

## BAM EARTHQUAKE, IRAN: LESSONS ON THE SEISMIC BEHAVIOUR OF BUILDING STRUCTURES

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### ABSTRACT :

The Bam earthquake on 26 December 2003 with magnitude  $M_w=6.6$  destroyed most of the city of Bam in Iran and nearby villages, and killed more than 26,000 people. The earthquake was by far the most devastating earthquake in the history of the region around Bam. After the earthquake the author undertook a field investigation and visited the affected area. The paper studies the structural damage on traditional as well as modern building structures during the earthquake. Adobe, masonry, steel and reinforced concrete structures are considered with some examples demonstrating the response of each type of the buildings. Discussion of the structural behavior is given with reference to existing seismic design codes and construction practice within the region. It is concluded that as a considerable number of buildings in central and eastern provinces of Iran, more specifically in villages, are built of mud-bricks and will not resist similar magnitude earthquakes. Due to specific materials and construction forms special strengthening procedures needs to be developed.

### KEYWORDS:

*Bam Earthquake, Adobe Structures, Earthquake Effects, Earthquake Field Investigation, Seismic*

### 1. INTRODUCTION

A large earthquake with a magnitude of  $M_w=6.6$  (USGS[3]) struck the city of Bam, located approximately 1000km southeast of Tehran, at 05:26:56 local time (01:56:56 GMT) on Friday 26th December 2003. The earthquake destroyed most of Bam city and the nearby villages and the official death toll exceeded 26,000 with more than 30,000 injuries and 75,000 left homeless.

The earthquake was strongly felt in the provincial capital of Kerman, about 190km (120 miles) Northwest of Bam, however the main damage from the earthquake was limited to a relatively small area near to Bam city, within a 20-30 km radius. In the Bam area the majority of the buildings that suffered extensive damage were of one or two storeys construction and were built from mud bricks or other masonry materials. This earthquake highlighted the particular vulnerability of other cities in this earthquake region and in general the built environment in Iran. The dramatic scale of the casualties associated with a relatively small affected region underlines the fact that urgent measures need to be taken to safeguard the increasingly urbanised population from the real risk posed by future earthquakes.

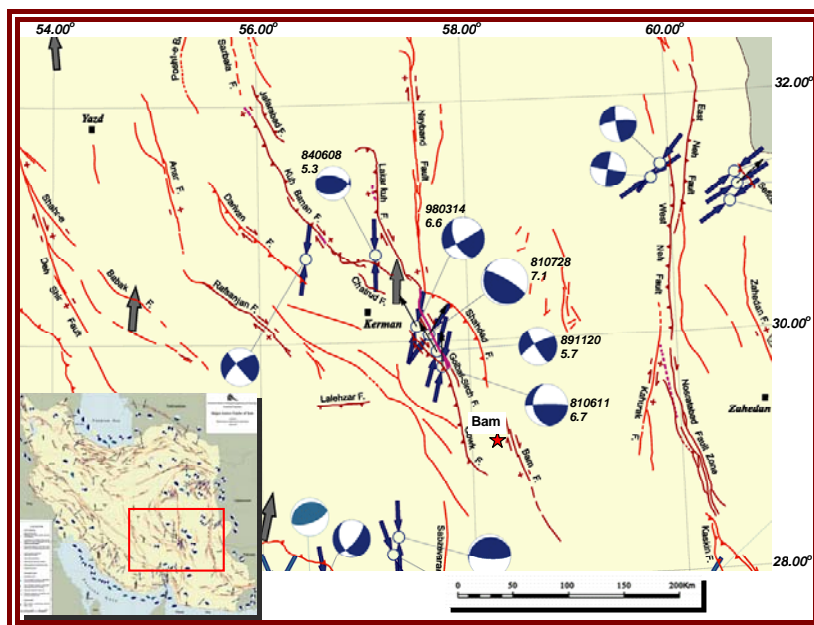
After the earthquake a field investigation carried out by the author from 11th to 17th of January 2004. The main purpose of this paper is to record and comment upon the causes of the various types of damage observed in the buildings and other structures and to determine what lessons can be learnt from this earthquake.

### 2. GEOLOGICAL AND SEISMOLOGICAL FEATURES

The Iranian plateau is part of the major Eurasian plate with the tectonic setting of the region dominated by the collision of the Arabian, Eurasian and Indian plates. The Arabian plate is moving northward against the Euroasian plate at a rate of approximately 30 mm/year with deformation of the Earth's crust taking place across a broad zone 1000 km wide, that spans the entire region of Iran and extends into Turkimanestan in the Northeast of Iran [3]. Earthquakes occur as a result of both reverse and strike-slip faulting within the zone of deformation.

The Bam area is part of the Lut-e-Zangi Ahmad desert that has hot summers with temperatures up to 50 °C and winters with below freezing temperatures. The geomorphology of the region also includes a range of mountains to the North of Bam extending northwest and also the Jebal-e-Barez mountain range to the Southwest of Bam extending in a Northwest-Southeast direction. Water sources within these mountain ranges are the main suppliers for the Qanat system in Bam, Baravat and their satellite villages. The seasonal Posht-Rood river that flows to the North of Bam city is dry during much of the year.

The geology of the region is dominated by lithologies ranging from recent Quaternary alluvium to Eocene volcanic rocks [4]. Based on 1:100,000 Bam geological map sheet published by Geological Survey of Iran (GSI) [8] Bam and Baravat and surrounding areas are covered by coarse brown sandstone deposits. The northeast area of the Arg-e Bam is founded on tuff and traciandesite rocks while other parts are built on alluvial deposits [9]. The thickness of alluvium in Bam varies between 0 and 30m. The main tectonic feature in the area is the Bam fault that can be identified on the geological map, between Bam and Baravat, along the line separating older fans from younger sediments.



**Figure 1: Regional seismology of Bam city (Courtesy of IIEES [5], The dates and magnitude of the earthquakes have been reproduced from references [6] and [7])**

In the central east area of Iran deformation from tectonic activities takes place along faults, which have predominantly North-South and Northwest-Southeast directional trends. Although no major historical or recent earthquakes have been reported near Bam or along the Bam Fault, northwest of Bam and within a range of 150km there have been several destructive earthquakes during past 30 years. The major faults in this region include the Nayband fault with a North-South trend, the Kuh Banan fault which trends Northwest-Southeast and the Gowk fault that starts at the junction of the two aforementioned faults and trends in a North-South direction towards the Jebal Barez mountains in the Southwest of Bam, as shown in Figure 1[7]. Five major earthquakes in recent years are shown in Figure 1 of which four are associated with the Gowk fault. There are also historical earthquakes reported in the region: The Sirch-Hassan-abad 1877 earthquake (Ms 5.6), about 130km Northwest of Bam, the Laleh Zar earthquake (1923, Ms 6.7) that killed 200 and the Golbaf earthquake (1949, Ms 6.0) [2].

### 3. RECORDED GROUND MOTIONS

Out of the 78 instruments within a 300km radius of Bam, the main shock of the Bam earthquake was recorded by at least 24 instruments. The maximum uncorrected accelerations recorded at Bam station (58.35E, 29.09N) were 0.82g, 1.01g and 0.65g in the longitudinal (East-West), vertical and transverse (North-South) directions, respectively. The recording instrument was located on the ground floor of two-storey Governor's office building in Bam which has recorded a ground motion very close to the epicenter. Uncorrected ground accelerations are shown in Figure 2, which show severe vertical and fault normal accelerations [11]. The duration of the strong motion based on Evolution of Arias Intensity was about 8 seconds for the fault-normal component [10].

The earthquake epicenter was located at 29:00N-58.34E, about 185km Southeast of Kerman with a focal depth of about 10km [11]. Studies by Talebian et al [13] based on interferograms derived from coseismic satellite maps suggest that the fault responsible for the Bam earthquake was a blind strike-slip fault located about 5 Km

to the west of the visible surface traces of the Bam fault. Accordingly the causative fault extends beneath the Bam City from the south.

A pre-shock was recorded in Bam station about 53 minutes before the main shock with maximum horizontal acceleration of 0.017g and maximum vertical acceleration of 0.08g, and an estimated depth of 10km. The pre-shock was sufficiently strong that a small proportion of the population took precautionary measures by staying out of their homes. More than 60 aftershocks were recorded in the 6 days following the main shock. The largest aftershock happened about one hour after the main earthquake with a magnitude of 5.3[11].

### 3. OVERALL DAMAGE PATTERN

Damage from the Bam earthquake was mainly concentrated in Bam City and the surrounding villages. Strong motion attenuation in the East-West direction was significantly higher than in the north-south direction. Total affected population estimated to be 145,500 [12]. The most of the population centers other than Baravat and Bam's satellite villages (less than 10km from Bam city) fall beyond the high intensity zones.

In overall terms the damage observed in the city of Bam varied depending upon location and building construction. The damage was very severe in the old part of the city in the Northeast and around Bam Citadel where the construction was dominated by adobe type building structures. Severe damage was also observed in newly constructed parts of the City in the Southeast. The aforementioned areas were densely populated while most of the Southern and Western parts had dual land use with many so called 'garden-houses' with palm trees planted in large courtyards. The damage in these areas was comparatively low, varying between 30% and 70%.

Ground failures and deformations were not significant in the Bam Earthquake. Lifeline infrastructure in the earthquake stricken region and within the city of Bam performed reasonably well, with the exception of the Qanats, a traditional irrigation system, which suffered severe damage. The damage to roads, bridges, railway and airport was minor. Many streets and most of the alleys were blocked after the earthquake due to debris from the damaged buildings. The airport was out of operation for a few hours after the earthquake due to damage to the airport control tower but later played a major role in the rescue and relief operations. Power transmission, electricity and telecommunication networks, and water distribution system also suffered minor damage.

Before the Earthquake there were more than 120 qanats (subterranean tunnels that tap groundwater and lead it to human settlements and agricultural lands under gravity) in the Bam region. Of the 65 qanats supplying water to Bam's world-famous date gardens, 25 experienced some local collapse and subsequently dried up. The remaining qanats suffered damage approaching 40 to 50%. The agro-economic effect on the Bam region was therefore particularly severe due to dependency on agricultural products such as dates.

Despite the fact that the most of the area near to Bam has a high proportion of loose sand and silt deposits there were no reports of damage due to liquefaction after the earthquake. This can be attributed to the low level of ground water in most parts of the region. Some minor effects from landslides in the form of separated earth blocks and falls in dry natural drainage channels were observed in southeast of Bam and near to Baravat.

### 4 DAMAGE TO ARG-E-BAM

Arg-e-Bam (Bam Citadel) is the oldest and largest mud-brick structure in the world and thought to be around

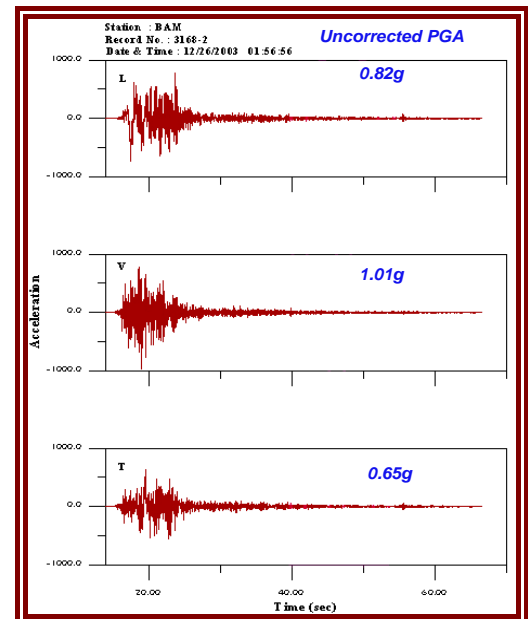


Figure 2: The accelerographs for the main shock recorded in Bam station [9]

2000 years old. The complex is located in the Northeast of the modern city and historically was the old city of Bam, partly inhabited until 180 years ago. The Arg was built out of clay, mud brick, straw and trunks of palm trees at the foot of a huge rocky outcropping and is surrounded by a rampart, consisting of 38 towers, and deep trenches that provided an effective defensive barrier against possible attack. The complex covers an area of about 200,000m<sup>2</sup> and incorporates three specific sections [15]. Since 1973 routine repairs were conducted on Arg to conserve this magnificent ancient mud brick structure and before the earthquake on 26 December 2003 it had become one of the most popular tourist destinations in the southeast of Iran.

The Arg suffered extensive damage during the earthquake. Approaching from the Southwest, some parts of the external walls of the complex were reduced to rubble, barely resembling the shape of the original construction. By climbing on top of their remains one could clearly see the complex's debris filled courtyard. The fact that this structure had been standing undamaged for around 2000 years has been taken by some [1, 22] as evidence that the Bam region had not experienced any earthquake of a similar intensity to the Bam earthquake during this period. Figure 3 shows damage to Arg-e Bam after the bam earthquake.



Before earthquake



After earthquake

**Figure 3: Damage to the Arg-e-Bam after Bam Earthquake**

## 5 PERFORMANCE OF BUILDING STRUCTURES

The Bam earthquake is by far the most devastating earthquake in the history of the region around Bam. Located at a relatively short distance from the epicenter, Bam city experienced particularly intense local ground shaking. Despite the enforcement of seismic code in the region, many of the building structures were too old for their construction to be controlled by modern standards. However a significant proportion of the new buildings should have been designed and constructed taking account of the seismic requirements in the Iranian codes.

It is well known that the building construction practice in Iran and more specifically in small cities like Bam has been poorly regulated and monitored. There is clear evidence of this from the observations made after the Bam Earthquake. The widespread total damage to the majority of newly constructed buildings in the private sector contrasts strongly with the more limited damage to the few structures, mainly in the (well-regulated) public sector, that remained standing. This strongly suggests that poor construction practice played a major role in the vast destruction and high death toll within the city.

In the following a summary of observations made to the extent of damage to building structures is presented.

### 5.1 Seismic Regulations and Construction Practice

Following the Buein-Zahra Earthquake of 1st September 1963 which killed more than 12000 people, the first Iranian regulations for seismic design appeared in the guideline "Seismic Safety Code for Building" published by the then Ministry of Housing and Reclamation in 1967. The seismic load calculation procedures for this code were subsequently published as "Standard No. 519, minimum loads for buildings" by the Planning and Budget Organization giving mandatory minimum loading standards for new building structures. The first edition of the



current “Iranian Code for Seismic Resistant Design of Buildings, Standard No. 2800” [16] was published by the Building and Housing Research Centre (BHRC) in early 1988 and since then has contained the official requirements for seismic design in Iran. The second edition was published in 1999 while the third edition has recently been published.

There are a number of factors affecting building construction in the Bam region such as cost, climate requirements and the availability of suitable materials. Types of construction range from mud-brick and adobe structures, fired brick masonry structures to reinforced concrete and steel structures. In terms of normal building practice, private homes are built by their owners who hire the builder and unskilled labour. There are no requirements for the registration of builders or contractors for these buildings and as a result there is no adequate system to prosecute negligent builders. However there is legislation in place requiring the production of construction drawings, for the control of construction by authorized professionals and for final approval of drawings by local authorities prior to the start of the construction. Nevertheless, in real terms, there is little control on the construction process itself.

## **5.2 Building Damage**

The most dominant structural systems in the Bam region are:

- Adobe buildings: built from adobe materials and unfired mud bricks. Most with a vaulted roof system.
- Masonry buildings: built from fired bricks or concrete blockwork as the main load bearing system and normally combined with a jack-arch roof system.
- Steel structures: Typical construction includes frame structures with steel beams and columns and sometimes a braced framing system to resist the lateral loads.
- Reinforced concrete structures: Only a limited number of these structures exist in Bam mostly used for public buildings or government offices.

Outside the city, in the villages, adobe and masonry buildings are the main structural types.

### *5.2.1. Adobe buildings*

Adobe and mud bricks are one of the oldest and most widely used building materials in the southeast of Iran. The adobe buildings normally have domed or vaulted roof system. For these roof systems the final finished level may still be flat. In this structural system thick and stiff walls provide the main load bearing system. From structural standpoint adobe structures are bulky and heavy. More importantly the roof can be very heavy due to the complex vaulted system, or due to additional weight accumulating by the application of insulating layers normally added every few years. Soil is a weak and brittle construction material and will disintegrate easily if subjected to strong vibration. Under seismic loads the heavy walls and roofs develop large inertia forces that cannot be resisted by walls often resulting in large cracks or collapse. Although the vaulted roofs perform well in transferring gravity loads, due to utilization of mud bricks in compression, they are not well suited to transferring horizontal seismic loads or strong vertical seismic loads. The result is a sudden collapse of the structure with insufficient time for evacuation and a dusty atmosphere afterwards, further reducing the survival prospects for the victims trapped under the building. The majority of these buildings collapsed in the old district of Bam, leaving a flattened area.

Figure 5 shows an example of damage to adobe buildings in the Bam earthquake. Severe damage to total collapse was seen in Bam city and Esfikan village while in Nartij village most of the buildings were standing with only moderate damage with a smaller proportion suffering collapse. Although most of the buildings with vaulted roofs collapsed within the city,



**Figure 5: Total collapse of adobe buildings in Bam**

few had performed well and remained standing after the earthquake with only moderate damage. Vaulted roofs were also seen in fired brick masonry buildings, again in some cases with good performance. From those vaulted roof mud brick buildings that did not collapse it could be seen that most of the vault infills and end walls, perpendicular to the direction of vault axis, had collapsed. This suggests that the deformation mode of the vaulted roofs and their supports differs from those of the perpendicular walls, and the lack of a shear transfer mechanism between these two parts resulted in the separation and subsequent collapse of the walls.

### 5.2.2. Masonry buildings

Masonry buildings constructed of fired bricks have become one of the most common construction methods in Iran since the early 1960's. Masonry walls are the main load bearing structural elements, and more often than not, are combined with a partial steel frame consisting of a few columns in plan with steel beams spanning between the columns and walls. The most commonly used flooring system consists of steel joists (standard I beams) at approximately 1m spacing and fired brick jack-arches between the joists. This flooring system is also very common in steel structures. The other common floor system is one with the floor constructed from prefabricated reinforced concrete joists, about 50cm apart, with hollow bricks between the joists and an in-situ reinforced concrete slab topping. In central and south-eastern Iran fired brick vaulted roofs are also very common practice for the construction of masonry structures.

Since the introduction of modern seismic design codes in Iran, masonry buildings are now required to have horizontal and vertical ties. The use of horizontal ties in Iran started in the 1960s and the use of vertical ties began in the 1970s. However this practice took much longer to be implemented in rural regions such as Bam. Many of the older masonry buildings in Bam have been constructed without ties and even some buildings, constructed as recently as six months before the earthquake, were found to be without ties. For masonry structures without ties observed main failure types include: a) horizontal displacement of simply supported joists in jack-arch system resulting in collapse of arches between the joist (b) horizontal movement and slippage of the whole roof system on the walls resulting in total collapse of the building. In addition, poor material properties and workmanship were a common factor and a contributory cause to the damage experienced by many structures. Mortar materials used in older masonry buildings are lime-clay, lime-sand or lime-sand-cement. Although in more recent construction sand-cement is predominant, lime-sand is still used in some private houses. An example of masonry building total collapse is shown in Figure 6.



**Figure 6: A residential masonry building without ties in Baravat. Construction finished about 6 months before the earthquake**

### 5.2.3. Steel structures

The Iranian seismic code only permits masonry structures up to two stories provided that they satisfy other specific limiting criteria. Beyond this limit steel frame structures are normally the first choice for engineers and owners. The single most important issue for these structures is the lack of welding quality control and generally poor workmanship. The secondary consideration is the lack of proper design due to the lack of seismic training for designers, in relation to the design of structural and also the non-structural elements. Many of the structures incorporating bracing systems to resist the lateral loads performed well and survived without collapsing and in some cases without any damage to their glassy facades. Conversely, other steel structures in the same neighbourhood suffered total collapse or severe damage. Simple frame structures that were obviously badly constructed were among the most severely damaged structures. In some recently built steel structures flaws in the design and/or construction had caused excessive deformations resulting in extensive damage to the internal and external walls or in the worst cases total collapse.

Figure 7 shows damage to Kimia Building which is a combined residential-commercial building with braced steel frames in Bam city centre. The building had 5 stories above ground towards the front but only 4 stories in the rest of the building. Two to three stories were flattened during the earthquake. This building is a typical example of the effect of geometrical, stiffness and mass irregularities which resulted in large lateral and torsional displacements. This combined with poor quality of welding have contributed to total collapse of the structure.



**Figure 7: Kimia building in Bam**

#### 5.2.4. Reinforced concrete structures

In Bam reinforced concrete structures were rare and of these very few, if any, were evident of being used for residential purpose, with the majority used for government or other communal buildings. Generally they performed well and survived the intense force of the earthquake with only minor to moderate damage to non-structural members. However poor design, materials and construction quality caused severe damage and partial collapse to newly constructed reinforced concrete Imam Sadegh mosque in Bam

#### 5.3 Stairwell extensions

Failure of the rooftop extensions to staircase structures was common in the Bam Earthquake. The largest damage to these structures was seen in masonry buildings where the structure is merely an extension to the staircase walls and covered with a flat or inclined jack-arch roof spanning between the two side walls that run parallel to stair axis in plan. The other walls normally have large openings for a door to the roof top on one side and a window on the other side, which make the structure very flexible and weak in the direction parallel to these walls, unless a proper framing system is implemented. The weakness in this direction has resulted in detachment of the whole staircase extension from the building below, large movements and also instances of collapse. The use of vertical and horizontal ties does not necessarily provide sufficient framing for the staircase extension to resist the earthquake force in the direction perpendicular to the stair axis. Due to the importance of the staircase structures in providing safe evacuation from buildings, and since failure in these structures was a common occurrence in the Bam Earthquake the issue of proper design of these structures and the provision of clear design guidance needs to be considered by local authorities.



**Figure 8: An Example of the performance of staircase extension structures in Bam**

## 6 LESSONS LEARNED AND CONCLUSIONS

Despite the history of tragic earthquakes it appears that the issue of seismic risk has not to date been addressed particularly effectively. This failing runs through every level of society and it is reasonable to ask why the obvious lessons of the earthquakes are being ignored. Perhaps the intermittent nature of devastating earthquakes tends to create a culture of acceptance of the status quo and failure to take responsibility in a society which has mainly focused on short term needs. It is obvious, that for any plan to work successfully this culture needs to change and the requirements for fundamental earthquake hazard reduction need to enter national consciousness at all levels of society and then be enforced with minimum tolerance of negligence.

The experience of Bam earthquake highlights once again similar causes and problems in the disaster preparedness system and the deficiencies in current construction practice, similar to most high casualty recent earthquakes. The following are specifically noted:



- Traditional mud-bricks buildings: Most of these buildings completely collapsed during the earthquake. A considerable number of buildings in central and eastern provinces, more specifically in villages, are of this type and will not resist similar magnitude earthquakes. Therefore, it is essential that any earthquake hazard reduction programme in the region take these into consideration.
- Non-engineered buildings built of masonry or a combination of masonry and steel without any specific seismic considerations: A good majority of the non-traditional buildings in many parts of Iran are of this type and are vulnerable to earthquakes. An active retrofit and renewal strategy should be formulated.
- Seismic design code: The implementation of the code is a major issue and in this regard effective training of professionals, providing additional guidelines for the code and effective construction control are essential.
- Lack of skilled labour and construction professionals: Most of the people working in the construction industry are unskilled and unlicensed. This results in poor material production and construction. A process should be implemented to train and licence professional working in construction.

Last but not least, as a country with high seismic risk and with its own seismic characteristics it is also necessary to invest in scientific institutions and research facilities in earthquake engineering to pave the way for technical and professional people to tackle the country-specific problems in seismic hazard reduction.

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