

**THE BAM EARTHQUAKE OF 26 DECEMBER 2003, IRAN**

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**Introduction**

At 5:26:56 am local time (01:56:56 GMT) on 26<sup>th</sup> December 2003 an earthquake of magnitude  $M_w = 6.5$  (ref:1) struck the ancient town of Bam about 800km south-east of Tehran in Iran (fig:1). The maximum intensity value was 9 EMS (fig: 2,3), and it caused almost total destruction of the town and the surrounding area of Baravat. Out of a population of 180,000 the Iranian government has announced an approximate loss of 30,000 lives with 50,000 injuries. Around 18,000 homes and hundreds of businesses were damaged beyond repair, at an estimated cost in the region of \$10 billion.

The form of construction in Bam was predominantly (90 %) adobe and masonry, with 8% steel and 2% concrete construction. Site surveys (ref: 2) indicate that 62% were beyond repair, 35% could be retrofitted and 3 % were safe.

The historical monument of Arg-e-Bam, parts of which date back 2000 years, was severely damaged (photos: 25, 26).

The majority of residential buildings were traditional one storey houses built with brick and clay and lime mortar without a structural frame and founded on shallow clay and mortar strip footings. Most such buildings collapsed (photo: 2,3,7,8). Some buildings were of site welded anchored jack arch roofs made of steel joists with infill brick arches supported on brick wall construction founded on comparatively deep clay and mortar strip footings. These generally survived, but with extensive structural damage.

Multi-storey residential and office buildings were generally constructed of steel frames welded on site, with hollow partition walls and joist and block flooring with concrete topping. A number of these collapsed because of poor site welded connections, lack of robustness and lack of lateral stability. Large open spaces at ground to first floor level, such as car park or shop spaces, caused a number of collapses due to soft storey failure (photo:11 to 18).

Long span steel portal frames fabricated and welded in the yard and assembled by means of bolted connections survived the earthquake well (photo: 6).

In Bam, the main source of agricultural and drinking water is from qanats, a tunnelled water distribution system originally built thousands of years ago to transport water trapped behind a geological fault several kilometres to the east of town to more populated and agricultural areas. About 40% of these qanats collapsed or were severely damaged by the earthquake.

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**Field Observations:**

The ground motion data of this earthquake were recorded by 27 stations of the Iranian National Strong Motion Network. The nearest instrument to the earthquake was in the centre of the city of Bam and the records suggest a focal distance of about 8km and also indicate a right-lateral strike-slip movement on a N-S trending fault rupture.

The peak ground acceleration of the horizontal components of the earthquake were 775 cm/sec<sup>2</sup> perpendicular, and 623cm/sec<sup>2</sup> parallel to the fault direction respectively. The peak ground acceleration of the vertical component was 992cm/sec<sup>2</sup> (fig: 3). Of 250 recorded aftershocks until 4<sup>th</sup> January 2004, 187 were located directly beneath the city of Bam (fig: 4).

IIEES have stated that the epicenter was located at 29.01N and 58.26E, a location 10 km south west of Bam; this is close to the coordinates calculated by USGS (28.99N, 58.29E). However, based on the surface evidence reported by Zare and Eshghi of IIEES, and the observations reported here, it is my opinion that the epicenter was in fact located directly under the town of Bam. Surface ruptures related to the earthquake indicate that the earthquake occurred along the right –lateral segment of the Bam fault zone (photo: 1).

A damage survey was carried out by the Building and Housing Research Centre (ref: 3) on a group of 94 buildings along the main streets in the centre of the town. The building stock comprised of 24% adobe, 26% simple one storey masonry, 29% simple masonry with steel frame, 14% simple frame with steel bracing, 1% simple masonry with reinforced concrete frame, with 4% of unidentified structural type.

**Adobe:**

Single storey adobe buildings are the traditional form of construction. More recent masonry construction uses low strength fired bricks as discussed later, and adobe buildings are generally more than 35 years old.

Traditional adobe construction for the area consists of mud brick (Kesht) walls and barrel vault roofs with lime mortar bedding, founded on lime mortar strip footings. Almost all buildings of this type collapsed due to failure of the walls which could not resist the tension from longitudinal waves and the increased vertical loading of the roof which was exaggerated by the earthquake vertical waves (photo: 3). In cases where the supporting walls survived the cylindrical or vault roofs performed well (photo: 4).

Adobe is also made of earth walls composed of layered mud and straw (Chineh) with barrel vault roofs again made of mud bricks (Kesht). Small arches built on top of the vaults occupy the space between the top of the vault and the flat roof surface, supporting the flat roof. Such adobe buildings usually have a wind catcher (Badgir) on the flat roof which ventilates the space between the flat roof and the vault, insulating the rooms from direct heat (photo:3).

Many of these houses had not maintained their traditional wind catcher and instead had added layers of mud straw on their roofs for insulation, increasing roof load which had significantly added to the vertical loading (photo: 2).

Some recent buildings have been built in traditional brick vault style, but using fired bricks and some cement mortar. These generally performed well, with some cosmetic cracks; and example is the Khorak Sara restaurant in New Arg.

Similarly, a mosque under construction and of traditional design with minarets of about 20m tall and a vault of about 13m high and 7m span survived with some damage to the false

plaster ceiling and some structural cracks to its minarets (photo: 5). The other minaret which was already completed with a layer of reinforced cement render belt around it and small pattern Sufi tiles fixed on top of the render survived without damage. Thick supporting walls integrated into the minarets survived horizontal loading and in turn supported the vault.

#### Arg-e-Bam (Citadel)

This ancient monument was built with layered (Chineh) earth walls of mud with pine tree trunks placed as horizontal central reinforcement inside the layer. The horizontal joints between the layers were smooth to allow some relative movement between layers while preventing vertical crack propagation from shrinkage or other natural causes from the above layers (photos: 25, 26). In some walls the horizontal movement joints above 3 or 4 layers are improved with two or three courses of mud brick (Khest).

The earth walls were weakened by the presence of termite infestations which had consumed the pine trunks and straw which were initially placed inside the Chineh for longitudinal and fibre reinforcement. This caused hollow narrow tunnels which severely undermined the strength of the wall.

In restorations which took place after 1974 (ref: 4) without sufficient structural engineering input on the Ice House, a heavy stepped dome was built on the existing walls (photo: 27). This additional loading resulted in damage to the inner part of the ancient internal wall as well as a vertical structural crack near its entrance (photo: 28, 29).

#### Single Storey Simple Masonry:

Some one storey masonry buildings were made of brick load bearing walls with lime mortar bedding supporting unanchored jack arch roofs and founded on a shallow lime mortar strip. The jack arch slabs are carried in steel joists spaced at 800 to 1000 mm (photo:8). The bricks are fired, but typically of low strength (around 0.1 N/mm<sup>2</sup>).

The soffit of the jack arch slab is levelled and covered with gypsum plaster and the floor above it is composed of tiles bedded in mortar. The gypsum plaster on the soffit may weigh up to 50 kg /m<sup>2</sup> and is not tied to the brickwork. As the bricks in the arch experience relative movement due to the cyclic loading, the stiff plaster separates and falls off.

Excessive layers of mud straw on the jack arch roof for heat insulation also increased the weight of many of these roofs (photo: 9).

The jack arch slabs are relatively flexible and cannot provide a monolithic diaphragm action to transfer the horizontal loading to columns and strong points. Normally the steel joists rest on bricks or concrete pad stones and do not have a ductile connection between the roof and wall. Almost all such buildings were destroyed in the earthquake.

In some cases the owners of non-engineered buildings had paid greater attention to detail for their one storey masonry houses. This generally consisted of adopting comparatively deeper lime mortar footings on consolidated gravel, while the roof was constructed as an anchored jack arch system, with cross bars welded to the joist top flanges and tied to the supporting walls through steel ring beams which were in turn welded to the steel door and window frames, with these then anchored to the load bearing walls.

Layers of 30mm cement grout were then laid on top of the anchored jack arch. Such building typically had an internal wall to floor area ratio higher than the code requirements, and also benefited from thicker perimeter walls. These buildings with some ductility at roof to wall connections had some structural damage but did not collapse. The Iranian seismic

code IS 2800 covers anchored jack arch beams, and design proposals by the University of Shiraz (ref: 5) recommend transverse beams at the ends and at the inter-span, and it appears that buildings which comply with this requirement performed well.

As cement for concrete construction is expensive for a rural house builder, this method of constructing one storey houses appears worthy of further investigation for rural parts of Iran with low seismicity.

#### Simple masonry with steel frame

Buildings such as 17 Sharivar High School which had a relatively even distribution of cross walls, where the maximum length of wall without cross wall does not exceed 7m, survived the earthquake with only minor structural cracks. In contrast, the two storey Governor's building had cross walls unevenly distributed with up to 11m length without any cross walls or piers, and suffered partial collapse.

Buildings constructed of infill solid brick walls in tie frames performed much better than poor quality welded steel bracings in moment resisting steel frames (photos: 16,17, 18).

#### Simple masonry with reinforced concrete frame

There were comparatively few RC framed buildings in Bam. However, despite poor detailing at connections and relatively poor quality of concrete, reinforced concrete framed buildings performed comparatively better than site welded steel framed buildings (photo: 24 & 32). The monolithic concrete beam/column connections performed better than the poorly welded connections of steel tie buildings. Solid infill brickwork which was well confined inside the RC tie frame also improved horizontal stability. Higher wall to floor area ratio in some of these buildings made a further contribution to their improved performance.

The airport terminal had many cracks in the masonry infill walls which had performed as shear walls and thus improved overall lateral stability of the building (photo: 31). The control tower also had non-structural damage. The terminal remained in use after the earthquake and a replacement portable control tower was temporarily installed to cater for frequent flights for rescue and relief operations (photo: 30).

#### Steel frame buildings with concentric bracing:

In Iran steel structures are generally site welded and are made of battened columns with "Khorjini" frame connections between the columns and the beams.

Battened columns are made of two universal beams coupled by welding plates to their flanges (photos:10, 15, 16 & 33). A typical battened column might be made of two parallel 180mm deep universal beams with steel plates of 200x100x7mm welded at 500mm centres to its outer flanges. In Iran, universal columns (Bal pahn) are rare and their use in construction is limited. This shortage of universal columns has therefore developed into the improvisation of battened columns. In some cases columns are site welded from channel sections to form a box section. Beams are typically universal beams, often site castellated. Korjini frame connections consist of angle sections welded to the column sides to support continuous multi-span beams.

Alternatively, some simple frames are made by connecting the beam to the centre of a column by means of two angle sections welding the beam's top and bottom flanges to the UB web or to a plate welded to the flanges of the battened column.

Bracing is typically used in both directions. However, because of the poor quality of welding bracing connections, those structures without steel bracing but with infill solid blocks

performed better than those with steel bracing, due to the frequent out of plane buckling and rupture of the connections of concentric X bracings (photo: 12, 13, 15).

The main beams support the floor joists, which is made of steel joists supporting jack arches, or of concrete and carrying hollow infill blocks with structural topping. Jack arch flooring is a heavy and relatively flexible flooring system which cannot transfer diaphragm action through floors to strong points. However, because of the high cost of cement it is still being used in most buildings.

The main cause of failure of steel structures was the poor quality of site welding at the connections of battens to columns or joints of boxed channels (photos: 12, 13, 16).

In battened columns, the batten plates are too weak to transfer the shear from horizontal loading to the coupled universal beams, resulting in vertical shear cracking and rupture at the batten ends or failure of batten welds to beam flanges.

The Iranian National Building Code for Steel Structures Part 10 (ref: 6) covers the design and detail of battened columns and states that the code covers vertical loading only.

The Structural Engineering Research Centre of IIEES has recommended (ref: 7) the prohibition of the use of battened columns in Iran until appropriate guidelines and provisions are introduced for their use in regions of high seismicity.

Box section columns also performed poorly, with rupture of the longitudinal site welds very common.

The behaviour of two steel frame structures at the Kimia Building and the Bank Tejart building in Bam are investigated as follows:

#### **Kimia Building**

A typical case of a steel frame failure was the five storey Kimia building. (photo:11). The building had battened columns on the south elevation (photo:13), channels welded back to back (i.e. not as box section) on the north elevation (photo:12) and corner columns made of single Universal Beams (UB). With moments generated from an east - west direction, seismic forces were resisted on the weak axis of the corner columns, the weak axis of the battened column and the weak axis of the back to back welded channel column. The columns buckled and failed prematurely.

The third floor of this building had shifted about 4m towards the west. The second floor was parking space, with a few cross walls made only of fragile hollow bricks. This floor therefore acted as a soft storey with horizontal displacement by the buckling columns. Initially, after the main shock, the building tilted about  $17^\circ$  from the vertical (photo: 14). However, the fourth and fifth floor collapsed two weeks later from frequent aftershocks.

Contrary to the code's recommendation, the fourth and fifth floors were asymmetrical about the centre of gravity of the whole building, resulting in a torsional response (photo: 13).

The concentric bracings were underdesigned, with some consisting only of T18 bars poorly welded in place. IS 2800 requires bracing members to have a minimum slenderness ratio  $K/r \leq 6025/\sqrt{F_y}$ , and the slender bars and small angle sections in this building were insufficient.

The concrete joist and hollow infill block floors lacked diaphragm action, missing the cross ribs at 2.5m spacing required by the code. Weak diaphragm flooring was a common feature with braced steel frame structures (photo: 13).

The lift shaft which is normally used as the strong point to transfer horizontal forces from diaphragm flooring to the foundation was made of fragile hollow blocks with weak angle steel corner columns (photo: 13 ).

**Bank Tejarat Building:**

This was a two-storey braced building (photo: 18), but the bracing was not concentric or symmetrical, and had poorly site welded connections with small gusset plates.

Concentric bracing with infill solid bricks was provided on the northern and western elevation walls. These walls provided some horizontal stability by transferring the seismic forces in both directions to floors of joist and block with structural concrete topping which acted as diaphragms transferring forces to its batten columns.

The batten columns were comparatively stronger, with battens at 300mm spacing rather than the common 500mm. The braced and confined batten columns transferred the seismic forces to the foundation.

However, the torsion due to an asymmetrical transfer of horizontal loading to the foundation by the north and west walls caused some buckling to the columns at first floor level near the south-east corner. The cladding separated and some of the internal walls collapsed

Reinforced concrete frame structures

**Water tank:**

The reinforced concrete frame structure supporting the 350 m<sup>3</sup> water tank in photo 19 is 20m high and is located at the fire station in the centre of old part of the town. This engineered structure, which was the tallest in the immediate area, survived the earthquake with some structural damage, although it should be noted that it was almost empty at the time of the earthquake. Almost all the nearby buildings collapsed (photo: 20).

This structure was built in 1972 and comprises 6 rectangular columns approximately 15m tall tied to one another at 2.5m, 9m and 14.5m above the ground level by rectangular reinforced concrete beams.

The structural damage from the earthquake was:

- ◇ horizontal structure cracks under the columns at the corner of beam to column connection (photo: 21).
- ◇ Diagonal shear cracks starting on the soffit of the beam close to the column propagated at 45° away from the column towards the top of the beam (photo: 21). This type of crack in the beam at beam column connection is common when a reinforced concrete frame is exposed to earthquake loading (refs: 8 & 9).
- ◇ At the face of one of the columns at the beam/column connection at 2.5m above ground level, the weight of the structure plus added vertical loading from the earthquake compressed the concrete in the column which in turn pushed the surrounding main bars outwards. This resulted in buckling of the main reinforcement and spalling of their concrete cover. The spacing of transverse confinement steel in this damaged area was

about 400mm (photo: 22) as compared to the recommendation of Iranian Code for reinforced concrete (ref: 10) which restricts the spacing of the transverse stirrups to 250mm.

**Rail way passenger terminal:**

This building, located outside the southern part of Bam, was at the cladding stage of the construction project. The perimeter circular columns support the end of a comparatively deep rectangular beam which in turn carries the floor slab. The beam/column connection had insufficient bearing length (photo: 23). The code requires the bearing length at supports to be larger than the depth of the supported beam. However, the equivalent square dimension of the circular column is about half the depth of the beam it is supporting.

**Development of Design Codes**

Almost everywhere in Iran is prone to earthquakes as two major earthquake belts run through the country. Every decade or so a major earthquake strikes Iran resulting in many fatalities and collapsed buildings. Traditional Iranian buildings, especially in the rural areas, have very little resistance to earthquakes of higher magnitude.

After numerous major earthquakes, in particular that of 1963 in Bouein Zahra, the Iranian government began the preparation of a code of a practice for earthquake protection. In 1967 Iran's Ministry of Housing published a code of practice for earthquake resisting construction which required buildings taller than 11m to be made of reinforced concrete or steel frames. The first chapter of the code covered masonry construction and the second chapter included guide lines and general analysis for a building exposed to earthquake loading.

This code was put in effect by Iran's Organization for Planning Budgets and the second chapter was added as chapter 8 to Iran's National Standard Code ISIRI 519 which until then covered only static vertical loading in buildings. In 1987 'Code of Practice for Seismic Design of Buildings' 2800 superseded chapter 8 of ISIRI 519. After the Manjil earthquake on 20 June 1990, a further revision of the code was found to be necessary.

In 1993 the Iranian Building Research Centre further revised the code and after three stages of research, consultation and design, the updated and revised Iranian Code for Seismic Resistant Design of Building was published in 1997 (IS2800). This code was revised in 1999 and covers seismic design for reinforced concrete, steel and masonry construction. The code's section 1.4 states that the following rules and recommendations should be considered in the design:

- a) All parts of the bearing structure should be connected to each other, so that in the case of earthquake the whole structure behaves as one unit and should have high ductility.
- b) The structure should be considered for earthquake loads in two perpendicular directions.
- c) For the reduction of damage to neighbouring buildings, buildings of higher than 12m or 4 storeys should be separated from each other by seismic gaps. The minimum width of the seismic gap is 0.01 multiplied by the height of the level considered from the foundation.
- d) The plan of the building should be as simple and as symmetrical as possible.
- e) Those parts of structures that are carrying vertical loads (i.e. columns and walls) on different levels are best to be continuous in elevation.
- f) For the purpose of reducing torsion, the distance between the centre of mass and the centre of stiffness should be less than 0.05 multiplied by the width of the building in that direction.
- g) Cantilevers of more than 1.5m should be avoided.
- h) Large openings in the floors should be avoided.
- i) Placing of heavy equipment on the roof should also be avoided.

j) The building should be so designed that the vertical elements (columns) are damaged after the horizontal elements (beams).

IS2800 (1999) covers steel, reinforced concrete timber and masonry buildings but does not cover bridges, marine structures, nuclear power stations, dams or traditional buildings built with bricks, clay and lime mortar commonly found in rural areas. It recommends that construction of the last should be avoided, since they have little resistance to earthquakes.

### Code Comparison

The majority of buildings built in Bam after 1990 were traditional buildings constructed from bricks bedded in clay and lime mortar and built on clay and lime mortar strip footings; 80% of them collapsed.

### Base Shear

Chapter 2 of the code covers design of earthquake resistant buildings and requires design of a structure to the base shear coefficient (C) for the region in which the structure will be built.

According to IS2800 (1999) chapter 2, the seismic base shear coefficient is obtained from:

$$V = CW$$

$$C = AB/I/R$$

$$B = 2.5(T_o/T)^{2/3} \leq 2.5$$

$$T = 0.05H^{3/4}$$

where:

V = Base shear

W = Total weight of the building (Dead load + 20% Live load)

C = Base shear coefficient

A = Design base acceleration or ratio to gravity acceleration which may be 0.20, 0.25, 0.30 or 0.35 depending on the region (0.3g for Bam in region 2 of the seismic microzonation map of Iran)

B = Building response factor obtained from design response spectrum (amplification factor)

I = Importance factor of building (=0.8, 1.0 or 1.2)

T = Natural period of the building (sec)

T<sub>o</sub> = Corner period of the acceleration response spectrum (sec) dependent on the soil type (0.4, 0.5, 0.7 or 1.0): 0.5 sec for the soil type II in Bam

R = Building behaviour factor varying from 4 to 11 (e.g 4 for simple masonry with tie frame and 6.0 for concentric steel braced buildings)

H = Height of the building from base (m)

For a two storey masonry building in Bam, by assuming B=2.5, I=1.0 and R=4, the base shear coefficient in the area may roughly be estimated as C=0.19.

In comparison, the Uniform Building Code 1997, Chapter 16 Division (IV) gives the following:

Seismic base shear

$$V = (C_v I / (RT)) W$$

$$\text{but } V \leq (2.5 C_a I / R) W$$

$$V \geq (0.11 C_a I) W \text{ or } \geq (0.82 Z N_v I / R) W$$

Parameter dependencies are Z on the region, C<sub>v</sub> and C<sub>a</sub> on soil, I on occupancy, T on height, and R on type of frame. If the structure is a moment resisting frame it must satisfy the

special requirements of UBC 97 chapter 22 for special moment resisting frames. Evaluation of the above parameters is obtained from tables (I,R,Q,K&N) in chapter 16.

Chapter 3 of IS2800 covers unreinforced masonry, which is described as confined masonry with reinforced concrete or steel elements as tie beams or tie columns. These buildings are limited to two floors with a minimum of 6% and 4% of the relative wall cross section area per floor in each direction for the first and second floors respectively.

For simple masonry buildings up to two storeys  $B=2.5$ ,  $l=1.2$  for government offices and hotels, and  $R=4$ , this leads to an approximate value of  $C=0.23$  for the base shear coefficient.

$$C = \tau A_w / w N A_f$$

where

$A_w / A_f$  = Wall sectional area ratio

$w$  = Floor weight per area  $\geq 750 \text{ kgf/m}^2$

$N$  = Number of floors,

$\tau$  for partly fired bricks produced near Bam =  $15,000 \text{ kgf/m}^2$

### Shear Walls

Iranian code ABA 1998 has no dimensional restrictions on the size of shear wall, whereas other codes do. For example, the New Zealand code N23101:1982 requires building taller than two storeys, wall thickness must be at least  $l_n/10$  in the plastic hinge zone, where  $l_n$  is the unrestricted height or clear span. Smaller thickness is possible if lateral restraint is provided by a flange or crosswall if the neutral axis depth is small. The Japanese code states that the wall thickness  $> (\text{clear height})/30$ , with a minimum of 120mm where all panels of walls must be surrounded by 'boundary' beams and columns.

### **Conclusions**

The main factors which contributed to the collapse of buildings in Bam during the earthquake of 26 December 2003 are as follows:

- Lack of understanding by the public and local builders of the need to build in a seismically resistant manner and to retrofit or replace older buildings
- The absence of adequate building controls on new construction
- The general poor quality of construction and of materials
- There are also some weaknesses in the design codes

These are discussed below.

### Understanding/Education

- The majority of rural construction in Iran is comprised of non-engineered buildings made of brick, lime and clay load bearing walls with jack arch roofing founded on lime and clay strip footing. However, the Iranian code states that such buildings are beyond the scope of the code and that this method of construction should be avoided.
- There is a lack of sufficient structural engineering input into buildings to design, detail and supervise the contract to ensure the contractors achieve reasonable quality welding, steel fixing, shuttering and bricklaying.
- it appears there are not sufficient training courses or continuous professional development courses in institutions, universities and colleges.

- There seems to be an urgent need for a monthly publication reporting on the structural engineering aspect of current national and international construction projects for the practicing engineers.
- Poor building maintenance as well as introduction of additional loading on the roof for insulation and waterproofing without considering the effects on the structure during an earthquake.
- A lack of awareness on the part of the local community and authority that Bam is in a highly seismic region.
- Inhabitants were not trained on how to respond after two preshocks that took place 5½ hours and 1½ hours before the main earthquake.

#### Building Regulations and Building Control

- In Iran there are no Building Regulations or an enforcement body such as Building Control to make inspections and approval at each stage of the construction of the foundation and structure similar to that of part A of the Building Regulations in the United Kingdom.
- Socio-economic factors have caused those living in the rural communities to build their houses without reference to building code recommendations and without the input from the local authorities. Regulating chapter 3 to socio-economic needs and making a parliamentary legislation of its content in the form of building regulations would enforce the construction of safe rural buildings up to two storeys.
- In Iran all planning and structural calculations are approved and signed by individuals called architect engineers whose competence has been approved by the Department of Housing and the Local Regional Office of the Association of Engineers. There is not an established organization inspecting the work of individual engineers.
- Engineers and other professionals do not carry professional indemnity insurance to protect the developer and occupier against structural or seismic failures or lack of integrity of the structure after completion.
- During construction the architect engineer approves and signs the report at all stages, similar to parts A to N of the Building Regulations in the United Kingdom. This report is finally recorded at the local authority's office based on which a Certification for Completion of Work is issued by the local authority. The client's approved architect engineer has responsibility for all stages of construction. The local authority does not independently inspect procedures at each stage to approve the structural integrity of the building.
- The only policing by the local authority in the planning department is limited to ensuring that an architect engineer who has authorization by the Department of Housing has signed all the construction stage approvals. In order to be a member of the 'Engineering Association' and 'Department of Housing' an architect engineer needs to pass an examination based on his experience.

- In a detailed structural survey and study by a Japanese team, their report stated that 'no big difference was observed among the buildings in relation to their construction age,' indicating that IS 2800 has been ignored by the Iranian engineering and regulating bodies since its introduction in 1987. This was also confirmed by the Structural Engineering Research Centre of IIEES (ref: 11&12).

#### Quality of Construction and Materials

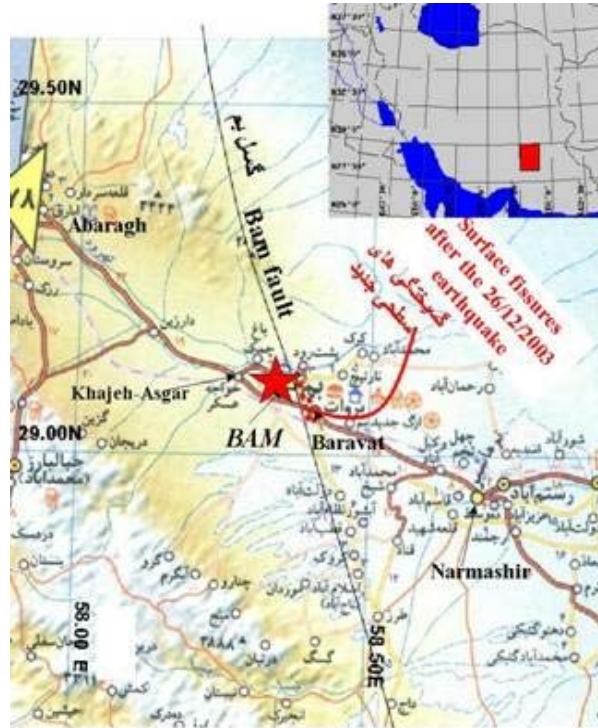
- The code recommendation for ties or bracing in multi-storey buildings is undermined by allowing the use of site welding of beam to column connections.
- Site welding of steel frames at height with torch cutting and basic welding equipment is a common practice in Iran. This results in poor quality connections, many of which failed. It was observed that long span steel portal frames fabricated and welded in the yard and assembled by means of bolt connections survived the earthquake loading well.
- There are shortages of steel fabrication yards where structural steel members for bolted frames are fabricated according to drawings, with quality assured welding and testing facilities.
- Production of concrete, bricks or steel trading are not supervised under a third party accreditation scheme. There are no companies with expert knowledge for third party accreditation of such products.
- Ready Mix companies are usually owned and managed by individuals who are experienced in transportation but without engineering knowledge. Without third party accreditation of the concrete quality the small buyers without site testing facilities receive poor quality concrete.
- Bricks can be kilned in tunnel kilns with a crushing strength of 30 N/mm<sup>2</sup> or can be fired with a strength of 0.2 N/mm<sup>2</sup>. Without third party accreditation, the small buyers may receive poor quality bricks from local building merchants.
- Steel traders normally operate from a shop or an office with little technical knowledge of the quality of steel they supply. Without third party accreditation of the steel quality the small buyers receive low quality reinforcement and structural steel.
- Iranian cement production is over 35 million tons per year, some of which is exported, and the necessary quality requirements for export can be met, demonstrating that the capability to produce good quality materials does exist
- Similarly, steel is an exportable product. Exported products again pass stringent quality assurance procedures to comply with international standards, but this is not being applied to domestic use.

#### The Code for Seismic Resistant Design

- Shortage of supply of cement makes cement expensive for rural house builders. In chapter 3 of the code regulating up to two storey houses, using correctly prepared and treated lime and clay mortar for brickwork or strip footing in areas of intermediate seismicity in drier parts of Iran for up to one storey houses requires further research. However, this should exclude northern parts of the country where high rain fall may

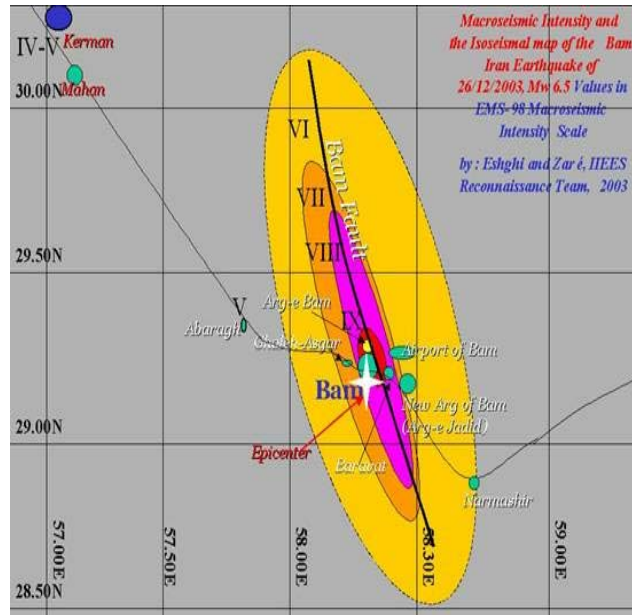
result in washing down the lime in the strip footing leading to eventual failure of the foundation.

- IS2800 does not clearly specify the minimum acceptable resistance for the ties to prevent progressive collapse. For example, in the British Code the lower limit for peripheral ties is 60kN within 1.2m of the outer boundary of the building.
- The code recommends horizontal and vertical ties, however it neither imposes a lower limit of strength nor the positioning of the ties.
- The code does not clearly indicate a load path for transfer of horizontal earthquake loading to diaphragm floors, to supporting beams, to the main monolithic reinforced concrete core to the foundation in order to transfer forces via cantilever action to the soil pressure.
- There is not sufficient emphasis on the construction of a main core in addition to the moment resisting frame structure. It was observed that moment resisting frames did not transfer the lateral loads through their connections which were poorly site welded or made of reinforced concrete without clear detailing. The lift shafts, stair wells and corner perimeter walls can provide strong points through shear walls acting as a cantilever to transfer the lateral loading to the foundation.



*Bam Earthquake of December 26, 2003,  
Mw 6.5*

**Figure 1: Location map of the area prepared by Eshghi and Zare (Ref:13) of International Institute of Earthquake Engineering and Seismology (IIEES 2003)**



**Figure 2: Intensity map of the area prepared by Eshghi and Zare of International Institute of Earthquake Engineering and Seismology (IIEES 2003)**

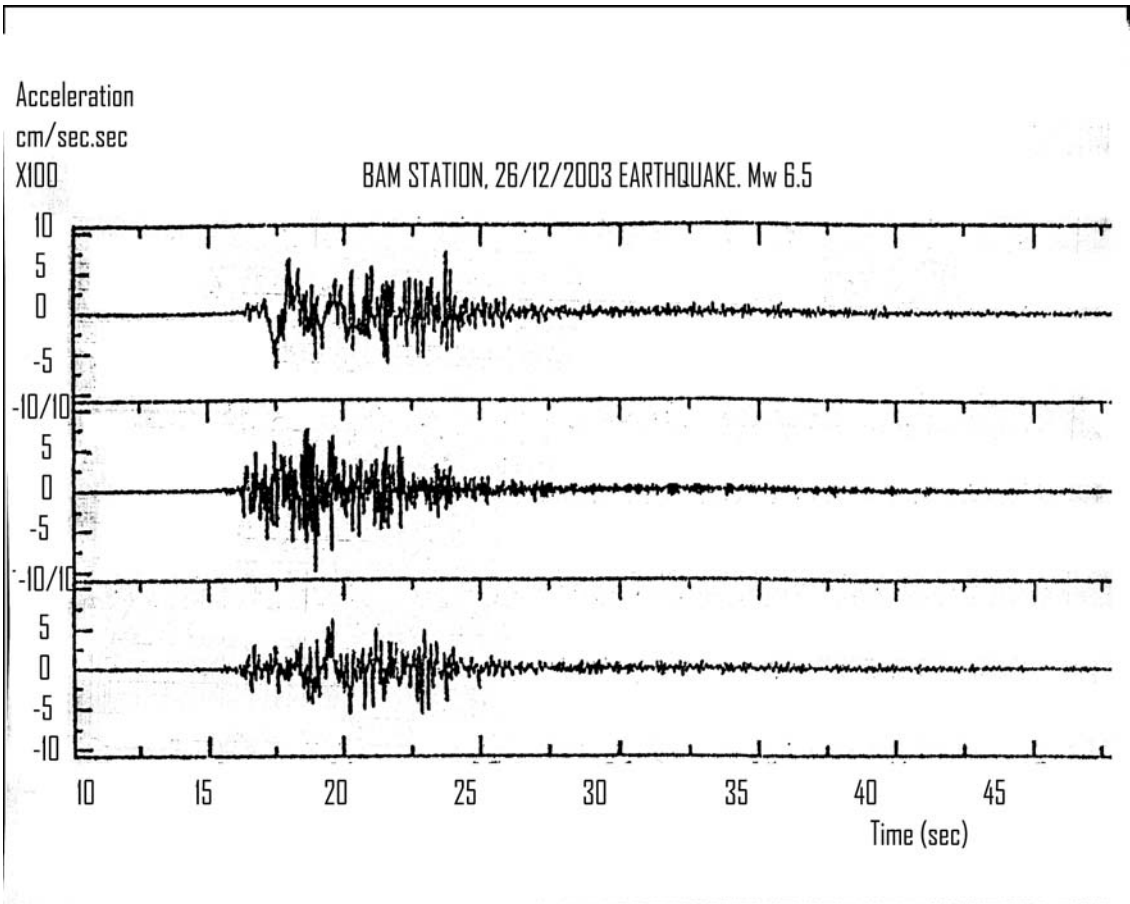
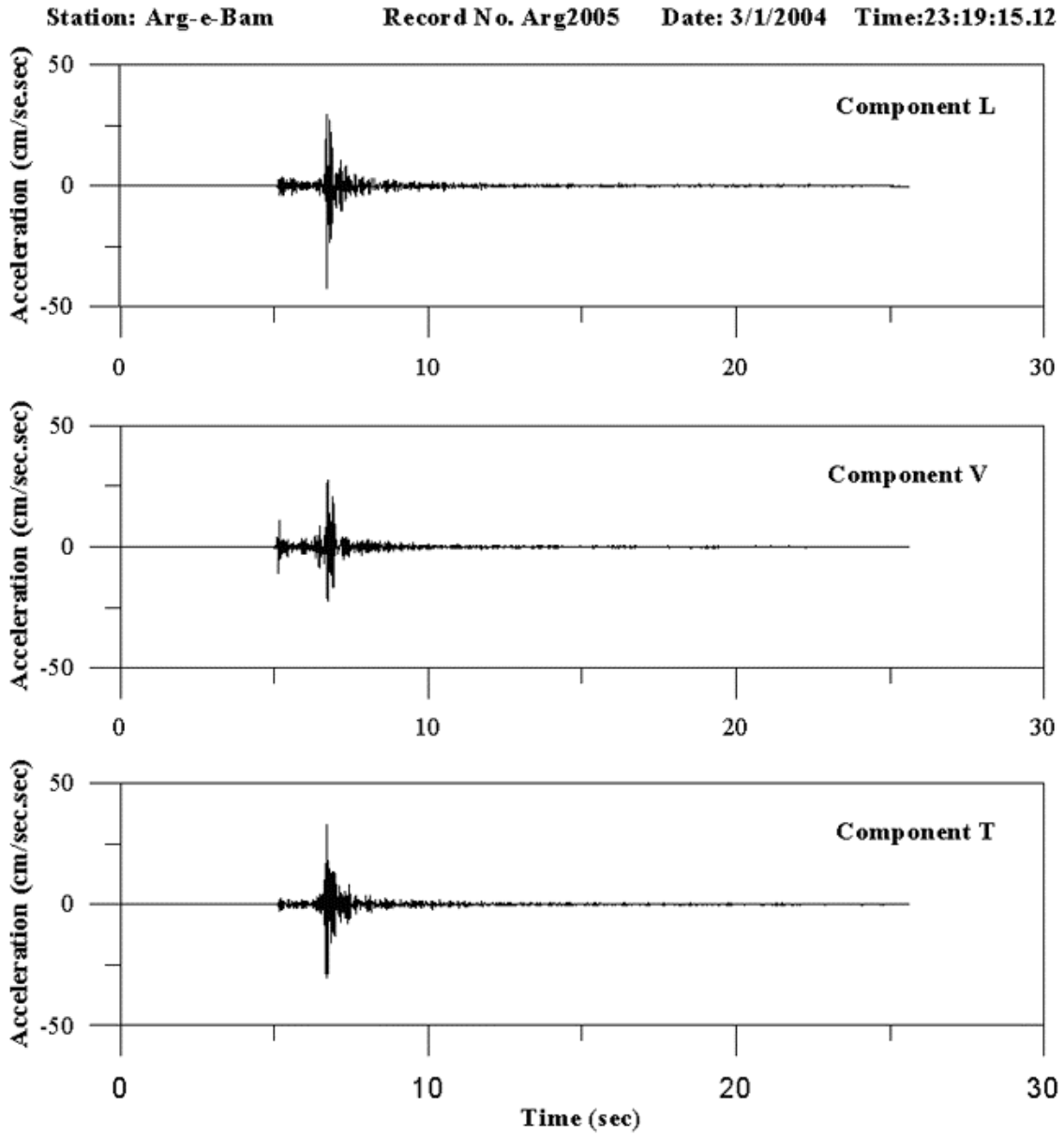


Figure 3: Corrected acceleration history of main shock Bam Earthquake recorded at Mayor's Building on 26 December 2003 at 5.27 am local time (01:57 GMT)



**Fig 4: Acceleration V Time graphs recorded one week after the earthquake in Citadel by Zare and Hamzeloo of International Institute of Earthquake Engineering and Seismology**



**Photograph 1: Surface cracks 50mm wide appeared near the fault on the main roads close to Baravat**



**Photograph 2: Successively layers of mud and straw insulation overloaded the roof increasing loading which was further increased with vertical seismic loading, resulting in failure of the walls which could not resist the tension from horizontal seismic loading resulting in progressive collapse of adobe( 9EMS)**



**Photograph 3:** This adobe's roof collapsed after the displacement and failure of its walls. Incidentally, the traditional form of air conditioning on the roof (wind-catchers) insulated the heat.



**Photograph 4:** This adobe 16 m span arch roof of the Henna factory survived ( 9 EMS) because the load bearing walls were strong and restrained enough to resist movement from lateral loading . The flank wall failed since it was not laterally restrained (Photo by:H. Darejati)



**Photograph 5:** This mosque with minarets about 20m tall and vault of 7m span wide 13m tall survived with damage to the false ceiling plaster and structural damage to the minaret with no tiles (Photo by: H. Darejati)



**Photograph 6:** Rafter stays (bracings) between the rafters at eave level and purlins and cable diagonal bracing between columns at every other bay provided sufficient stiffness to stop longitudinal collapse of this mosque hall.



**Photograph 7: Lateral movement in the wall resulted in the jack arch beams losing their bearing and collapse**



**Photograph 8: Gypsum and clay and skim of plaster fell of the soffit of brick arch because of movement of flexible brick arch**



**Photograph 9: Successive layers of mud straw on jack arch roof in combination with seismic load resulted in plastic hinges on top and bottom of the columns and collapse of the shop with 4m displacement towards west into the pavement area**



**Photograph 10: Steel structure frame of batten columns, Khorgini beams and connections supporting jack arch beams. Gausset plates at bracing connection cannot be welded to the centre of flange of Khorgini beams because the beam is supported on the side of the column resulting in weak bracing**



**Photograph 11: Western elevation of Kimya building with the 3<sup>rd</sup> and 4<sup>th</sup> floors displaced about 4m towards west in to the pavement**



**Photograph 12: Northern elevation view of the above building showing deformations were concentrated on column heads at second floor car park area ( 9 EMS). The corner columns are single UB and intermediate columns are back to back welded channels with no buckling stiffness, poorly welded weak diagonal bracing made of 80mm channels or T18 bars in East-West direction had no resistance towards lateral loading.**



**Photograph 13:** Southern elevation building load was unevenly distributed about its centre of gravity, the 5<sup>th</sup> floor was about 33% of 4<sup>th</sup> floor and located on the south side, 4<sup>th</sup> floor was 50% of 3<sup>rd</sup> floor and located on the west side. This resulted in clockwise torsion about its centre of rigidity in combination with soft behaviour on the 2<sup>nd</sup> floor displacing South-West corner of the third floor 4 m towards South-West direction .



**Photograph 14:** The same building leaning 17° out of plumb 6 days after the main shock, the 4<sup>th</sup> and 5<sup>th</sup> floors collapsed a week later. This building was not designed for seismic loading.



**Photograph 15: View of south-east corner of Kimia building 4m displaced from inside the undamaged neighbouring building under construction where the floor has cross ribs every 2m and the battens on the columns are spaced at 300mm c-c compared to 500mm c-c in the next photograph**



**Photograph 16: The batten column at front elevation of this two storey commercial building buckled about its hollow axis.**



**Photograph 17:** The cladding of the building in the previous picture separated from the front elevation after the front batten columns buckled



**Photograph 18:** Southern view of Bank Tejarat with irregular and bracings.



**Photograph 19: Buildings surrounding the water tower were severely damaged.**



**Photograph 20: The main reinforced concrete water tower in the centre of Old Bam, in the fire station. Survived with shear cracks in the beam at column beam connection (9EMS)**



**Photograph 21: Structural shear cracks in the beam at beam column connection, reinforced concrete water tower shown in Photograph 20**



**Photograph 22: Buckling of column reinforcement resulting from missing confinement traverse bars, Main reinforced concrete water tower in the centre of Old Bam. The earthquake intensity was 9 EMS**



**Photograph 23: Bam Railway terminal, failure of support due to insufficient bearing (extract from figure 13 taken by M.Moghtaderi-Zadeh, *et al.* Ref: 14 )**



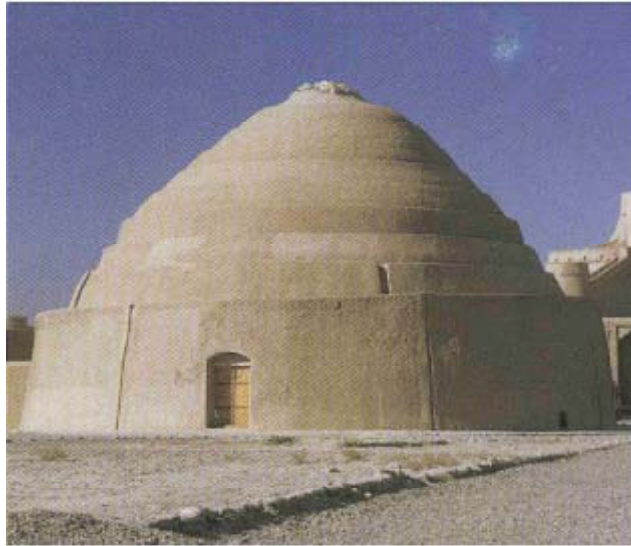
**Photograph 24: The reinforced concrete structure of the main building of Aflatoni hospital survived, however, the extended canopy structure of the jack arch on brick walls collapsed due to wall failure**



**Photograph 25:** Citadel Arg-e Bam which was restored during Safavid about 600 years ago with original parts dating back 2000 years. The above picture was taken two months before the earthquake of 26 December 2003



**Photograph 26:** The main building of Citadel was 50% destroyed. The picture shows the same elevation of Citadel after 26/12/03 earthquake intensity of 9 EMS.



**Photograph 27:** The northern elevation of the Ice House with reconstructed dome, located on the northern part of the Citadel (Arge Bam). The aerial photographs by James Blair for The National Geographic Magazine in 1974 show that the dome was not reconstructed at the time of that aerial survey



**Photograph 28:** Southern elevation of the Ice House, after the earthquake. The dome was reconstructed between 1974 and 2003, the original earthen walls survived the seismic forces (9EMS) with a vertical crack near the entrance in spite of the additional loading from the dome



**Photograph 29: The reconstructed part of the inner wall of the Ice House collapsed inward as the result of the additional weight of the recently reconstructed stepped dome**



**Photograph 30: The airport's control tower collapsed, non structural brick infill panels between the columns acted as shear walls when exposed to intensity of 8 EMS**



**Photograph 31: Airport's non structural walls acted as confined masonry walls improving the stability of the columns**



**Photograph 32: Reinforced concrete column-beam connection under construction. ABA (ref:10) recommends maximum spacing of column confinement links at connections not to exceed (0.5xwidth) of column) 100mm. The picture shows a spacing of more than 200mm between links in the column after failure.**



**Photograph 33: Ground floor level shop with high floor to ceiling and no internal cross walls. The steel frame cross bracing at ground floor level is missing at the rear, batten column buckle about its hollow axis resulting in soft storey structural damage. (photo by: H. Darejati)**

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