks. The beams are joined together at

Figure 11. Ability of the anchored jack arch slab to act as a diaphragm.

Figure 12. Ability of the anchored jack arch slab to undergo large deformations.

Figure 13. Resilience of anchored jack arch slab in withstanding diverse loading conditions.

their ends by transverse steel beams. Under the earthquake loading the end support wall has completely collapsed leaving the 3.5*m* span of the slab to act as a cantilever, supported by the remaining load bearing wall. The fact that such a large cantilevered slab was capable of supporting its own weight and the subsequent large out-of-plane earthquake loading is witness to the abilities of the anchored jack arch slabs.

A large number of buildings, which survived the earthquake, had anchored jack arch slabs. In many instances the floor slabs were so intact that even minor failures in the form of cracks in plaster could not be seen. The code-designed single-storey masonry building with concrete ring beams shown in Figure (14) is but one example of such behaviour. Some of the anchored jack arch slabs had construction material and details and workmanship similar to the slabs of the building seen in Figure (15). This unfinished building also survived the Bam earthquake. The brick arches of the slab consist of lightweight perforated brick units and lime/clay mortar. The lightweight perforated bricks are far more suitable for jack arch construction as they reduce the weight of the slab as well as provide better bond between the mortar and bricks. The parallel load bearing beams of the slab are also well restrained by transverse beams at their ends.

Figure 14. No damage in this code-designed masonry building having ring-beam supported, jack arch slab.

Figure 15. Good seismic performance of anchored jack arch slabs made with lightweight perforated bricks.

It should be noted that the contemporary jack arch slab construction in Iran is still considered as a non-engineered slab in the Iranian seismic code as there are no particular design procedures for their engineered design. They still suffer from weaknesses in transferring in-plane axial and shear loads as well as the out-of-plane bending loads and the detrimental effects of dynamic interaction between steel beams and brick arches. On the other hand, considering the advantages of this type of flooring system compared to other types of flooring, the author and his colleagues have conducted a number of investigations on the jack arch slabs evaluating their seismic response [7]. Simple methods of increasing the seismic performance of the slab in the form of inter-span transverse beams were then proposed and their effectiveness investigated both experimentally and numerically [8, 9]. Finally, procedures for their engineered design and construction were introduced [10]. Although these design procedures were not applied in the construction of the jack arch slabs in the city of Bam, some existing anchored slabs had details compatible with the proposed engineered version of the slab. An example of the effectiveness of the use of mid-span transverse beams can be seen in Figure (16). It can be seen in this figure that the portion of the slab in which inter-span transverse beams are utilised to join the main beams together, has remained in place, whereas the front section of the slab which lacks similar transverse beams has disintegrated and collapsed.

4. Performance of Concrete Beam-Hollo Block Slabs

In recent years, the concrete beam-hollow block roofing system has become popular in flooring the framed structures. As a result a number of buildings in the city of Bam were floored with this type. The seismic performance of concrete beam-hollow block roofing systems were generally more favourable than the jack arch slabs. The materials and construction details of the floor provide homogeneous slabs capable of diaphragm action. The state of the concrete beam-block floors of the unfinished building in Bam

Figure 16. Effectiveness of inter-span transverse beams in keeping the integrity of the slab.

shown in Figure (17) is indicative of the good seismic performance of this type of flooring. Although the floor is inherently robust with favourable seismic response, poor workmanship could be identified as the main reason behind the failure and collapse of a number of floors of this type during the Bam earthquake. The poor workmanship may result in one or more of the following points of weakness.

i) Pre-construction damage to concrete beams and hollow blocks: In many instances the cause of slab failure could be traced back to the state of the constituent elements of the floor prior to the earthquake. Mishandling of the rather delicate pre-cast concrete beams and hollow blocks during transportation and construction had resulted in cracks and breakages in these elements prior to the earthquake.

Figure 17. Good seismic performance of well-constructed concrete beam-hollow block slabs.

ii) Lack of proper connection between the slab concrete beams and the slab support beams: During construction, the pre-cast concrete beams of the slab are positioned in place with their exposed reinforcements extended into the slab support beams. Some extra bars acting as negative reinforcements are also positioned over the slab beams and the support beams. The support beams are then cast together with the slab so that an integrated slab-support beam is obtained. It is too frequently observed that the slab beam reinforcement extensions are inadequate or non-existent and that the all-important negative reinforcements are altogether omitted. In steel framed buildings, these connection details are even more problematic as the connection arrangement between the slab concrete beams and the steel support beams is difficult to administer. This can be seen in Figure (18) in the form of separation of the slab concrete beams from their supporting steel beam.

iii) Separation of the slab reinforcement and the overlying concrete: During construction of this type of floors care should be taken to provide enough cover space between the hollow blocks and the slab reinforcement. This construction detail however is often ignored and the slab reinforcement is slackly placed directly over the hollow blocks. In this way the overlying concrete is reduced to an unreinforced cover, susceptible to brittle failures. This can clearly be seen in the collapsed slab shown in Figure (19) in which the slab reinforcements can be seen between the blocks and the overlying concrete and detached from the latter.

Figure 18. Lack of proper connection between the slab concrete beams and the steel support beam.

Figure 19. Poor workmanship in construction of concrete beam-hollow block slab.

5. Conclusions

The performance of different types of roofs and floor slabs during the Bam earthquake of 2003 as discussed in this paper may be summarised as:

- ❖ The poor seismic behaviour of the traditional Iranian domed or vaulted unreinforced masonry buildings as observed repeatedly in past earthquakes was also well apparent in the Bam earthquake. More that 90% of this type of construction collapsed or were damaged beyond repair during the earthquake. As far as the performance of the dome and vault roofs are concerned, although they are incapable of providing sufficient anchorage for the walls, as long as the supporting walls remained in place they also did not collapse.
- ❖ The non-engineered unanchored type of jack arch slabs also performed poorly during the earthquake. However, ample examples of the potential of this flooring system as an earthquake resistant slab could be seen when the slab was anchored. It is noted that the seismic performance of existing unanchored and anchored jack arch slabs may be greatly enhanced by the provision of transverse beams at the ends and at the inter-span of the main beams according to the design provisions detailed by the author in other publications.
- ❖ The concrete beam-hollow block slabs are well suited for earthquake resistant construction. However, good workmanship is a key factor for realisation of their good seismic response.

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