VULNERABILITY OF MASONRY ARCHES IN IRAN
Case of Bam Earthquake

Azadeh Ajamy

ABSTRACT
Historical arches are one of the most states of Iranian arts in history. Arches and domes were the most important elements in Iranian buildings. These forms are one of the main features of traditional building in small cities and villages in the neighborhood of the desert. Since Iran has been placed on the numerous active faults, unfortunately many of the aforesaid arches have been destroyed in the various earthquakes. Therefore, studying and research on the arches in Iran is an important subject for the researches in all over the world. After the earthquake in Bam we departed to Bam for studying and providing the related reports. Regarding to our interest we concentrated on arches and series of reporting were provided. Based on the reports we started a deep studying in respect to the arches. In this way we have used the scientific resources such as related articles and computer programs. This article describes the type of Bam earthquake, geotechnical soil in Bam different types of arch, comparison of them and finally we have concentrated on effect of internal forces on the arch structure in earthquake. The related pictures of the destructed arches of the Bam have been included in the article.

1. BAM EARTHQUAKE

1.1. Introduction
The Bam earthquake of December 26, 2003 (Ms 6.6) occurred at 01:56:56 (GMT,05:26:26 local time) around the city of Bam in the southeast of Iran (Figure-1).

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The earthquake happened in 5:26 AM local time when most of the inhabitants were slept, that can be one of the causes of the great life loss. The epicenter was in the city of Bam and a section of the Bam fault that passes from the city of Bam is reactivated in the earthquake. The Kerman province is one of the greatest provinces in Iran, with an area of 186,422 km2, that is located in southeast of the country. The city of Bam is well-known by the historical castle of Arg-e-Bam which is 2000 year old, that is destroyed in the 26/12/2003 Bam earthquake (Figure-2).

Arg-e Bam is the biggest mud-brick complex in the world. Total area of this castle is about 6 km2 and is constructed of sun dried bricks, and masonry arch shaped elements are most commonly used shapes in this ancient structure.

1.2. Focal mechanism
The focal mechanism of the Bam earthquake was reported as strike slip fault (Figure-3), which coincides well with the surface evidences of right-lateral strike slip movement of the Bam fault.
1.3. Source parameters
Based on a preliminary estimation of the seismic moment, a Ms = 6.6 is assessed for the Bam earthquake. The focal depth of the Bam earthquake is estimated to be 8km.

1.4. Surface fault ruptures
The Bam fault with a near north-south direction passes from the vicinity of the city of Bam (Figure-2). The surface fissures created after the Bam earthquake are observed around the Bam fault between the cities on Bam and Baravat (Figure-4).

The fissures are created in the form of the sinkholes in the city of Barvaat (Figure-5).
1.5. Seismic Gap
The existing records on historical seismicity indicate no major earthquake in Bam since the historic time. It seems that Bam earthquake has ended a seismic gap along the Bam fault. This seismic gap could be verified with the Arg-e Bam castle, which is constructed about 2000 years ago and not demolished at all since then, until the 2003 earthquake of Bam.

1.6. Strong Ground Motion
The strong motion in this event is recorded in 18 stations of the national Iranian strong motion network. The record obtained in 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 for the vertical component (all non-corrected values). The preliminary observations on the strong motion record obtained in the Bam station, as well as the observed damages in the region shows a vertical directivity effect caused by a near-fault effect.

2. THE HISTORY OF ARCH
Civilization growth in Iran is accompanied with Foundation Hakhamaneshian Government. In this era architecture style is known as “Persian Architecture”. Before this, various arches, jack arches and Roman arches were applied in structures. This method has been developing as the time passed on. Since that time up to now, it has changed to “Sasanian”, “Old Islamic” and “Modern Style”, accordingly.
Arch construction style evolution was happened in Sasanian era. The arches were applied in some famous structures, such as “Kasra Palace” and “Sistan palaces”. These arches were developed based on mathematical and geometrical hypothesis to bear compress forces. The arches which have known as circular arches “belong to this era.
Islamic age caused construction of high balconies in sacred places, which are called “Mosque”. It was in this era that sharp arches were developed and completed.

![Figure 6](image)

Totally all kinds of the arches are categorized in three main categories:
1. Circular arches: This type of arch is constructed to bear compress forces and is used as decoration arches.
2. Sharp arches: This type of arch was made in various shapes, used in particular domes.
3. Decoration arches: This type of arch was used for decorating in structures.
3. GEOMETRIC DATA
Structure of resistant shape is defined as the ones whose shapes are configured to resist versus the forces in a better manner. In this respect generative element of simple arch is used.

4. MATERIAL
Materials are considered in two different views, mechanically and rheologically. Mechanical view is rigid materials like brick and stone and rheological view is semi fluid materials like mortars.
From point of stability view, stone as the material is the best, because its stability is more powerful versus compression. Earth material such as clay soils provide cohesive between various components, after getting dry. Other elements have various usages in respect to their thickness.

5. MECHANICAL DATA
Regarding to what mentioned above, materials used in traditional arches are stone, brick and mortars. These materials present good strength versus compression but they are weak in respect to bending or tension. From point of mechanical view the arches are very complex.
For this sake the authors/researchers are looking for a simple method and in this way they use simple compression/tension via using polygon curve.
Polygon curve is a shape, which is developed through resultant of different forces, orchestrated in a regular manner. The final polygon shape is a resultant curve. Regarding to the definition of polygon curve, we have used it in simple arch. Since this model should act as a simple compression, so it is necessary to be constructed using masonry materials.

6. SUPPORTS

6.1. Support Reactions
To observe the stability it is necessary that resultant forces are transferred through supports to foundations and soil. Resolution of forces in any point of resultant can be resulted to horizontal drift and vertical force.
The horizontal drift causes a big problem for arch stability. For this reason, tensile stress appears in the outer fibers of the arch. Therefore, it is necessary to use the thick layer of masonry material in the supports.
Importance and stability of the supports is directly determined through resultant forces, resultant intensity and its eccentricity. These characteristics depend on many parameters.

6.2. Generative cross Section
Drift is relative to total force and span, and inverse related to its height. Achieving to minimum drift, necessitates that the arch is designed as light as much as possible. This point leads us to a more economical condition.

6.3. Loads Importance
Loads distribution has an important role in the intensity of horizontal drift. The material which is used in an arch can be reduced in the path of resultant forces. The load reduction method is achievable through using light material.

6.4. Masonry Structures
Considering masonry structures depends on internal forces of material building. This forces are provided with mortar. Cohesiveness loads in uniform mass that cause horizontal drifts.
7. Under Consideration Arch Types

Four types of arch could be remarkable. They are:
1. Sharp Segmental Arch
2. Semi Circular Arch
3. Semi Elliptical Arch
4. Sharp Arch

7.1. Sharp Segmental Arch
The curvature of this type of arch is more than segmental type and less than semi circular’s. That is why, it could bear the compression forces. These forces are transferred from the highest level of the arch, uniformly, into supports. To prevent the horizontal drifts, the connection of the arch to walls should be satisfactory. Therefore these arches are constructed continuously with numerous spans.
7.2. Semi Circular Arch
In this type, the load is less than sharp arches. Strengthening of such arches is possible through the following methods:

1. In case of single arches, it must be anchored using wood or profiles.
2. Otherwise the arches should be constructed in multiple modes to amplified each other from point of strength view.

![Figure 12](image12)

**7.3. Semi Elliptical Arch**
This type of arch is not so powerful to bear large compression forces and usually it can bear its gravitational loads, only. Empowerment of such arches depends on their strength.

![Figure 13](image13)

![Figure 14](image14)
7.4. Sharp Arch
As it was mentioned above; in this type, loads are transferred from the highest level of the arch to the supports. The height of these arches is very much, specially in very sharp ones. Therefore, its strength is more than other types and failure would not be happened under the same loading.
This arch is categorized in three groups, based on its height:
1. Very sharp arch: High height and large strength are inseparable part of its specifications.

![Figure 15](image15)

2. Intermediate sharp arch: The height of this type is moderate and its strength is satisfactory so, it could be applied for both bearing and decorating.

![Figure 16](image16)
3. Low sharp arch: The height of this type is low and its strength is litter, so its application is more decorative than bearing.

8. Geotechnical Conditions in Bam
Generally Bam soil is very dense and as the result its natural frequency is high. There for in case of Bam structures which were low in height, occurring of resonance phenomenon was very likelihood. This is one of the main reason for disaster of vast destruction in Bam. The consequences of three boreholes have been presented in the following table, correspondence whit BHRC report.

*Borehole 1:*

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<th>Soil Groups</th>
<th>SPT</th>
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<tr>
<td>1.5 to 3</td>
<td>SP</td>
<td>&gt;50</td>
</tr>
<tr>
<td>3 to 5</td>
<td>GP</td>
<td>&gt;50</td>
</tr>
<tr>
<td>5 to 7</td>
<td>GP</td>
<td>&gt;50</td>
</tr>
<tr>
<td>7 to 9</td>
<td>GW</td>
<td>&gt;50</td>
</tr>
<tr>
<td>9 to 10</td>
<td>GW</td>
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*Borehole 2:*

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<tr>
<td>2 to 4</td>
<td>GP</td>
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<td>4 to 6</td>
<td>GW - GM</td>
</tr>
<tr>
<td>6 to 8</td>
<td>SP</td>
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<tr>
<td>8 to 10</td>
<td>SP – SM</td>
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<td>38</td>
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<td>10</td>
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<tr>
<td>1 to 1.5</td>
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<tr>
<td>1.5 to 3</td>
<td>GW</td>
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</tr>
<tr>
<td>3 to 6</td>
<td>GW</td>
<td>&gt;50</td>
</tr>
<tr>
<td>6 to 7</td>
<td>SW - SM</td>
<td>&gt;50</td>
</tr>
<tr>
<td>7 to 9</td>
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</tr>
<tr>
<td>9 to 10</td>
<td>SP - SM</td>
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REFERENCES


