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DESTRUCTIVE EFFECTS OF THE 2003 BAM EARTHQUAKE ON STRUCTURES

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ABSTRACT

On 26 December 2003 at 1:57 GMT, the historical city of Bam, located in the south-eastern region of Kerman province in Iran, was shaken by a relatively strong and destructive earthquake. The earthquake located at 29.0°N and 58.26°W had a M_b of 6.3 by Geophysics Institute of the University of Tehran and an M_s of 6.5 estimated by the U.S. Geological Survey (USGS). The main shock killed nearly 35000 people, left more than 50000 homeless, and destroyed virtually all buildings in the region. Based on the reconnaissance visit by the authors, most common types of damaged buildings in the earthquake-affected area were non-engineered adobe, un-reinforced masonry houses and steel buildings. Most houses in the epicentral area were of adobe construction, made of sun dried clay brick walls, and heavy domestic roofs or vaults with clay or mud mortar. This earthquake clearly demonstrated that combination of relatively rigid load-bearing external brick walls and flexible internal steel columns, existing similarly in most other regions of the country, is quite hazardous. Also use of steel beams and columns in buildings without observing proper seismic provisions showed no improvement over non-engineered buildings. Unlike Some researchers who claimed that the performance of reinforced concrete structures in the area was satisfactory, probably due to the fact that the number of the reinforced concrete structures in the stricken area was for less than the other type of structures, authors believe that it was not so better than others. In this paper after summarizing the seismological and engineering field investigations of the devastating earthquake, the performance of the existing structures during the earthquake is discussed.

Keywords: earthquake, field investigation, damaged structures, seismic performance, laterally resisting systems

1. INTRODUCTION

On December 26, 2003 at 01:56:56 GMT, (05:26:26 local time) a destructive earthquake hit the city of Bam in Kerman province and caused near source effects. The Kerman province is

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one of the largest provinces in Iran, with an area of 186,422 km^2, located in southeast of the country. The population of Bam was about 100,000 at the time of the earthquake in 2003[1]. Shortly after the earthquake, the authors spent 4 days in the region to study the earthquake effects on the ground and building structures. The epicenter of destructive earthquake is located at 29.01°N - 29.01°E, 10 Km, southwest of Bam city. Its magnitude was measured with M_b of 6.3 according to the Geophysics Institute of the Univ. of Tehran and M_s of 6.5 estimated by the U. S. Geological Survey (USGS). According to the official reports, this earthquake took the lives of around 45000 people. Also more than 50000 people were declared to be injured. The earthquake happened at 5:26 am local time when most of the inhabitants were in bed, which could be one of the causes of the great casualty.

The macro seismic intensity of the earthquake is estimated to be I_0=IX in Bam city (in the EMS98 scale), where the strong motions and damaging effects seem to be attenuated very fast especially in the fault-normal direction, as shown in Figure 1. Most of the buildings in the region were destroyed completely and the rest were damaged from 30 to 70 percent [1]. The intensity levels are estimated to be VIII in Baravat, VII in Modern-Arg (Arg-e Jadid) and the airport area. The intensity level was estimated to be around IV to V in Kerman and Mahan.

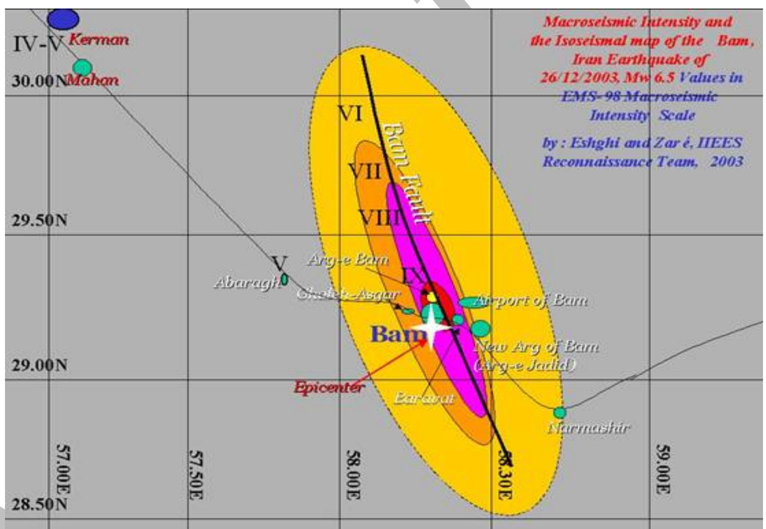

Figure 1. Intensity map of the damaged area [1]

The existing records on seismicity history indicate no major earthquake in Bam since the historical time. It seems that the Bam earthquake of 26/12/2003 has ended a seismic gap along the Bam fault. This seismic gap could be verified with the Arg-e Bam castle, constructed about 2000 years ago and since then, until the 2003 Bam earthquake, remaining unaffected. The Bam fault with a near north-south direction passes from the vicinity of the city of Bam (less that 1km distance to the east of Bam, and between the cities of Bam and Baravat as shown in Figure 1). The focal mechanism of Bam earthquake was reported to be strike slip and its focal depth was estimated to be 8 Km. The strong motions in this event were recorded in stations of the national Iranian strong motion network [2]. The record obtained in the Bam station shows the greatest PGA of 0.8g and 0.7g for the east-west horizontal and north-south horizontal components, respectively, and 0.98g (relatively high acceleration) for the vertical component. The Bam residents that survived the quake explained to the reconnaissance team members that they felt strong up-down displacements during the main shock. The accelerographs of the Bam earthquake are shown in Figure 2.

Most popular types of buildings in the region were non-engineered adobe, un-reinforced brick buildings and steel ones. Similar to most of the dry areas in the country, reinforced concrete buildings were rarely found in Bam. With a few exceptions, all buildings in Bam, mostly non-engineered adobe or un-reinforced brick buildings were damaged and more than half of them collapsed. This paper summarizes the seismological and engineering field investigations of the devastating earthquake.

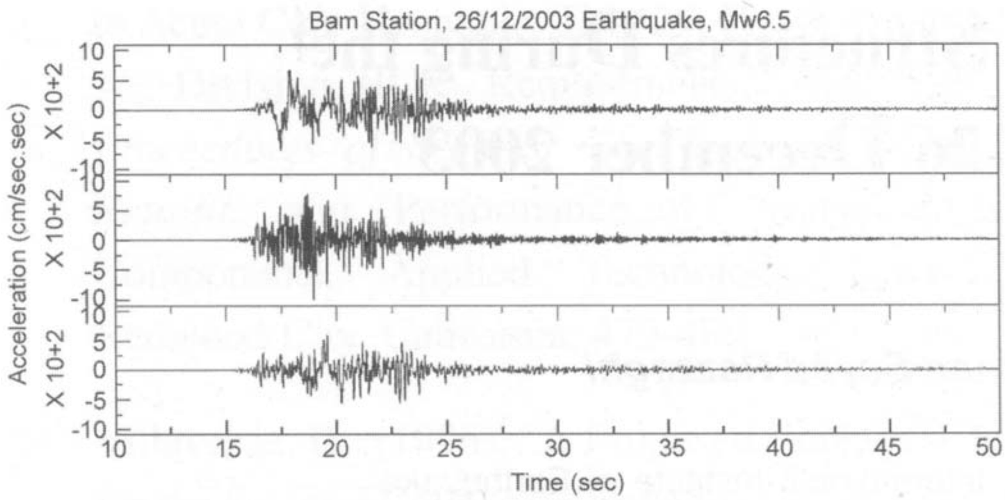

Figure 2. The accelerographs of the Bam earthquake

2. GEOLOGY, TECTONICS AND SEISMICITY OF THE REGION

Iran lies on the Alpide earthquake belt which runs west-east from the Mediterranean to Asia. Major geological structures of iran are the Alborz Mountains in the north, the Zagros belt in the west and south, the Kopet-Dagh range in the northeast, and the depressions of Great Kavir in the center, Lut in the east, and the Caspian sea in the north. Recent geological investigations have suggested the existence of various tectonic subplates in the region moving northward at different rates. Under riding of the Persian plate by the Arabian plate along the Zagros thrust fault is the most conspicuous tectonic feature of the region [3].

The province of Kerman is surrounded by the depressions of Great Kavir in the north and Lut in the east, and Zagros ranges in the south and west. The major Quaternary faults in the area are the Kuhbanan fault, apparently a high angle reverse fault, with northwest-southeast direction and Nayband fault with north-west trend. Some other faults in the region are Chahar-Farsakh Anduhjerd, Gowk, Sarvestan and Bam faults. The NW-SE faults (Kuhbanan and Ravar faults) and the north-south faults (Nayband, Chahar-Farsakh, Anduhjerd, Gowk, Sarvestan and Bam faults) have determined the border of the north-south structures in the Lut area with the NW-SE structures. These intersection zones were some of the main sources for the disastrous earthquakes.

In addition to the recent earthquake, 12 other destructive earthquakes of Richter magnitude greater than 7 have hit Iran during the 20th century. On the average, at least one earthquake of Richter magnitude equal or greater than 6 has struck Iran every year during this century. Around 200,000 people have died in earthquakes in Iran during the last 100 years [3].

Four great earthquakes have struck the region during the recent 20 years: The Golbaf earthquake of June 11, 1981, Ms6.6, the Sirch earthquake of July 28, 1981, Ms7.0, the South Golbaf earthquake of November 20, 1989, M_b5.6 and the North Golbaf (Fandogha) earthquake of March 14, 1998, Mw6.6. The Golbaf earthquake of 11/06/1981 has struck the region of Golbaf in the southern parts of the Golbaf valley (with the strike of N5-15E). The Sirch earthquake occurred 49 days after the Golbaf earthquake and caused 877 life losses. The South Golbaf earthquake induced 4 fatalities and 45 injured and some damages in Golbaf. Some surface faulting and folding have been reported to be related to this event. The North Golbaf earthquake caused 5 casualties and 50 injured, and were associated with surface faulting (about 20km length) in northern Golbaf. The focal mechanism of these earthquakes shows the compressional and strike slip mechanisms along the Gowk and Kuhbanan fault systems [1].

3. SEISMIC PERFORMANCE OF EXISTING BUILDINGS

Although there is an updated building design code that is comparable to the Uniform Building Code (UBC) of the United States and it is mandatory for practicing civil engineers, its application has been mostly limited to larger cities and for major building structures. In smaller towns and villages, however, current standards for seismic design and construction of buildings have not been properly observed. They usually build their own houses at minimal cost and thus sometimes with insufficient safety measures in place. As a result, severe damage is expected during even a moderate earthquake. Based on the post-earthquake inspection of the stricken area by the authors, the most common types of structures in the area are:

1. Adobe: adobe bricks with mud or lime mortar
2. Masonry: brick or stone and concrete block performed using cement mortar and jack arch roofs
3. Steel buildings: braced frames or rarely defective moment-resisting ones with jack arch or concrete beam-hollow block slabs and masonry infill walls. It cab be mentioned that a lot of steel frames had no lateral resisting system.
4. Reinforced concrete: reinforced concrete frames with concrete beam-hollow block slabs and masonry infill walls. However the number of reinforced concrete buildings

in the area was far less than the number of the other types of structures.

Since the common slab system in the area was the brick jack arch, this special type of slab which is rather popular in the country, will be discussed here. For the first time, around the middle of 20th century this type of floor construction was introduced into Iran from Europe [7]. The system consists of parallel **I-**shaped steel beams at a distance around 80 to 100cm. The space between these beams is filled with performing superficial brick arches, as shown in the Figure 3. The maximum height of the arches is around 3 to 5cm.

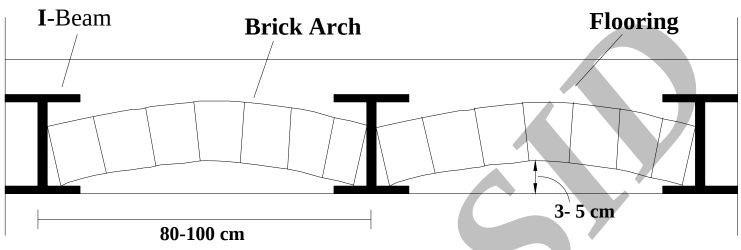

Figure 3. Schematic view of brick jack arch slab typically found in the region

As cab be imagined, the execution of this slab is rather simple and does not need much expertise and at the same time its cost is lower than that of the other slab systems. Furthermore, it can be performed in a very short time. Therefore many people in rural or even urban regions still prefer to use such a system without knowing or regarding their construction guidelines. As it is widely known, if seismic provision detailing is not considered, these systems could be rather dangerous during earthquake. These slabs are heavy and in its traditional way have poor rigidity and if they are not tied together very good, they may cause building failure and casualty in the earthquake. Regarding this fact, the National standard code No.2800 for seismic resistant design of structures, limited and prohibited the use of these slabs without performing sufficient tie bars and concrete or steel ring to maintain required rigidity against lateral loads. Based on the results recently obtained in an experimental research project by the first author conducted at the Building and Housing Research Center of Iran, jack arch slabs can perform well when subjected to lateral loads provided that sufficient bracing be used using rebars.

3.1 Adobe Houses

Most houses in the epicentral area are adobe construction, usually one-story made of sun-dried brick walls, and domed roofs or vaults with clay or mud mortar. This type of construction is common in the dry areas of Iran because adobe houses need only local materials and can be built by farmers when their work is lax. The walls and roofs of these houses are thick (usually 40 to 80 cm) and heavy so that they easily protect their inhabitants from the cold and hot weather, but they are very weak in resisting horizontal vibrations particularly at the junctions of vertical walls and domed roof (Figure 4). Based on the reconnaissance visit, most adobe houses in the epicentral region are either partially or totally collapsed. Their failure normally started in a corner by separation of the walls from the domed roof. In some region the ground shaking was so severe that the abode houses were turned into their original sun-dried bricks.

Figure 4. Heavy walls-thickness of wall in some adobe houses is around 1 m

3.2 Masonry Buildings

Masonry buildings are the second most common type of buildings in the earthquake-affected area. They normally consist of brick walls with shallow Jack arch roofs supported by steel **I** shaped beams which is discussed before. The mortar used in these buildings is sand-lime-cement, or sometimes sand-cement. The performance of un-reinforced masonry buildings which lack tie beam or jack arch tie rods was not so better than adobe buildings. The common modes of failure of these buildings were shear failure of walls, separation of walls from the roof, and separation of roof beams from each other (Figure 5). In most cases the steel beams of the roof were not braced together by steel bars or joists. As a result, dropping of the bricks between them during the earthquake could be expected.

Figure 5. Shear failure of walls, separation of walls from the roof, and separation of roof beams from each other are observed in typical brick buildings

A number of reinforced masonry buildings, with vertical and horizontal reinforcing tie beams, were recently built in the city. The performance of these structures was good and in many cases saved the lives of their inhabitants (Figure 6). In many cases the material used for tie beams or their execution quality was so bad that the element hardly could resist earthquake. It is found that the philosophy of the tie beam to protect the unity and integrity of the walls was not understood well. For example in some cases the bond between tie beams at the wall corners has poor conditions. However, wherever the tie beam had a relatively good condition, the performance was satisfactory.

Figure 6. An example of reinforced brick buildings in the earthquake-affected area with a relatively good performance

3.3 Steel Buildinds

Many modern residential and office buildings in Bam are steel building structures that can be divided into two groups. The first group includes buildings with steel internal columns, load-bearing external brick walls, and roofs, often, made of shallow Jack arches with steel **I**–beams. The performance of this type of construction as a sort of un-reinforced masonry structure was very poor. The flexible steel columns tended to displace much more than the rigid external walls resulting in inclining of the steel columns and mostly the collapse of the whole structure (Figure 7). This earthquake clearly demonstrated that the combination of relatively rigid load-bearing external brick walls and flexible internal steel columns is very hazardous. This type of structure is not limited to Bam, and it can be easily observed in most of the cities in the country.

Figure 7. First group of steel buildings, combination of steel internal columns and load-bearing external brick-walls

The second group of steel buildings consists of steel frames just in one direction with bracing in one or two directions. They are actually designed for some horizontal forces. The performance of this type of construction was generally satisfactory (Figure 8). Exceptions are made when the bracing were placed non-symmetrically or incorrectly. In these cases, the infill or curtain walls usually experienced severe damage; i.e. due to the weakness of the lateral load bearing element, the infill or curtain walls had been activated during the earthquake and resisted the applied loads resulting in their severe damage. In braced steel structures, the bracing and their connections had different defects like insufficient cross section area, insufficient connection plate, improper connection execution, and so on. Therefore most of them could not effectively resist applied loads. In fact this earthquake proved that use of steel beams and columns in building structures without observing proper seismic code provisions for earthquake resistance showed no improvement over non-engineered buildings.

Figure 8. Steel building with good performance during the Bam 26.12.2003 earthquake

Figure 9. Incorrectly bracing with single I shaped brace only connected to the column

Figure 10. Unacceptable bracing system where the cross-section of bracing member is insufficient

3.4 Reinforced Concrete Buildinds

As mentioned before, similar to most of the dry areas in the country, reinforced concrete buildings are rare in Bam, however some of them were found and their performance during the earthquake was assessed. Unlike Some researchers [6] who claimed that the performance of the reinforced concrete structure in the area was satisfactory, authors believe that it was not so better than other structures. Authors believe that this mistake arises from the fact that the number of the reinforced concrete structures in the area was much less than the other type of structures. On the contrary it is believed that that seismic performance of the reinforced concrete buildings was rather poor. Their most important problems are:

A. Poor performance of stairs as shown in Figure11.
B. Poor quality of concrete.

Figure 11. Poor performance of stairs in reinforced concrete structures

A. Lack of homogenity between the structural components. For example in one case in a reinforced concrete structure, steel stair case was used (Figure12).

Figure 12. Use of steel stair in a reinforced concrete structure

As a result, authors believe that most problems of reinforced concrete structures would be removed if they were designed and constructed properly. Even, higher RC buildings might be equipped with earthquake resisting elements other than the conventional moment resisting frames such as shear walls. In this order authors propose that the responsible authorities such as national regulations on seismic design (No. 2800 regulations) impose tough rules on construction quality control or limiting the use of moment resisting frames alone at least in the areas with high seismicity.

4. SEISMIC BEHAVIOR OF NON-BUILDING STRUCTURES

There are some notable structures other than buildings in the area from which the most important are a reinforced concrete mosque; an elevated reinforced concrete water tank tower and multi span Reinforced Concrete Bridge. As a whole, all of them had a satisfactory performance and do not sustain any significant damage. In the case of the mosque, it has a three dimensional dome and it is very difficult to find a crack created from the earthquake and all the walls remained undamaged (Figure13). Some researchers such as Adeli [5] believe that due to the three dimensional behavior of dome, the structure is treatsed rigidly during the earthquake. Also field investigations showed that the structural elements (beams and columns) had adequate steel bars and cross sections. The concrete and brick infill walls were observed to have good conditions. It is believed that the infill walls greatly increased the stiffness of the structure in both directions.

Figure 13. A reinforced concrete mosque after the earthquake which had a satisfactory performance

The other important structure is an elevated reinforced concrete water tank tower with approximately 20m in height and 350m^3 in capacity which can be seen in Figures 14 and 15.

The tower has eight legs. The tank was apparently full of water during the earthquake.

According to Figure15, the general performance of the structure was good but as shown in Figure15, some joints cracked so that the steel bars can be seen. As a matter of fact the only observed defect in this structure was improper reinforcement detailing. Investigations showed that the used steel rebars in the structure were round ones to which the cracks to some extent can be related. In addition, one will be surprised knowing that the columns are not reinforced with ties (at least in the joints). It is believed that the cracks in the joints to a great extent are related to the lack of ties in the joints.

Figure 14. The elevated reinforced concrete water tank tower, where some cracks in the structural joints can be seen but the general performance is satisfactory.

Figure 15. Clos-up view of the cracks in the structural joints of the elevated reinforced concrete water tank tower (note the rebars with no threads).

The other important structure in the area is a reinforced concrete bridge having piers lined by stone to resist against the river flow and its probable erosion (Figure 16). Like the mosque and the water tank tower, the mentioned bridge had good conditions being under service after the earthquake**.** Some parts of abutments cracked slightly, but there was no lateral displacement. Some spans got separated about 3 centimeters from the abutments (Figure17). As a result we can conclude that this bridge withstood the intense earthquake approximately without significant damage.

Figure 16. General view of the multi spans Reinforced Concrete Bridge after the earthquake which is in good condition and of course under service.

Figure 17. Separation of bridge Spans from the abutment

5. CONCLUSIONS

The tragic event of 26 December 2003 in Bam with a M_s of 6.5, was the most destructive earthquake in recent century in the country with a loss toll of about 35000 people, after the Manjil earthquake of 20 June 1990 with a M_s of 7.2 that took lives of about 40000 people. Most of the casualties in this earthquake were due to the collapse of the adobe houses. The common modes of failure of masonry buildings were shear failure of walls, separation of walls from the roof, and separation of roof beams from each other. In steel buildings there were two great problems. One refers to the combination of steel internal columns and load-bearing external brick-walls as a hazardous system, i.e. a sort fof typical masonry buildings and the other is lack of observing proper provisions for seismic design and construction.

Although the earthquake magnitude was high, it was generated in a shallow depth, and it induced near source effects on the city, however, the main reason for serious destruction was due to the poor design and construction and the selection of poor building materials. Considering frequently occurrence of strong earthquakes in the country, serious measures must be taken to control and improve the seismic design and construction of new building structures and also at the same time to retrofit existing ones. Incidentally, this earthquake proved that the vertical component of earthquake needs more attention for design purposes. A considerable part of damage in the earthquake-affected area is related to vertical component.

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