

THE CHOICE OF INTERVENTIONS FOR STRENGTHENING OF HISTORICAL ADOBE STRUCTURES AND REMAINS IN BAM CITADEL "ARG-E BAM"

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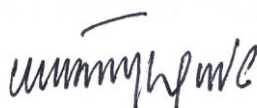
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Abstract

Bam Citadel is a unique complex with some mediocre buildings in it. Construction started in the Achaemenid period (550–330 BC) and is still being completed and repaired up to the 21st century. Although the Bam region is located in south-western Iran in an active seismic zone, the City of Bam had not reported any major historical earthquake before 26th Dec. 2003. The massive earthquake that day killed or injured more than 37,000 people and most of the city collapsed. Bam Citadel became a unique adobe complex for the World Heritage community after this disaster. According to the surveys, the earthquake caused damage to about 23% of the ancient monuments close to and inside the Citadel. Most of the ruins were the parts that already added to the main body of work or were repaired during the last intervention of 1993. For this reason the technical method, used for the enhancing of the adobe building, is highlighted as the main task. There are four items which are very important for any seismic upgrading in heritage sites: seismology of the area, quality of the construction, function of the building and cultural values. A wide variety of intervention strategies and techniques have been considered for the repair and the seismic retrofitting of the adobe buildings in the Citadel. With respect to that point, the possible relationship between the cultural values and seismic upgrading are always polar opposites. Obviously the buildings in Bam Citadel have many problems, for example the geometry data are not available, there are large variability layers, construction sequence is unknown, existing damage in the structures is very serious, regulation and codes are non-applicable and so on. In fact in this research I am trying to adjust the stability and safety measures with values of the cultural heritage property as much as possible; on the other hand I am trying to optimize the strengthening methods to an acceptable amount of side affect on values. This PhD thesis focuses on the strategies and the techniques that have been applied to preserve the historical monuments and to evaluate the traditional and modern engineering methods that are used in conservation projects in Bam Citadel.



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1 Introduction

Bam Citadel, which is located in the central desert area in Iran, is an adobe complex. It is an interesting example of a fortification, with special monuments presented in continuity with history, culture, and architecture of Iran since 2000 years ago [38]. It was designated a national property in 1966 and the efforts for conservation and restoration started 6 years later. The monuments like “Jame Mosque”, “Tekyeh” and “Pyambar Mosque” not only were noticed because of architectural values, but also were respected and used for prayer and religious ceremonies for years, [12], [42], [47].

The earthquake of 2003, however caused the tragic loss of many lives and destruction of an overwhelming part of Iran’s cultural heritage. On the other hand, it provided an unconditional opportunity for researchers and experts to study and investigate the deeper parts and layers, which was not possible under normal conditions. Immediately after the earthquake, the wish to aid was strongly stated by institutes and universities, who began to cooperate in the conservation of Bam Citadel; to understand the behaviour of adobe structure in an earthquake, suitable methods of restoration, reconstruction and improvement of the earthen material according to the conservation ISCARSAHⁱ and available engineering codes were investigated. On the occasion of the international Day of Monuments and Sites (on April 18) Iranian Cultural Heritage Organization (ICHTO), United Nations Educational, Scientific and Cultural Organization (UNESCO) and International Council of Monuments and Sites (ICOMOS) organized an International Workshop for recovery of Bam’s Cultural Heritage in 2004. 38 international, 23 Iranian experts and 31 ICHTO members participated and represented their research; it concluded to the Bam Declaration and stressed the need to strengthen the remains and to promote earthen buildings, [54].

Finally, the Committee of Stakeholders proposed that CRATerreⁱⁱ start a series of researches on the Second Gate, the Italian Ministry of Cultural Heritage study Tower Number One, Tehran University provide a three dimensional map, University of Milan work on Mirza Naeim Complex and Technische Universität Dresden reinforce Sistani House. Sistani House has been chosen as a pilot project for reconstruction with reinforced adobe masonry as a part of restoration program of the Recovery Project for Bam’s Cultural Heritage and in close collaboration with the Iranian Cultural Heritage, Handicrafts and Tourism Organization (ICHHTO)ⁱⁱⁱ. Prof. Jäger and his team started this project at first with restoration of two rooms and then later it was extended to the entire building and it is still a work in progress. UNESCO, Cultural Preservation Program of the Federal Foreign Office in Germany, ICHHTO and the Japan Fund in Trust have sponsored the project since they started in 2006.

In this research, I am trying to analyse the decision that has been made, and to evaluate the methods that have been applied for cases after the earthquake in Bam Citadel.

The primary questions that lead to this task were: Can collapse and monumental damage cause the extinction of a historical property like Bam Citadel? What will happen to the artistic values without a physical body? And which necessity terminates in strengthening historical adobe buildings and extend their life longer than the expected natural lifetime?

I have organized this thesis into nine chapters. After the short introduction in chapter 1, a terminology has been provided that is necessary to utilize the meaning of the words with

ⁱISCARSAH is an abbreviation for International Scientific Committee on the Analysis and Restoration of Structures of Architectural Heritage (ICOMOS). For more information refer to <http://iscarsah.icomos.org>.

ⁱⁱ International Centre on Earthen Architecture.

ⁱⁱⁱ Iranian Cultural Heritage Organization renamed to Iranian Cultural Heritage, Handicrafts and Tourism Organization (ICHHTO) in 2006.

different interpretation; this terminology is referenced to the meeting with the experts of ICHHTO (I was a member). I have stated the main subject in chapter two to present the area, the site, history and structure of the monument; chapter three describes the rest of the damages in the Citadel both because of the erosion during its lifetime and the spontaneous earthquake in 2003. Chapter four is about the different strategies in seismic zones and shows how the different methods are approaching to become an optimum decision. In chapter five, the history of wars and earthquakes in the Citadel has been reviewed and the aim is to understand the events and the duration of the time since the historical documents have existed and approve of them. Chapter six is based on professor Modena and professor Binad's studies about lifetime and durability of structures and professor Bekker's creative model for lifetimes, which is based on a statistical model to reach to a suitable lifetime for Bam Citadel. Chapter seven deals with the restoration and reconstruction projects in the Citadel, and chapter eight provides a classification of them. Chapter nine, the last chapter, is the conclusion of the research and the recommendation that results.

1.1 Methodology

This research will be the first PhD thesis regarding analysis and classification of different levels of intervention for historical adobe buildings in Bam Citadel according to the value, function and status of stability of the structures and remains.

The idea was shaped in my mind soon after the earthquake in 2003, when UNESCO World Heritage Centre considered Bam Citadel a monument in danger. The earthquake and consequently the heavy destruction was a new disaster for the city of Bam; and it seemed that the traditional technology of restoration could not afford protection of the Citadel against a subsequent earthquake, which might happen in the future.

Many questions were raised. What type of restoration is suitable in the Citadel? Would the buildings in the Citadel be able to survive another earthquake if we keep using the traditional methods of restoration? How can engineering knowledge and modern technology support restoration of the historical citadel? Which kinds of frame and regulation should be proposed for repair and reconstruction to provide enough stability and safety for the structures and the residence?

Generally, there have been very limited resources since before the earthquake. The previous restoration documents included the draft of Comprehensive Restoration Plan (1994), documentation and restoration plans (students' work) for a few buildings in the Citadel and associated area, and historic books. The only available site plan was provided by a combination of the students' projects that includes many mistakes and errors with the measures and dimensions in 20,000 km².

A lack of documents about history and architecture are notable and sometimes disappointing in Bam. The most significant difficulties are as follows:

The geometry data before the earthquake are missing, information about the inner part of structures are not precise, construction sequences are unknown, most of the structures were badly damaged during the earthquake, regulation and codes are non-applicable, and finally there is a strong probability of future earthquakes in Bam area.

In this research, three kinds of references - historical, archaeological, architectural -and structural information have been used: The recognition and documentation projects, scientific papers, restoration plans for Bam Citadel and fieldwork reports. Few papers regarding the natural lifetime of a structure were helpful in determining the proper time for repair and reconstruction of the Citadel.

The guidelines, engineering codes, ICOMOS Charters and ISCARSAH, and 2800 Earthquake Code of Iran, general information books related to urban design, history, architecture, structure of adobe buildings, and construction material. Specific information books related to the history of Bam and building specification in desert areas.

“Comprehensive Management Plan of Bam 2008-2017” and the “Comprehensive Archaeological Plan for Bam and its Cultural Landscape” were used as valuable and reliable resources. The former was provided by UNESCO (the organizer) and Iranian Cultural Heritage Handicrafts and Tourism Organization (ICHHTO) and contains chapters of updated information about the Bam and its Cultural Heritage. The latter was still a work in progress when I was doing my thesis.

Two Annual books (2005 & 2008) were published by ICHHTO after the earthquake. The articles include both the recognition projects for the particular buildings in the Citadel and the archaeological reports. Dr. Asghar Karimi (historian) translated old historic books from Arabic to Farsi. This historical information is about the dates of settlements, short and long term military sieges in Bam Citadel, warfare that occurred in the Citadel and the damages reported in the old references. Most importantly, it includes notes regarding the history of settlement and abandon, which I could have very carefully relied on as a history of repair and reconstruction in the Citadel. The archaeological reports in the Annual Books were done under the supervision of Dr Shahriar Adle (archaeologist of ICHHTO and representative of Iran at UNESCO World Heritage Centre). This research has been used in fieldwork reports wherever the consequences of so many layers of construction, done over the generations, were needed.

From material and engineering aspects, the works that Prof Jäger and his team have done are distinguished. Their studies about the strengthening of the adobe bricks and method of reinforcement with glass fibre bars were supported with laboratory tests, simulation and analytic calculation for the first time in the history of restoration of the Citadel. The instruction for reinforcing adobe units with the cut date fibres are widely used in many projects in the Citadel, and are the same as in Tower Number 1, Payambar Mosque, Stable and Barracks. I studied the reports and associated PhD thesis, which are available in the Archive of Lehrstuhl Tragwerksplanung, Technische Universität Dresden. For more information with the papers and research reports, see the reference list at the end.

CRATerre did a series of wall tests in the Citadel to measure the efficiency and characteristics of the reinforced adobe walls with bamboo in 2007, [46]. The project for strengthening of the Second Gate in the Citadel has not been done yet. Prof. Binda also conducted a notable body of research regarding the application of pipe connections with self-screws inside the adobe walls in Mirza Naeem Complex in the Citadel. Both of the recent proposals are works in progress. The final results have not been published at the time of writing this thesis. Tower number one is an executed restoration project, considering the seismic improvement, which is organized and conducted by ICHHTO and the Italian Ministero per I Beni e delle Attività Culturali/Dipartimento per I Ricerca.

The publications of the Scientific Committee of ICOMOS were other reliable references for my research. I used Charters specially for providing a terminology that both engineers and heritage designers could use. Going forward, this could provide them with a common terminology for the recognition of projects and suggested levels of restoration. I referred to ICOMOS resources many time during my research from start to end.

The figures were selected from the archive of the Recovery Project of Bam's Cultural Heritage, ICHHTO and Jäger Consulting Engineers Ltd. After the earthquake in 2003, professionals and tourists sent donations of pictures to ICHHTO. Unfortunately, identifying the photographers is not possible because most of the photos were saved without details such as names or addresses.

In addition to the lack of reliable references, it was a challenge for me to make the Farsi references compatible with the western pattern. The information associated with the editors and publication is not clear enough and it was hard for me to reach or to even trust translated links on the Internet. The next challenge was how to reference the pictures whenever the data was missing. I tried to follow up the addresses with my previous colleagues in ICHHTO and reference them as much as possible. However, most of the time access to those people related to the photos in question was not successful.

1.2 Charters and Bam terminology^{iv}

I have started this thesis with a short terminology on cultural heritage works in. It is useful to understand the exact definition and meanings of many usual words between architects and engineers and to avoid the misunderstanding and mistakes especially when they want to choose a method or a technology for repair, restoration and reconstruction, [36]. It has been sorted by the alphabet; the references are at the end with explanation:

Adaptation [20]: It means modifying a place to suit the existing use or a proposed use.

Additions [62]: It can be allowed so far as they do not detract from the interesting parts of the building, its traditional setting, the balance of its composition and its relation with its surroundings.

Authenticity [24],[72]: Value and authenticity of architectural heritage cannot be based on fixed criteria because the respect due to all cultures also requires that its physical heritage be considered within the cultural context to which it belongs.

Compatible [72]: The characteristics of materials used in restoration work (in particular new materials) and their compatibility with existing materials should be fully established. This must include long-term impacts, so that undesirable side effects are avoided.

Conservation [20], [59], [62], [63]: The object of conservation is to prolong the life of cultural heritage and, if possible, to clarify the artistic and historical messages therein without the loss of authenticity and meaning.

Diagnosis [72]: It is based on historical, qualitative and quantitative approaches; the qualitative approach being mainly based on direct observation of the structural damage and material decay as well as historical and archaeological research, and the quantitative approach mainly on material and structural tests, monitoring and structural analysis.

Durability [72]: Each intervention should be in proportion to the safety objectives set, thus keeping intervention to the minimum to guarantee safety and durability with the least harm to heritage values.

Integrity [72]: The value of architectural heritage is not only in its appearance, but also in the integrity of all its components as a unique product of the specific building technology of its time. In particular the removal of the inner structures maintaining only the façades does not fit the conservation criteria.

^{iv}This terminology has been based on the weekly reports with Dr. Eskandar Mokhtari (The previous head of Recovery Project of Bam's Cultural Heritage, 2003-2009) and the honoured members of the World Heritage who often joined for providing Management Plan of Bam Citadel; I myself attended as an expert and the key person to prepare the Annual Reports for World Heritage; I reference to weekly reports of the ICHHTO for this part additionally to the references in the next pages. These reports are available in Archive ICHHTO, both in Bam and in Tehran. ICHHTO is Iranian Cultural Heritage Handicrafts and Tourism Organization; it is responsible for all the national properties, monuments and World Heritage in Iran.

Intervention [72]: The peculiarity of heritage structures, with their complex history, requires the organization of studies and proposals in precise steps that are similar to those used in medicine. Anamnesis, diagnosis, therapy and controls, corresponding respectively to the searches for significant data and information, individuation of the causes of damage and decay, choice of the remedial measures and control of the efficiency of the interventions.

Maintenance [20]: The best therapy is preventive maintenance; it means the continuous protective care of the fabric and setting of a place, and it is to be distinguished from repair.

Preservation [20]: Means maintaining the fabric of a place in its existing state and retarding deterioration.

Protection [61]: Of the archaeological heritage constitutes an integral component of policies relating to land use, development, and planning as well as of cultural, environmental and educational policies. The policies for the protection of the archaeological heritage should be kept under continual review, so that they stay up to date.

Reconstruction [20], [62]: It means returning a place to a known earlier state and is distinguished from restoration by the introduction of new material into the fabric.

Rehabilitation [73]: It is the act or process of making possible a compatible use for a property through repair, alterations, and additions while preserving those portions or features, which convey its historical, cultural, or architectural values.

Repair [60]: Replacement or renewal of any part of a building, structure, device, or equipment with like or similar materials or parts, for the purpose of maintenance of such building, structure, device, or equipment.

Replacements [62], [72], [74]: Missing parts must integrate harmoniously with the whole, but at the same time must be distinguishable from the original so that restoration does not falsify the artistic or historic evidence.

Restoration [20], [62], [73]: The process of restoration is a highly specialised operation. Its aim is to preserve and reveal the aesthetic and historic value of the monument and it is based on respect for original material and authentic information sources.

Reversibility [72]: It means the possibility that all the measures or parts of them could be removed or replaced in the future if it is needed.

Safeguarding [22], [23]: It means the identification, protection, conservation, restoration, renovation, maintenance and revitalization of historic or traditional areas and their environment.

Safety evaluation [72]: It is the last step in diagnosis, which is based on analysis of the quantitative and qualitative analysis.

Seismic retrofitting [10], [57], [72]: It means the modification of the structure to make it resistance to the seismic activity. It concludes both strategies, which is involved directly in the structure to strengthen and the ones that are not necessary to increase the strength.

Stabilization^v [7]: All the action and measures to stop deterioration process on structure and material decay. It applied to actions to prevent the partial and total collapse of a damaged structure.

Strengthening [10]: It addressed to all actions which providing additional strength to the structure or upgrading the structure to engineering codes for new use and more safety.

^vIn archaeological sites specific problems may be posed because structures have to be stabilised during excavation when knowledge is not yet completed. The structural responses to a “rediscovered” building may be completely different from those to an “exposed” building. Urgent site-structural-solutions required stabilizing the structure as it is being excavated, should not compromise the complete building's concept form and use.

2 Bam Citadel

2.1 Geography

The City of Bam is located at 29° 11' northern and 58° 36' eastern latitude at an altitude of 1050 meters above sea level, 1000 kilometres of Tehran, the capital city of Iran, and 193 kilometres southeast of Kerman, (Figure 1), in a plain bordered by the Barez and Kabudi mountain ranges. The tall mountains surrounding Bam provide the region, in which mountain cold coexists with a hot and dry climate, with ample water. The area of Bam is about 17755 km² and about 78000 people lived there before the earthquake [44].

The fair weather and fertile soil of Bam have prompted agriculture and animal husbandry to flourish in this region. The main products of Bam are citrus fruits, dates, summer crops and henna. Silkworm breeding and silk weaving have also flourished in the city since time immemorial. Indeed, the silk and linen fabrics of Bam were famous and sought throughout the ancient world.



Figure 1 Iran, Kerman Province, Bam City

2.2 History

No precise information concerning the first human settlement in Bam is available; historic sources, however, indicate that the first habitation was in the Achaemenid period, or in Parthian and Sassanid times according to others [38].

It seems that the first settlements in the area began when Achaemenians (579-323 BC) built a fort in the area. Later on, during the Parthian rule, it was expanded further and it became Arg-e Bam^{vi}, or the Citadel of Bam, Karimi (2005)^{vii}.

^{vi} Arg-e Bam is a Farsi translation for the Bam Citadel; it is called to the whole old City of Bam.

^{vii} Dr. A. Karimi is a historian and has researched on the history of Bam Citadel. His article in annual book of Bam (2005), has been used as a major reference for the history of Bam Citadel.

During Sassanid Rule, it was conquered by Ardeshir and expanded with new fortifications and walls from 224 to 637 AD. In 645 AD Kerman was conquered by the Arab dynasties and the Citadel probably suffered also from the war.

In 656 AD a group of fanatic Moslem, the Khavarej, was defeated by Imam Ali and they escaped to Kerman and Bam where some lived in the Citadel for many years on. In 869 AD, Yagoob Leyth Saffari, who was fighting Abbasid Rule, defeated the Khavarej and conquered the Citadel. It then became the permanent base camp.

After the Mogul invasion of Iran, the Bam & Kerman regions were turned over to a dynasty called Qarakhataian and they ruled the region from 1342 to 1363 AD.

During Safavid Rule (1502-1722), Iran went through a period of relative calm and stability. Therefore, the Citadel was developed further at this time, as was the rest of the country.

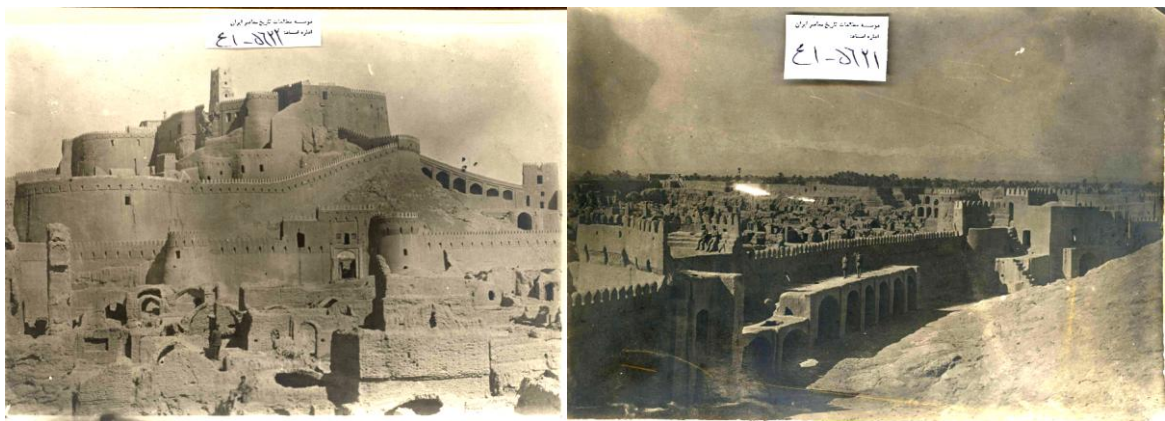


Figure 2 Bam Citadel, Qajar period, 1742-1930

Towards the end of the Safavid Period, the founder of Qajar Dynasty, Agha Mohammad Khan, who used it as a strategic base to fend off Afghan and Baluchi incursions and thus turned it into a military camp, conquered the Citadel.

In 1810, Arg-e Bam had to again withstand other invaders from Shiraz. In 1839, Agha Khan Mahallati, founder of the Esmaili sect, rose up against Mohammad Shah Qajar and took refuge in Arg until Prince Firooz Mirza, who was later known as Farman Farma, arrested him.

The increasing military presence within the walls of Arg gradually led people to settle outside the limits of the ramparts: in 1880 Firooz Mirza (Figure 2 and Figure 3) wrote that only military personnel must now reside within the Citadel area and he suggested that the old and abandoned city that sits at the foot of the Citadel be demolished and the area turned into garden.



Figure 3 Left: Local ruler of Kerman and Farmanfarma, 1880; right: Bam Citadel and the troops on the top of Governor Seat

Until 1932 Arg-e Bam was used as a garrison (Figure 4) and it seemed that at this time nobody was living anymore in the old city at the foot of the Citadel. Therefore, since this time the Citadel was completely abandoned. During this time, the Citadel served as a residential town, while villages and farmlands were scattered around it. Some 180 years ago, however, people began leaving the Citadel to build the new town, which soon developed beyond its ramparts. Today the Citadel of Bam lies on the northeastern edge of the city of Bam.

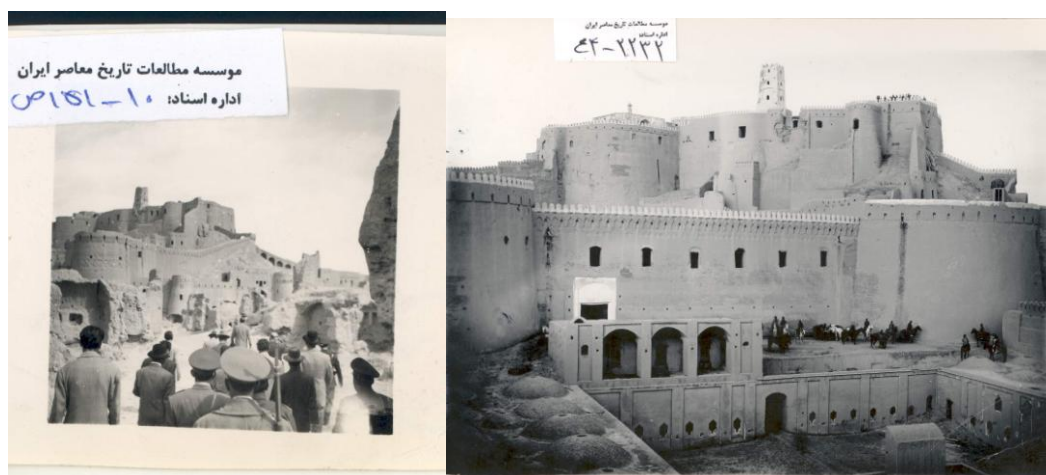


Figure 4 Last occupation of the military groups in the Citadel, 1932

After the Islamic revolution, Arg-e Bam was placed under the responsibility of the Iranian Cultural Heritage Organization and restoration work began in 1973.

Arg-e Bam combined the development of a castle and a human settlement, with the city at the foot of the castle. This brief history shows that beyond the usual evolution and development of every human settlement, Arg-e Bam faced many wars. They led to constant remodelling of the castle and settlement: Repairing the damaged structure, rebuilding what was ruined and adding fortification and new buildings next to each other.

It seems that this remodelling has often happened on unsound existing structures as the former ones were damaged and not necessarily well repaired structurally. This can be noticed in the way the citadel, the premises of the castle (Barracks and Stable) and the ramparts collapsed.

2.3 Archaeology

The Archaeology Organization^{viii} started the first archaeology in the Citadel in 1956. The excavation was related to the determined zones of the Citadel, to provide the plans from the towers and walls, their structure, and also the comparison studies among the other citadels in the area of Bam and Kerman. The excavation and investigation also are appropriate for the valuable architecture of outstanding buildings in the Citadel to define the age and the details during the lifetime of the building, [43].

According to the archaeological evidence and reports [58], the oldest findings go back to 4000 years BC; and have been found in the Bidaroon in the west of Bam and Tal-e Atashi, in Darestan, which is located 30 km from north eastern Bam. The location of Bam was very important for transportation and trade; and joined the Middle East (Beynonahrein) to Indian. At that time the fabric industry had a very important role in the economy and was very famous among the countries [56].

The findings are supplied by the ceramics and potsherds, and a significant number of them belong to Sassanid Rule and first Islamic Period, from 224 up to 651 AD (Figure 5). Another activity was done after earthquake was "Rescue Archaeology" in the Citadel, which was applied immediately after debris removal in many sites inside and outside the Citadel. For more information, there is storage for the findings and a data bank beside the Citadel; also the annual reports of Bam Citadel are very reliable reference [1]. According to the report, the studies on the debris, and the findings through the debris removal inside the Citadel, it is clear that the settlement has been existed since 4000 BC continually up to now.

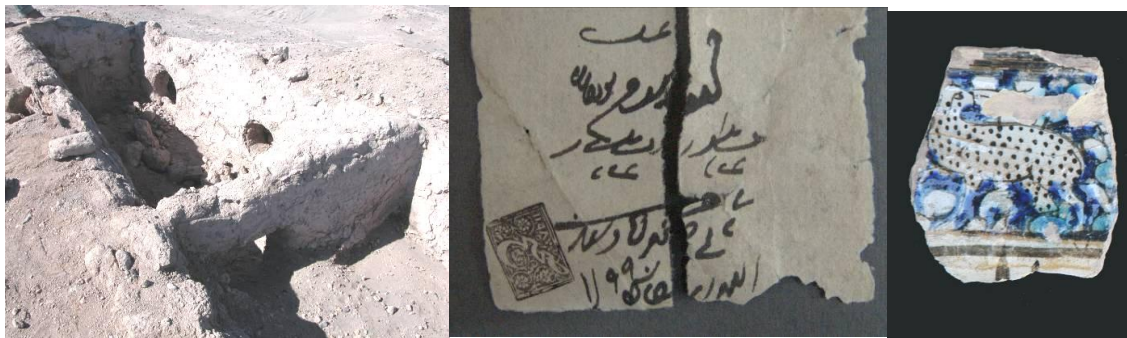


Figure 5 Excavation and findings in Bam Citadel

^{viii}It was the first organization that started archaeological excavation in Iran; at that time Iranian Cultural Heritage, Handicrafts and Tourism Organization did not establish.

2.4 Architecture

Generally the main urban parts, which are found in the most cities of Islamic world, include fortified buildings, the courtyard houses, public services, the street system, surrounding walls and gates. Bam Citadel, however has been established before Islamic period, obeys the same style and rule; it includes a bazaar, residential quarters, mosques, public baths, governor quarter, and their components, within a large fortified enclosure, and defensive walls which contains the remains of the old town and its different structures [58].

The residential quarters of historical town have occupied the southern section of the enclosure. A quasi orthogonal street pattern with the principal streets connects north from the south gate and east to west among the residential quarters, Figure 6. A Bazaar has extended along the street (or could be called a corridor) from the main south entrance (Main Gate) towards the governor's quarters [3].

Access inside the Citadel is possible by two type street systems, open ended street, which was considered a public right of way and had to be at least wide enough for a packed camel or horse to pass. The other one is the private property of the people having access from it to their front doors. The private one normally could be seen for the houses, which are much larger and more luxurious [16].

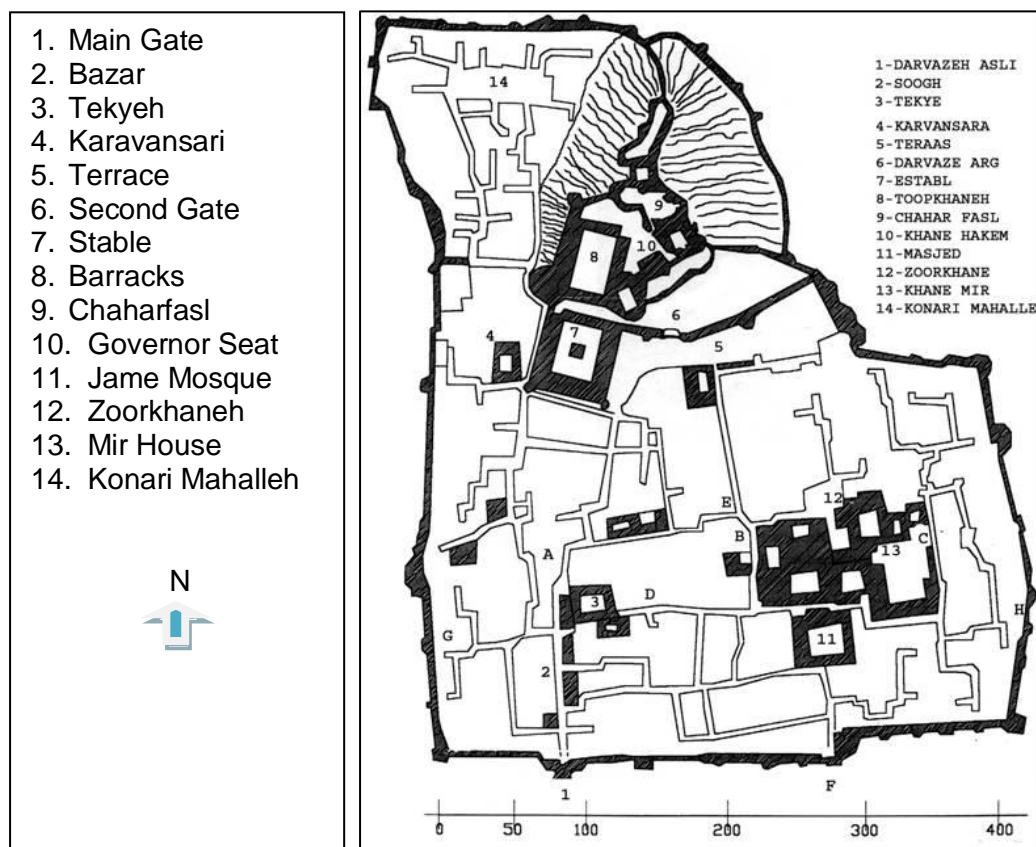


Figure 6 Street systems in the Bam Citadel

Element above the street, which is called "Sabat" usually covers Baazar, Figure 18, the governor quarter and sometimes between houses acts as bridging the street and the buttressing arches spanning between walls on either side of the street to provide structural strength and support for both opposite walls. It also makes shadow for the passerby, who is walking through the streets in hot days.

The courtyard buildings (for example Mirza Naeim Ensemble, Figure 21) have been the basic module used for housing and public buildings in the Citadel. In housing the courtyard takes up approximately 24% of the ground coverage [16], and the building is one, two, or occasionally three stories in height. Public buildings differ in their ration of courtyard size to ground coverage and the height is one to three stories, for instance in Caravansary, Barracks and Stable [8].

How have the neighbourhoods of the Citadel been formed? It is a question which needs more investigations and studies to reach to a complete or a precise answer. An old sketch of the Citadel divided it to the following neighbourhoods by the direction of the location but there is not more precise information to clarify history of the development there; the governor quarter is not considered in this classification, Figure 7:

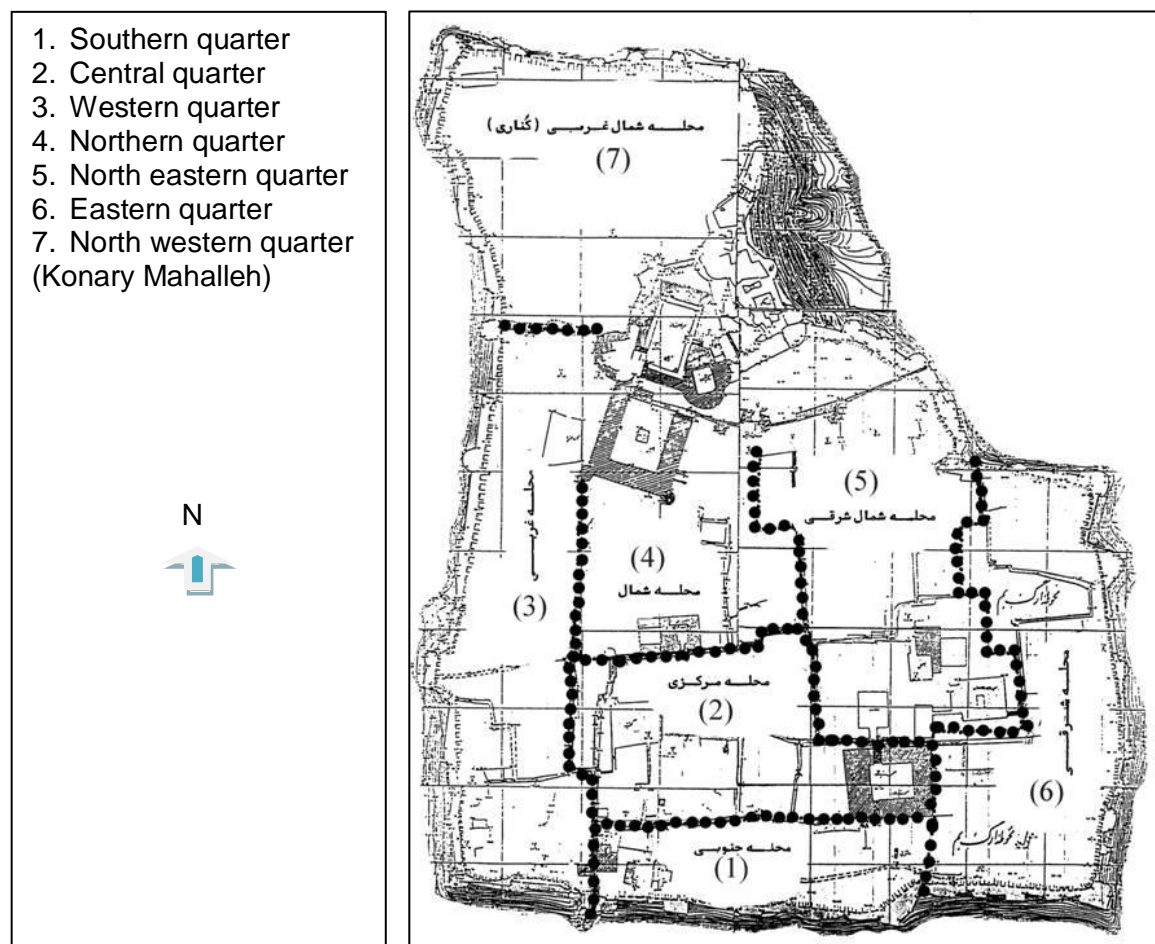


Figure 7 Old classification of the quarters in Bam Citadel



1. Main Gate
2. Bazar
3. Tekiyeh
4. Sistani House
5. Stable
6. Caravansari
7. Pyambar Mosque
8. Public Bath
9. Second Gate
10. Barracks
11. Commander's House

12. Mill Tower
13. Governor's House
14. Chaharfasl
15. Governor's Bath
16. Jameh Mosque
17. Mir House
18. Mirza Naeem Complex
19. Konari Mahalleh
20. West House of Sabat
21. Cot-e Kerm

22. Old Gate
23. Small House
24. Zoor Khaneh
25. Ammehneshtin
26. Water Storage
27. Iced House
28. Rock Building
29. Shahrast Wall
30. Garden
31. Moat

Figure 8 Latest Map of Bam Citadel, 2009

The neighbourhoods in the east, west and south of the Citadel, were all commercial and residential and the access to the public services same as baths, mosques and Bazaar has been easily possible by the streets and alleys."Konary Mahalleh"^{ix} (number 7 in Figure 7), which is located on the northwest side of the Citadel at the lower level of the town, supports the hypothesis of being a prison or a place for the captives.

Decision, about the development of the city, were usually made by the local rulers; they concerned the birth, growth, and revitalization of the city and would include the location of primary mosque, the distribution of the land in the projected boundaries of the city to various ethnic, familial, or tribal affiliations and the location and configuration of the city's gates and walls [16]. It could be the results of decision taken in the first years of city's founding. The decision occurring during the city's expansion involved the building of major public services such as mosques and public bathes or commercial parts of the city. However depends on the needs and function, owners of the houses personally made changes, added some parts to the original structure, or remove other spaces in the residential building. It justifies the variety of the construction layers in mediocre houses in Bam Citadel. Revitalization activity often took place under the leadership of ambitious rulers and government during eras marked by security and prosperity. Site conditions and locations of determining factors such as water and natural features useful for defensive purposes had an impact on decision making and the urban form [19].

It is obvious that the natural base of the land had a very important role for the original form of the quarters. The rocky and high level of the base in the north was a strategic place for both governor and soldiers to defend the probable attacks, to keep the military power and to protect the ruler and its families. Some archaeologists believe that this part is the most original and the oldest part of the Citadel. Based on the location of the quarters, another type of classification could be applied for the Citadel, due to the different levels of the natural height of the ground and its related function. It is divided into three distinctive sections, which each section is surrounded by the walls.

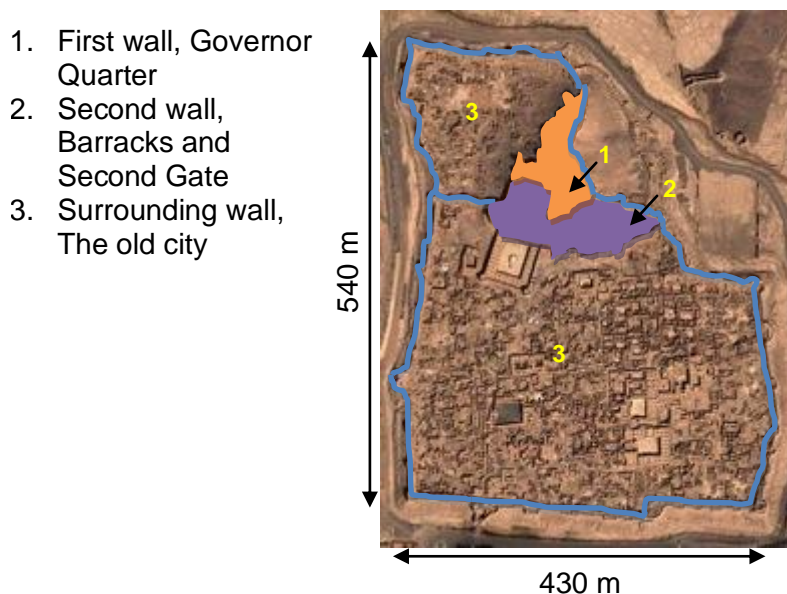


Figure 9 Three distinctive sections in Bam Citadel, 1956

^{ix} Mahalleh is an Arabic word and neighborhood is its translation in English.

The upper part, in the north east, is the governor quarters, Figure 10, is situated on a rocky hill about 45 meters height. The natural topography has provided the possibility for the ruler and the soldiers to guard the area, to provide the safety and to protect the city. This section features the governor residential place, the “Chaharfasl”, watchtowers, and the governor’s bathhouse. The watchtower is located on a rocky hill north of the present enclosure, Figure 11. It is connected to the old wall of the town through a narrow fortified corridor. The Chaharfasl is situated to the north of the governor’s residence consists of four rooms round a domed central hall. The building in its present form belongs to the Safavid Period [3], provides beautiful view of the area, and was used by the ruler of the Citadel to entertain honoured guests. The southern side; the yard is smaller and more protected than the other residential houses in the Citadel. On the north side of the governor’s residence there is a four-sided watchtower, which is referred to as the main tower of the Citadel. It has been said that the tower was used to send signals with fire by night and smoke by day to the surrounding countryside, and thus came to be known as the “Atash-Khaneh” (fire tower), Bam CMP^x (2009). The name may also be related to a

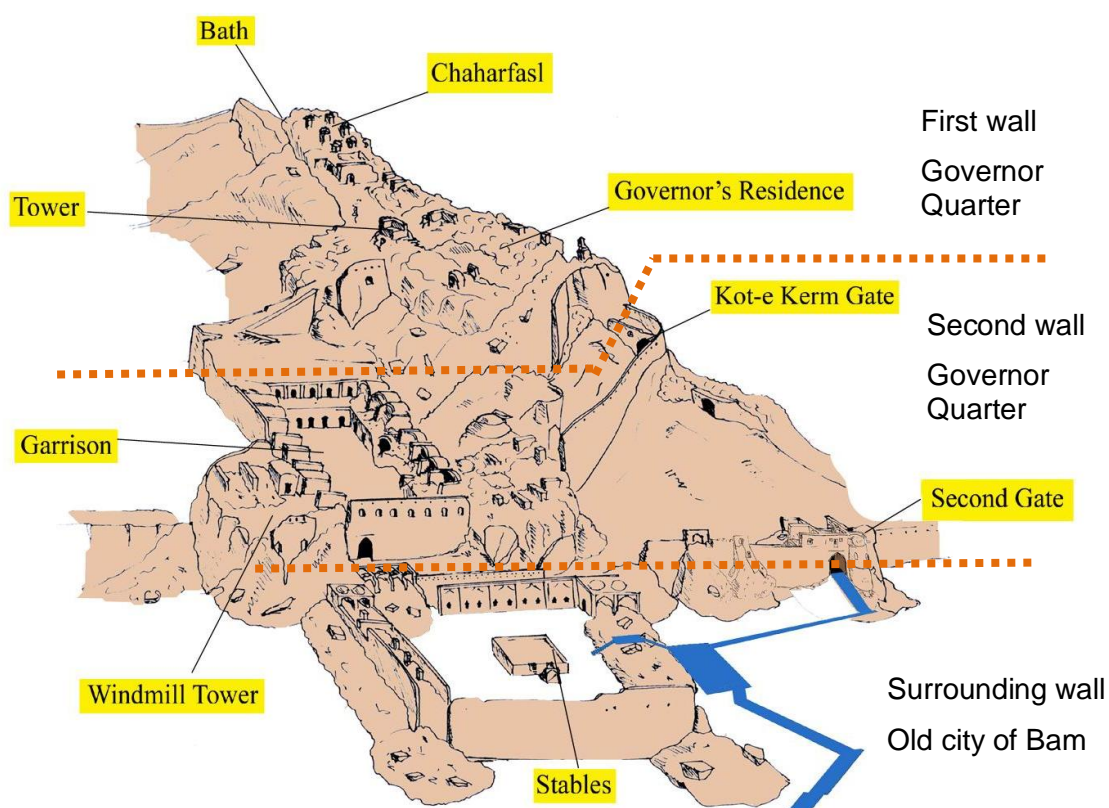


Figure 10 Governor Seat and Second Wall, Bam Citadel

fire temple and a place where sacred flame was tended.

^x CMP is Comprehensive Management Plan of Bam referring to [58].

The governor residential house divided to two sections; winter section in the north and summer section with the rooms on the southern side; the yard is small we and more protected than the other residential houses in the Citadel.



Figure 11 Governor Seat and the watchtowers^{xi}, Bam Citadel, before earthquake in 2003

The second section of the Citadel was confined by the second and the third walls, Figure 12; the military quarters and comprises the stables, the soldiers' barracks, and the residential building of the army commander. The buildings in this part date back to the Seljuqid, Mongol and Timurid time [3].



Figure 12 Second Wall, Second Gate and the Kot-e Kerm on the right before earthquake in 2003

^{xi} The highest watchtower is found into the north, with a short distance from governor's residential place and further on there is also the Chaharfasl.

The “Darvaazeh-ye Kot-e Kerm”, which means the “Gate of the Worm”, is situated in the last wall of the Citadel, which separates the Governor’s Quarter from the military sector. A path on the top of the wall of the Gate facilitated the movement of troops. Naturally, the name of the gate refers to the legend of “Haftvad^{xii}”, [3].

The Barracks^{xiii} lies at the south west side of the governor quarter; in the past, it was used as storage for artillery in the later periods, end of the 19th and beginning of the 20th century. It has two levels, Figure 13. A platform has been located on the south side of the Barracks where the commander would stand and observe military parades. Three wells on the southeast side of the Barracks supplied for water the whole area. The Citadel’s barracks is the last location between governor quarter and the military sector; guardrooms and a watchtower are located next to in the south west of it.



Figure 13 Barracks, before earthquake in 2003; the vertical platform in the middle with acoustic effect

A remarkable peculiarity of the site is its acoustic effect; words spoken even in a low voice from the platform are easily heard all around the yard. It approves the idea that precise calculations were carried out during the construction.

The Second Gate, Figure 14, is located at the entrance to the second wall. This high wall featuring three towers is connected to the main way from the east, while from the west it is terminated by the Stable. It was erected in the Seljuqid Period, [3]. It is two-story building and very notable building not only because of the architecture but also because of the location that separates the governmental section of the Citadel from the residential quarters. The Second Gate has had a homogeneous architecture, embellished by the

^{xii} Historians believe that the story of Haftvand in Shahnameh (Ferdowsi’s Book of kings) occurred in Bam Citadel; Haftvand was the father of seven sons and a daughter. They hardly meet their daily needs until one day the daughter found a worm in an apple. She took care of it but she made it hidden from her father. The story is about how this worm brought wellness to their life; for more information look the related reference.

^{xiii} Both Barracks and Garrison have been used in different references, for instance Barracks has been used in CMP and Garrison has been utilized in earlier guidebooks of the Citadel and in Figure 13, which I have found in archive of Bam; it is a translation for “Sarbazkhaneh”. However the translation may not meet all the features of a real Barracks or Garrison.

vaulting system, decorated doors, the crenulations and the traces. Before the earthquake it was used as Tea House and was a convivial asset of visiting the Citadel.



Figure 14 Second Gate, top: southern façade, below: northern façade, before earthquake in 2003

The old city of Bam is located inside the surrounding wall of the Citadel. A characteristic of the Citadel of Bam is its surrounding wall; the first, outermost, rampart, which encompasses the people's dwelling quarters and may perhaps be considered the most visually striking urban planning element of the ensemble. It rises as high as 18 metres in some places and is interspersed by platforms reaching 6 metres in width.

It is a rough rectangle (430 m in the south, about 390 m in the north and north-east, 280 m in the east, and 540 m in the west) corresponding to the fortified enclosure (with 52 watch-towers), to the north of which lies the fortified buildings. The wall has been made

by adobe bricks. It is surrounded by a moat, 10-15 meters wide. Actually, the surrounding walls acted as the second defensive element after moat, during the wars in the past. In war periods and times of enemy's attack, the moat was filled with water.

The moat goes round the fortified enclosure; archaeologists believe that the original moat was much deeper and there is evidence of regular silting caused by periodic flood, [3].

The rampart had four gates at that time, known as Narmashir Gate, Kusgan Gate, Esbikan Gate and Kurjin Gate, [58]. Of these four gates, only the Main Gate has endured; possibly the Narmashir Gate. The "Main Gate" is located in southernmost point of the outer wall, Figure 15. Before entering the Citadel, however, the rampart and moats of the old structure are seen, Figure 8, number 31.

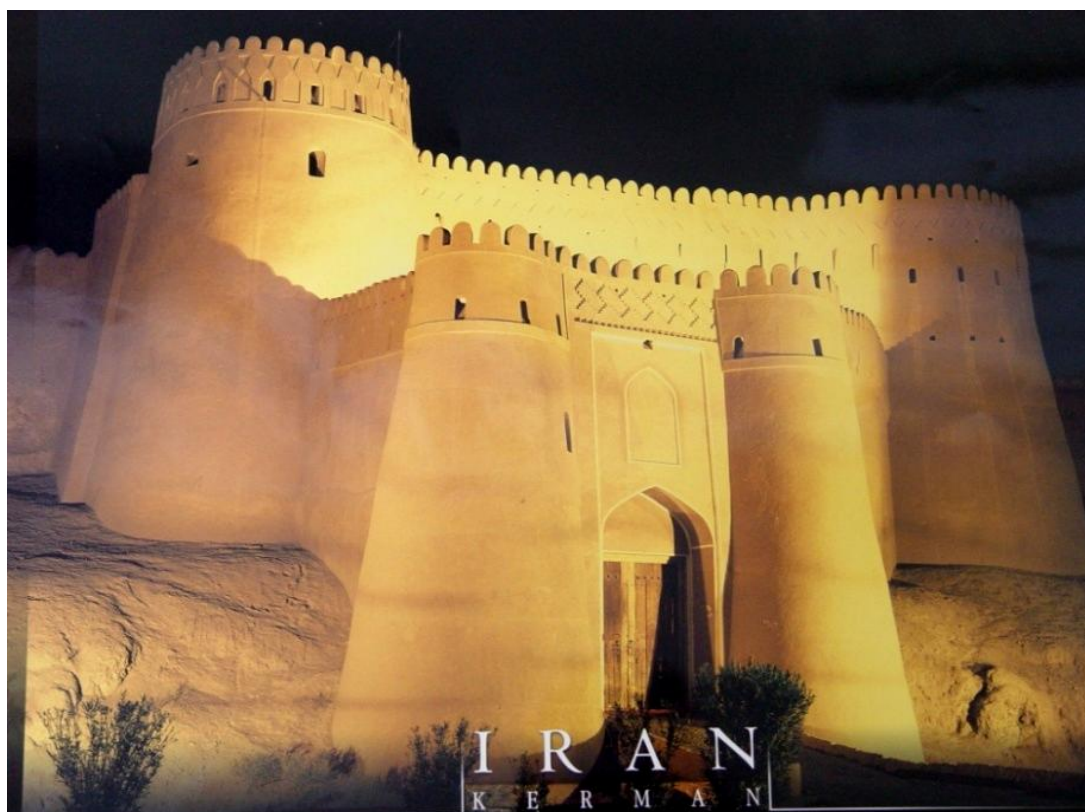


Figure 15 Main Gate, before earthquake in 2003, Bam Citadel

To the north western and the western corner of the town, within its own enclosure is the "Konari Mahalleh" (Figure 16), which contained probably a popular and not so rich a neighbourhood of the town. Strangely enough, its humble houses were not much damaged by the earthquake. The case surely needs a scientific explanation.



Figure 16 Konary Mahalleh, Bam Citadel, after the earthquake in 2004

“Bazaar” is consisted of a corridor about 60 meters long from south to the north, Figure 17. This is the trade street of historic Bazaar, dating back to Safavid Period [3]; numerous shops are located on both side of the corridor, which are consisted of an out store and a small storage behind. The dimensions of the shops and merchants’ compartments located at the beginning of the Bazaar in the south differ from those found at the end of it in the northern part of the Citadel. In the middle, there is an intersection “Chaharsuq”, which was once covered by a dome in mud bricks. In fact the whole alley of the Bazaar used to be vaulted much the same as all other Persian bazaars, Figure 17.



Figure 17 Bazaar, before earthquake in 2003

All the structure had been made at the same time and roofed, [3]. After the earthquake in 2003 no traces and roof presently remained.



Figure 18 The long corridor, Sabat and Chaharsuq of Bazaar after last restoration in 1993

Most of the trades over there were related to Spice Road that led from India, Send, Makran and Baluchestan and later was connected to the Silk Road. The textile industry in Bam especially in Islamic Period was notable and famous in the world [58].

At the intersection of the Bazaar's main row of shops and the paths that lead to the governor quarter, there is a square where religious performances took place; this is "Tekiyeh" or the religious theatre, Figure 19. Tekiyeh consisted, in fact, of a large open central courtyard flanked by rooms and two-storied stores. It was used as a main square of the city and the most important place for trade, buying and selling silk, cereal, spice and so on. People who worked or associated with a business or industry got together and meet there. The construction of it dated back to different times in the past; the eastern part is the oldest one probably founded in 1687 AD, the western part and central terrace date back to Safavid Period [58]. These buildings used as stores; a large Muller has been found at the back yard of the eastern stores; probably used for oil extraction.

Religious ceremonies took place there until the earthquake in 2003; after that, ICHHTO tried to revitalize the ceremonies and they have been revived; the last one was held on April 11, 2004.

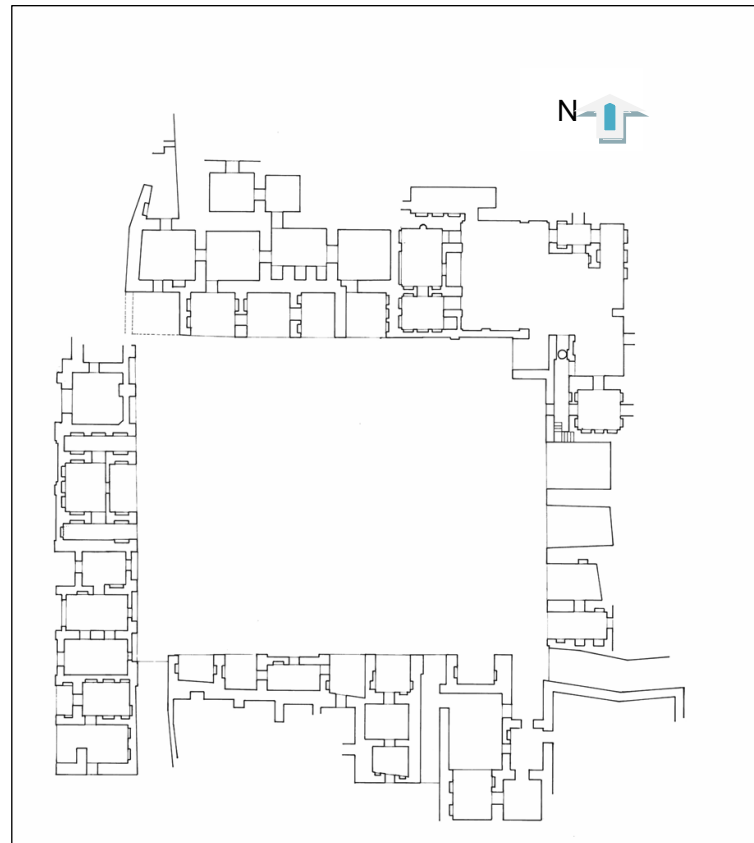


Figure 19 Plan of Tekiyeh before earthquake in 2003

The “Stables” are located on the west side of the second wall and its entrance, Figure 20. This is a roughly square building (60 x 70 m), and is one of the largest constructions in the Citadel. Mangers are placed all around the Stables. The covered winter stables lie on the east, west and north sides; they are roofed with 46 domes in mud brick. In the centre of the Stables courtyard, there is partly subterranean water reservoir which once supplied the necessary water to the building. The reservoir’s well is 28 m deep and is dug out all the way through solid rock. After the last restorations in 1993, the Stables were turned

into exhibition halls, and were before the earthquake amongst the best-preserved parts of the Arg.

At the foot of the Citadel area is the residential quarter of the town. There lies the “Sabat-e Johudha” or the Jewish passageway to the east of the Stables and the extreme north of the town before the wall of the Citadel. One of its buildings, carefully restored, is known as the West “Sabat House”. It consisted of a relatively large house with a central courtyard flanked by two series of rooms in two floors. The residence was one of the loftiest buildings in the Arg; the earthquake damaged it invasively. The most well known historic events related to the Citadel occurred in the Stables.

It was said that the arrest of the Lotf-Ali Khan, the last Zand pretender to the Persian throne, took place in late autumn 1794 in Stables. The prince was handed over to his unmerciful foe, Agha Mohammad Khan Qajar, who killed him under torture. Agha Mohammad Khan founded the Qajar dynasty that ruled Iran until 1925, [58].



Figure 20 Stable, before earthquake in 2003

The eastern parts include two distinguished buildings; Mirzaa Naeim Ensemble and the Jame Mosque.

Almost located in the middle of the town lay the ensemble, which consists of a “Khaneghah” (the cloisters), a “Tekiyeh” and a “Madreseh” (religious school). There is not a precise evidence to describe the spaces and the function very clearly; specially at this moment, when this valuable ensemble totally collapsed during the earthquake. The information on the plan in Figure 21, is based on my personal observation and experiences in Bam Citadel from 2003 up to 2009. The plan shows that it is kinds of donated buildings by rich and famous people in the area, which are very common in Islamic societies. It consists of several courtyards, surrounded by the residential rooms of Mirzaa Naeim and his family.

In this kind of schools, usually the students have lived in the school and this premise, which could be reasonable that the western part was an accommodation place for the students. The north east side, there was a stable. But any more information in this regards needs more archaeological investigation.

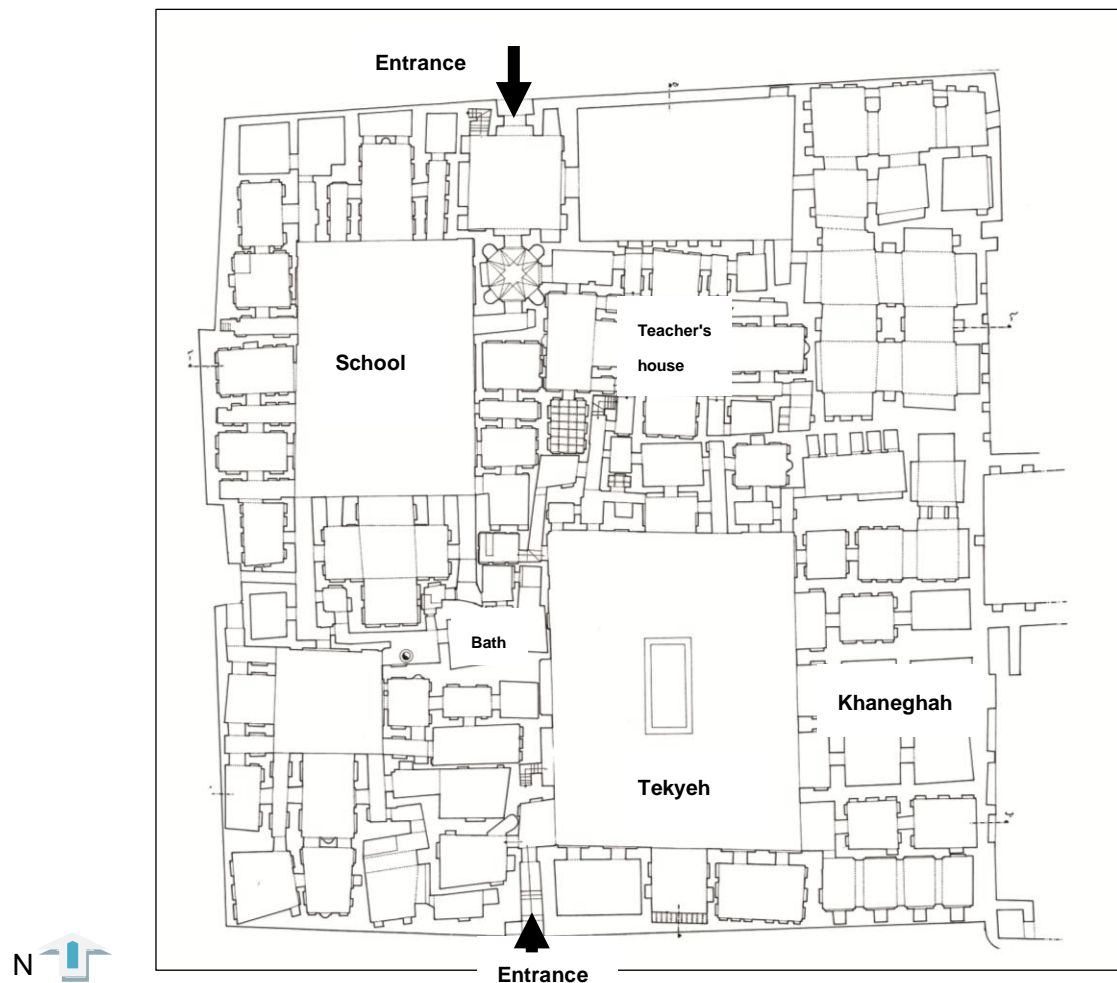


Figure 21 *Mirzaa Naeim Ensemble, Bam Citadel*

The ensemble was built by Haji Seyyed Mohammad, who was one of the most prominent figures of Bam probably at the end of the Safavid Period (early 18th cent.), Behzadi (2004). The ensemble had several intertwined courtyards in one of which Mirzaa Naeim was buried. A major wind-catch tower with 30 openings crowned the buildings.

To the south of this ensemble lies the “Jame Mosque”, which was and in spite of its destruction by the earthquake still is one of the most important edifices in the Citadel, Figure 22. It has been said that it was one of the oldest mosques ever built in Iran. It has also been suggested that this mosque is one of the three mosques in Bam mentioned by Moqadassi in the 9th century [58]. The mosque, dating back to 8th Century AD and it is thought to have built over Zoroastrian fire temple. In its earliest from the Mosque faced due east. Its internal arrangements were reconfigured later so that the congregation prayed south west towards Mecca. The Mosque continued to be in use until it was destroyed by the earthquake. The archaeological investigations associated with the clearance of the earthquake debris have enabled the exploration of the evolution of the Mosque into its present form. In the north side of the building there was a “Mihraab”, with an inscription dated to 1747. The mosque had a courtyard surrounded by three prayer hall and “Eyvaans”, Figure 22. It had been used since years ago and because of that variable layers of construction could be seen which dated back to the different periods of time. There are two Eyvaans, in the north and it the south, five Mihraab and three Shabestan in the west. There are archaeological evidences that show these three

Shabestan had not been built at the same time; the differences between the height of the columns and the length of the arches between the columns support that hypothesis of the different time of construction [58]. In compare with the other mosques, it has not had any decoration, without artistic tiles and mirror works and plaster works. The significance of the building is because of artistic dimension of the mosque with a turning to Mecca in Mihraab, and the different layers of construction; in the remains of a certain ancient building, the ruined Saffarid Wall, a Mihraab of the Timurid period, the gallery dating back to the Seljuqid time, the Safavid redecorations, adornments belonging to the Zand's Dynasty, the Qajar- dating stone-pebbled pavements and even the latest Pahlavi amendments, Behzadi, 2004. The "Chaah-e Saaheb-e Zamaan" is a well, which dug in the south eastern corner of the mosque; it is much venerated by the population in Bam area. Still there are many questions regarding to Jame Mosque, which make it an interesting case study for the future research.

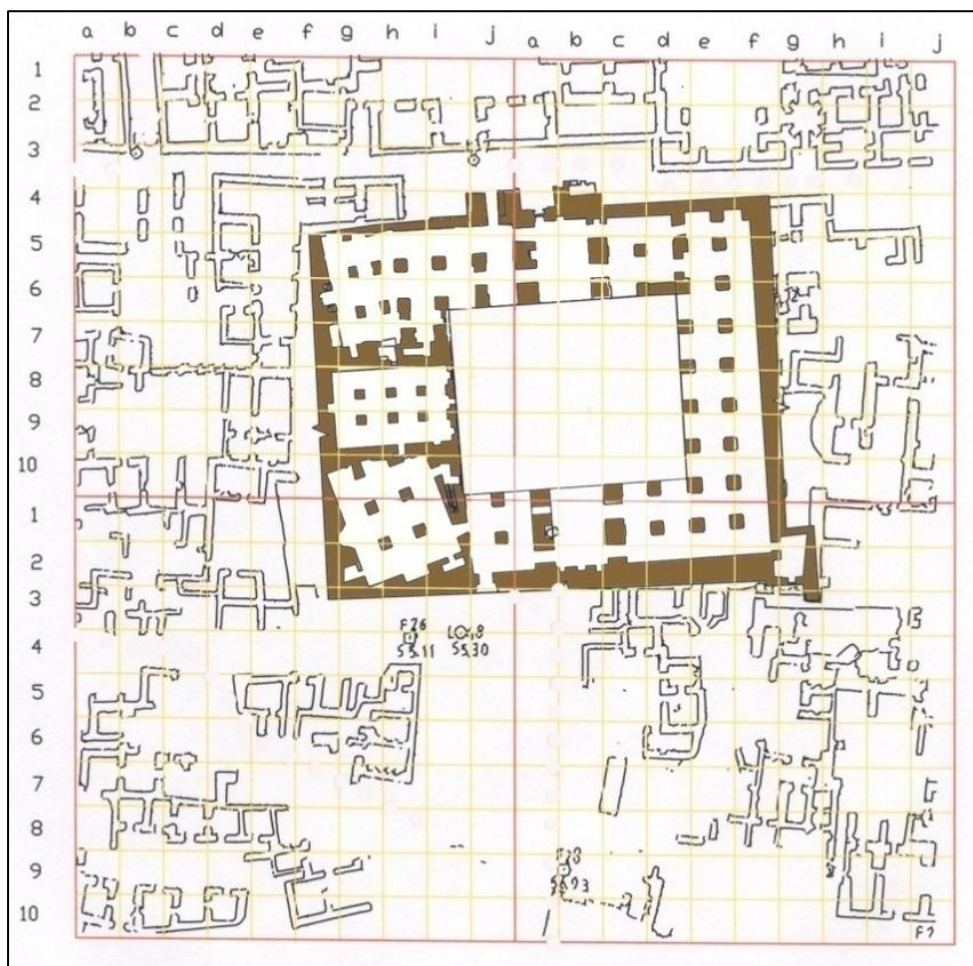




Figure 22 Last page: plan of the Jame Mosque; left: Mihrab; right: Eyvan in Jame Mosque 1996

2.5 Structure and construction

The structure of the Citadel is composed of adobe bricks (sun dried ones), which held together by mortar; the walls are very delicate and sensitive to moisture, humidity, temperature, wind and definitely earthquake. Chineh is made of mud and sometimes reeds, which are mixed together, particularly in the base of the walls. Generally masonry buildings have a very low tensile strengthened shear resistance; this is the reason why all shapes and structural forms are founded on a compression resistant conception based on pillars, walls, arches, domes, etc., while the role of tensile forces is reduced to a minimum. In most cases, even with disconnections and cracks, structures can maintain their overall bearing capacity without reducing their global safety level, [5]. The materials used in traditional houses are adobe (Khesht^{xiv}) and backed brick for the final stages of construction. Load bearing walls made of adobe make thick walls that transfer loads to the ground. For various reasons that were pertinent at the time, roofs were made of materials such as Khesht and baked bricks as well. In fact, a homogeneous load-bearing system would start at the roof and then rest the resulting shell on the walls by means of mediators at the corners and the joints between the ceiling and the walls. This characteristic of adobe or backed bricks of working in compression has influenced the form the roofs took at the time. The resulting forms were the barrel vault or the dome, which became stable as a result of compressive forces between one unit and the next, Figure 23. The structural system of load-bearing walls imposed a particular logic on the architecture. In this system the walls would preferably line up, and since they also had a structural role, they were not as free and easy to manipulate, as are walls today.

^{xiv} Khesht is a Farsi word for adobe.



Figure 23 Left: Arches^{xv} in Jame Mosque Right: Dome of Jame Mosque

The walls that also had a structural role were, as much as possible, placed on a side that needed fewer openings, so that a complete diaphragm could transfer loads without the adverse influences of openings and the like. Structural elements are:

- Foundation:

Generally there is not a designed foundation for most of the buildings in the Citadel, [44]. Traditionally the masons dug the ground and laid the adobe bricks like foundation cores. They used the natural base of the ground for this purpose. Obviously because of the heavy weight of the adobe building, an initial settlement happened and the soil under this base was consolidated under the pressure. Two kinds of bed soil could be seen in the Citadel: Rock bed base, Figure 24 and consolidated bed base, Figure 25. The first one is mostly found in the north parts, the Governor's Seat.



Figure 24 Foundation of the Second Walls, the bed is from rock and stone

^{xv} Taq and Tavizeh; it is a very usual vault and dome in historical buildings in Iran. The width about 4.2m has been seen in the Citadel.



Figure 25 Consolidated foundation of the Caravansary, the bed is from compacted soil and the natural ground

- Walls:

Using the thick walls in traditional houses and carving them out to provide niches for putting things has turned the wall from a surface to a volume. The openings, like doors and windows, gives an extra visual aspect, brings in more light, and also gives more volume to the wall, Figure 26.

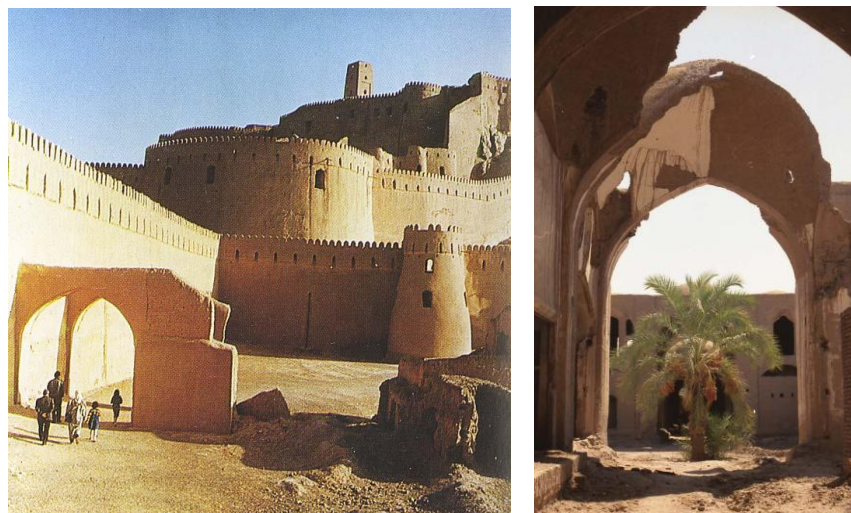


Figure 26 Variety of structures in Bam Citadel

- Roofs:

The ceilings tend towards three dimensionalities and get close to the overall definition of the spaces, Figure 27. This attributes a specific identity to such ceilings. This aspect is more evident in the case of the Pool House (Hoz-Khane^{xvi}), with its dome, roof lights, and wind tower. The ceiling in most rooms and the main hall is mostly in the form of barrel vault. The ceiling of the Talar is higher than the form of a barrel vault. It must be mentioned that this diversity in form and height stems from the construction logic of such buildings. The element of the roof has an identity both externally and internally. Externally, with their mud- brick vaults, domes, and wind towers, the houses of Bam give character to the general appearance of the city. From the inside too, the ceilings are subservient to the whole. The following principles can be stated as the features of ceilings and roofs in traditional houses: their volumetric aspect, variety, identity, external and internal harmony, and subservience to the overall order of the building, [5], [7], [8].

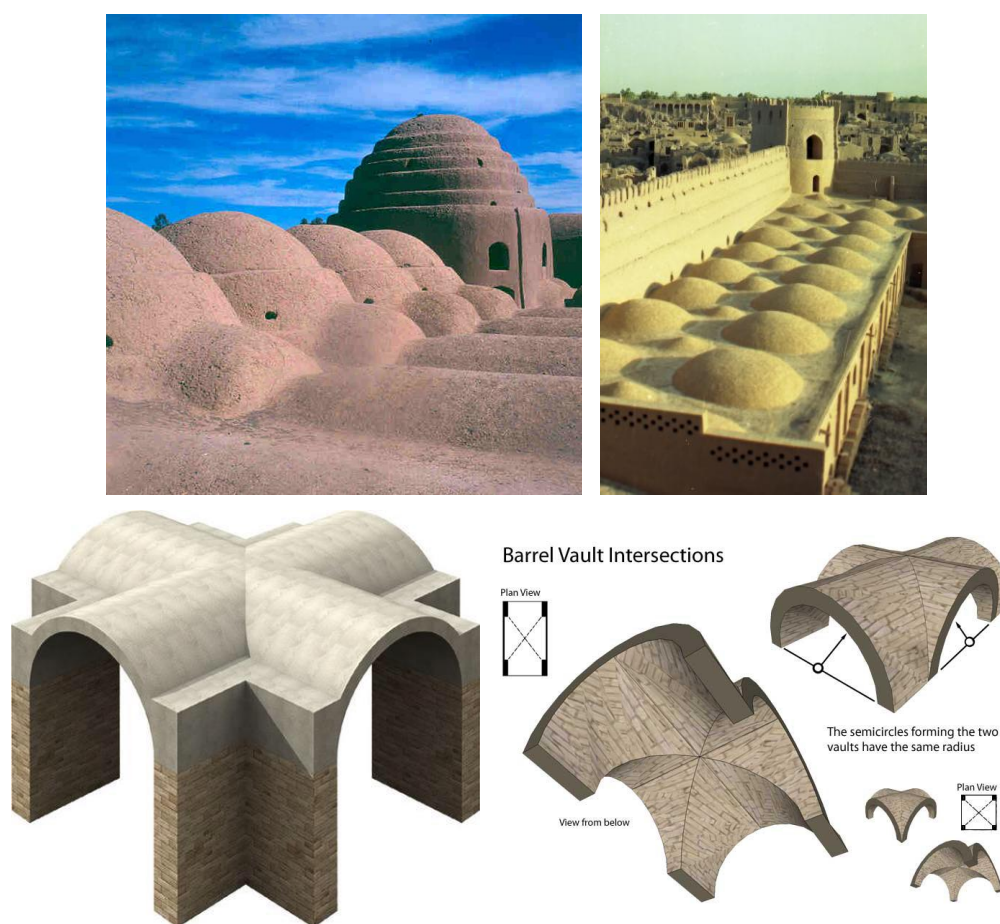


Figure 27 Barrel vaults which are applied for most of the buildings in the Citadel

^{xvi} Pool House can be a clear translation for “Hoz Khaneh”; it is a part of a space in the plan, which there is an indoor pool in the old Iranian houses; it is a place which used for listening to the sound of water and for holding the ceremonies and parties.

2.6 Inscription in ICHHTO^{xvii} & WHC^{xviii}

State Party: Islamic Republic of Iran

Name of the World Heritage Property and WH ID Number:

Bam and its Cultural Landscape C 1208

Geographical coordinates to the nearest second:

58° 46' 06" E- 57° 28' 43" E

29° 35' 11" N- 28° 50' 56" N

Date of inscription on the World Heritage List:

July 2004

Organization or entity responsible for the preparation of this progress report, [52]:

Recovery Project of Bam's Cultural Heritage

Research Organization for Cultural Heritage, Handicraft and Tourism

Iranian Cultural Heritage, Handicrafts and Tourism Organization

Government of the Islamic Republic of Iran

Justification of Outstanding Universal Value (OUV)

"Bam and its Cultural Landscape", Islamic Republic of Iran, which was inscribed on the World Heritage List in 2004 on the basis of criteria: (ii), (iii), (iv) and (v)^{xix}, [58]:

^{xvii} Iranian Cultural Heritage Handicrafts and Tourism Organization

^{xviii} Iranian Cultural Heritage Handicrafts and Tourism Organization

^{xix} The Criteria explain in the Operational Guidelines for the Implementation of the World Heritage Convention, which besides the text of the convention is the main working tool on it. The criteria are regularly revised by the Committee to reflect the evolution of the World Heritage concept itself:

(ii) to exhibit an important interchange of human values, over a span of time or within a cultural area of the world, on developments in architecture or technology, monumental arts, town-planning or landscape design.

(iii) to bear a unique or at least exceptional testimony to a cultural tradition or to a civilization which is living or which has disappeared.

(iv) to be an outstanding example of a type of building, architectural or technological ensemble or landscape which illustrates (a) significant stage(s) in human history.

(v) to be an outstanding example of a traditional human settlement, land-use, or sea-use which is representative of a culture (or cultures), or human interaction with the environment especially when it has become vulnerable under the impact of irreversible change.

Criterion (ii): Bam developed at the crossroads of important trade routes at the southern side of the Iranian high plateau, and it became an outstanding example of the interaction of the various influences, Figure 30.

Criterion (iii): Bam and its Cultural Landscape represent an exceptional testimony to the development of a trading settlement in the desert environment of the Central Asian region.

Criterion (iv): Bam represents an outstanding example of a fortified settlement and citadel in the Central Asian region, using in its construction a combination of mud layers (Chineh) and mud bricks (Khesht), Figure 28.

Criterion (v): The cultural landscape of Bam is an outstanding representation of the interaction of man and nature in a desert environment, using the Qanats, Figure 29. The system is based on a strict social system with precise tasks and responsibilities, which have been maintained in use until the present, but has now become vulnerable to irreversible change.



Figure 28 Left: Core zone (the red one) and buffer zone (the blue one) of Bam and its Cultural Heritage; right: Bam Citadel, Arial photo 1996

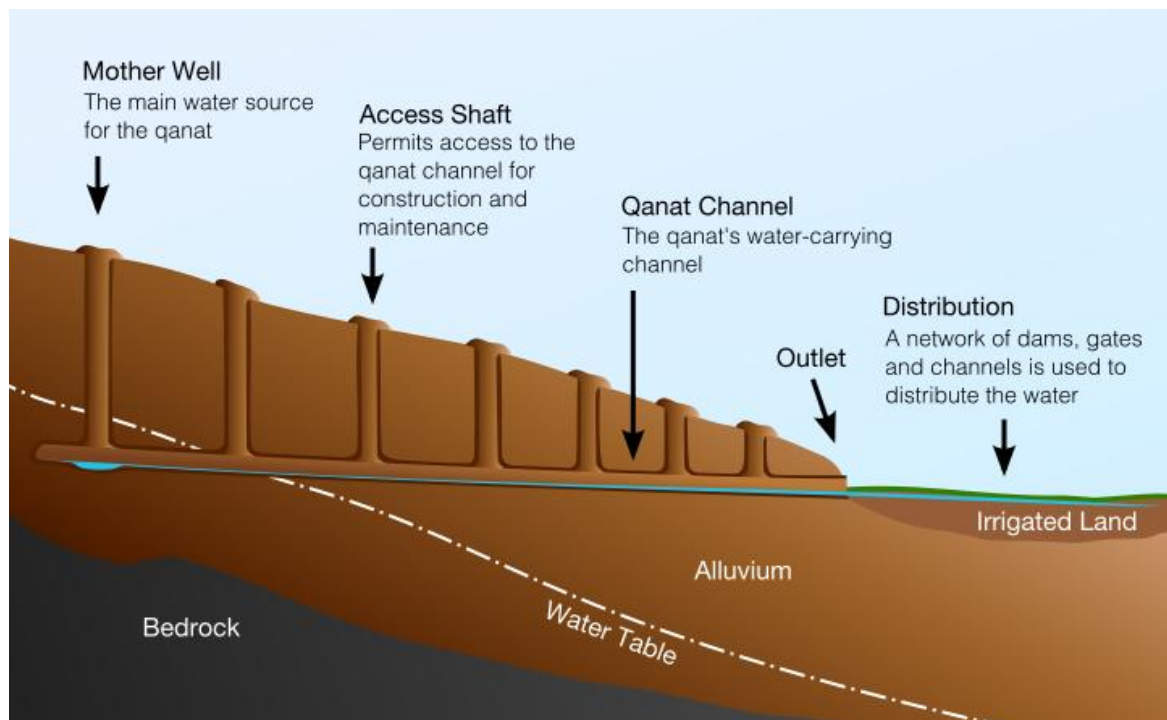


Figure 29 Qanat Left: Arial photo 2006: It is a genius hydraulic system in arid area. Right: it brings water from inside the ground to the surface for agricultural needs. Bellow, there is a plan and section of Qanats.

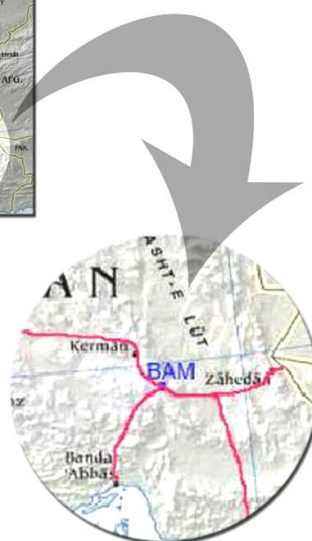


Figure 30 Silk Road, [52]

2.7 Status after the earthquake

Immediately after earthquake, the restored parts of the enclosure wall of the Arg including some of the towers in the south side have fallen down whereas the walls themselves are not in relatively good shape. The northern sector of the town known as Konari, Figure 33, is more or less intact. The Citadel and its components were the object of severe shock and were heavily damaged. The upper structures of the building known as Chāhārfasl have been destroyed; only some of the lower parts have been left. The tower was entirely collapsed as well as the south-western side of the Citadel. As for the Barrack compared to other structures it is in good state of preservation, but its upper storey and its towers are damaged. The upper structures of the Stables have also been damaged, but the mud brick vaults are relatively well preserved. Beside the Citadel, buildings in the town are the most shattered structures. Most of the houses have collapsed, but the building known as the Tekiyeh (Religious Theatre) has been preserved and some of its side structures were damaged. The Caravanserai, the Bazaar and its alleys were damaged to a noticeable degree. The Jame Mosque (Figure 31) was totally destroyed. Of the Mirza Naeem Ensemble only the eastern vaulted part of the School is still standing in a shattered state of preservation. The south Main Gate to the Arg has also been damaged to a considerable extent. Outside the Arg, the round structure known as Yakhadān (Ice House) has been damaged, but a significant portion of its outer walls is still intact.



Figure 31 Jame Mosque, left: before, right: after the earthquake



Figure 32 Kot-e Kerm Gate, left: before, right: after the earthquake



Figure 33 Konary Mahalleh, left: before, right: after the earthquake

3 Damages

The term 'damage' is used to describe a situation in which a structure has lost some or all of its bearing capacity, a condition that can lead to failure and collapse, Croci (1998). Damage is usually marked by cracks, crushing, crumbling, braking away of elements, permanent deformation, etc. and is related to mechanical actions. It is important to understand about the kinds of damage that has happened in Bam, because the structure and its component and the technology of construction are part of the architectural values. When any change of use or function is proposed, all the conservation requirements and safety conditions have to be carefully taken into account, [55]. This chapter describes the types of damage that can occur and is leading this research to the amount of acceptable damage in historical adobe buildings.

3.1 Collapse

Earthquakes are unique among natural disasters because they come with little or no warning, [56]. Analysing the failure pattern is essential in understanding how historic adobe buildings behave in an earthquake. While it is true that portions of, or entire, adobe buildings may collapse during a strong earthquake, it is not true that adobe buildings are unstable simply because the walls have cracked.

3.1.1 Earthquake in Bam Citadel, Bam, Iran on December 2003

The Bam region is located on a very young active seismic zone; however, the city of Bam itself had no reported major historical earthquake before 26.12.2003. The earthquake was associated with two fresh surface rupture 5 km apart trending north south and 2 km wide. A zone of hairline fractures developed between two main ruptures in the north of Bam, [15].

The Bam fault with a near north-south direction passes from the vicinity of the city of Bam (less than 1 km distance to the east of Bam, and between the cities of Bam and Baravat), Figure 35. The other segment 5 km to the west of the Bam fault passes through the city. The whole system of fresh ruptures associated with the main event is not direct manifestation of the earthquake faults, but secondary structures. No direct surface faulting was associated with the earthquake; however, the surface created after the Bam earthquake is observed around the Bam fault between the cities of Bam and Baravat.

Considering the Bam earthquake was multiple events; the focal depth of the main event is estimated to be 8 km, while the second event was 10 km. Mw 6.5 was calculated for this event, based on the seismic moment of main shock. Using the data from a dense network in Bam, the focal depth distribution of the aftershocks show a nearly vertical alignment of aftershocks located between 6 to 20 km depths. The focal mechanism of the main events and aftershocks indicate right lateral strike slip faulting on N-S trending fault, which is compatible with the fault trace that were observed by the IIEES^{xx} tectonic group.

^{xx}IIEES is an abbreviation for International Institute of Earthquake Engineering and Seismology in Iran.

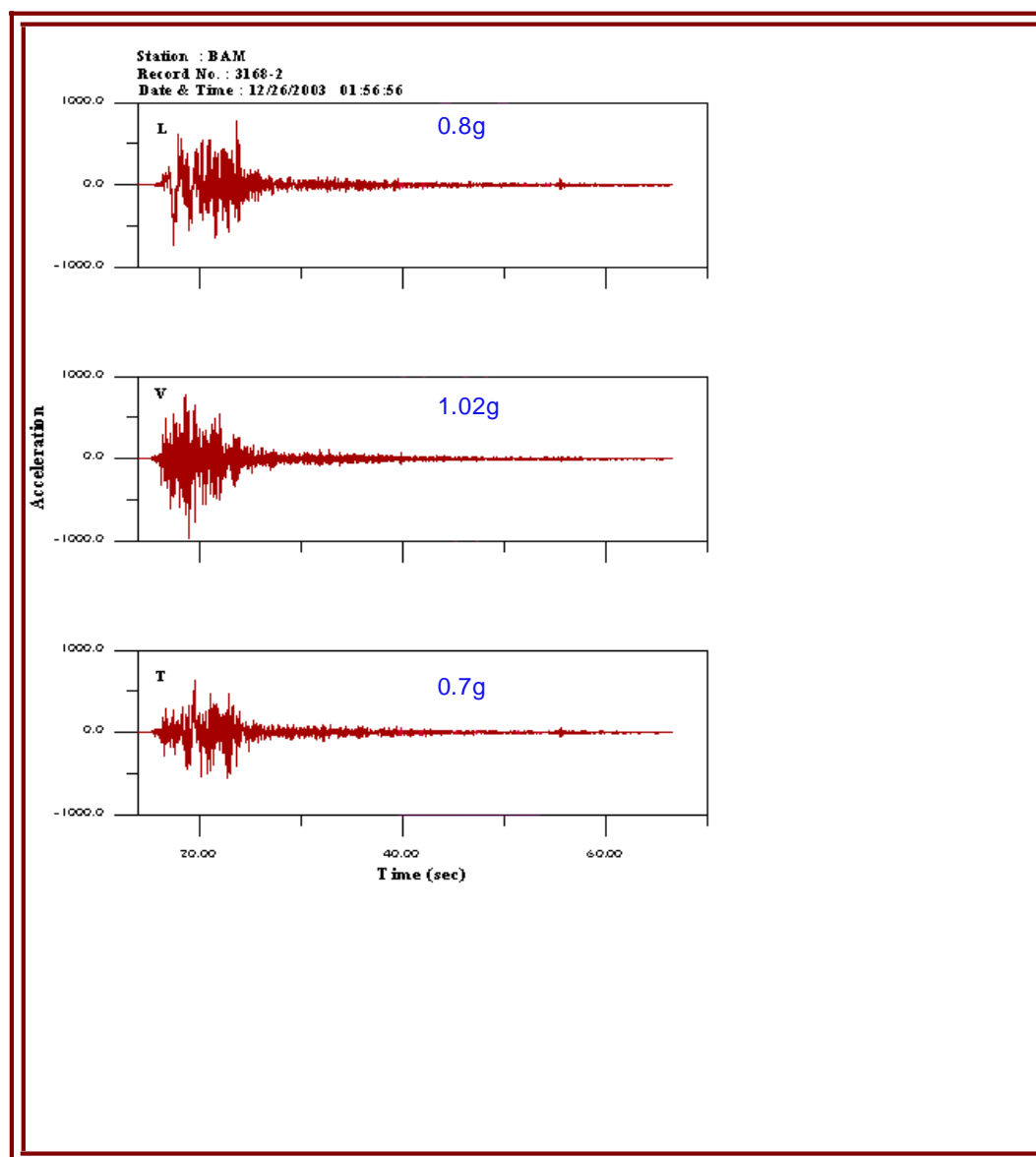


Figure 34 The accelerographs for the main shock recorded in Bam station, [15]

The strong motion record obtained by BHRC in Bam station shows the Horizontal PGA of 0.8g and 0.7g, and 1.02g for the vertical component (Figure 34). The effective duration of the earthquake was estimated between 7 and 10 seconds. Two strong phases of the energy have been seen in the accelerograms; the first is interpreted to represent a starting sub-event with right-lateral strike slip mechanism and located south of Bam.

The preliminary observation of the strong motion record obtained from the Bam station; the observed damages in the region show vertical directivity effects, which caused the amplification of the low frequency motions in the fault- normal direction as well as the greater amplitude of motion in the vertical direction. The demolished walls and buildings of Bam are representative for such effects in the up-down (vertical) and east-west directions (fault-normal). The attenuation of strong motion was rapid, and even faster in the fault-normal direction. This fact has been observed from the damage distribution as well. The dominant period of this earthquake (1 sec. for the vertical component) is around

the period of the damage of the adobe buildings, which can be one the main causes of

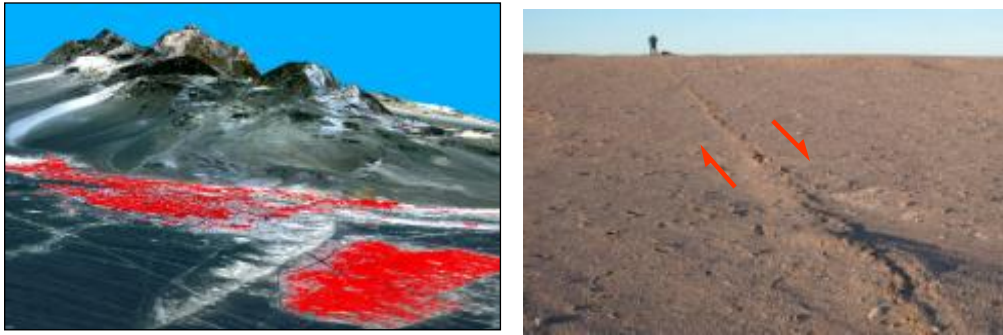


Figure 35 Bam Fault, a historical fault and a young one after the earthquake in 2003.

their failure, [48].

3.1.2 Demolition percentage in Bam Citadel

This research has been done by Keramatfar (2005) to calculate the volumes of damages and is based on the difference of the volumes before and after the earthquake. Reaching to the expected result, the main plan (only plan) before earthquake, the aerial and satellite photos have been used. According to this research the volume of the Bam Citadel before the earthquake was 295935.10 m^3 and after the earthquake it was 225789.39 m^3 . The difference, 70145.70 m^3 is the debris volume through the earthquake. For finding the amount of the volumes, all the area has been calculated according to the plan and the height has been measured in the site. The author mentioned in his article that, for some cases that the specification was not available, he presumed according to the remaining structures, [39]. The results of this research help us to have preliminary information about collapse and debris during the earthquake; for example according to this paper, the volume of the debris for the circumferential walls is 10.23% of the whole parentage of the debris, whereas the walls are 57% of the whole of the structure of Bam Citadel (Figure 36). It shows that about 23.7% of the whole Citadel collapsed during the earthquake and in comparing with the percentage of walls, it shows that the walls have proper dynamic behaviour with consideration the weakness of the material, the height of the walls, and the variety of the layers so on. There are some important points about this demolition percentage, which need to be considered when other researchers are using the results:

- The measurement errors of inspectors based on both knowledge and observation.
- The previous stage of the building; a lack of precise data with respect to the dimension and specification of the buildings before the earthquake.
- The architectural and artistic value did not affect this calculation; for example, in comparing the value between a monument and a building, 10% damage for a monument is more important than 90% damage of another building.
- The shape and consequently the height of the roofs are not clear and based on assumptions.

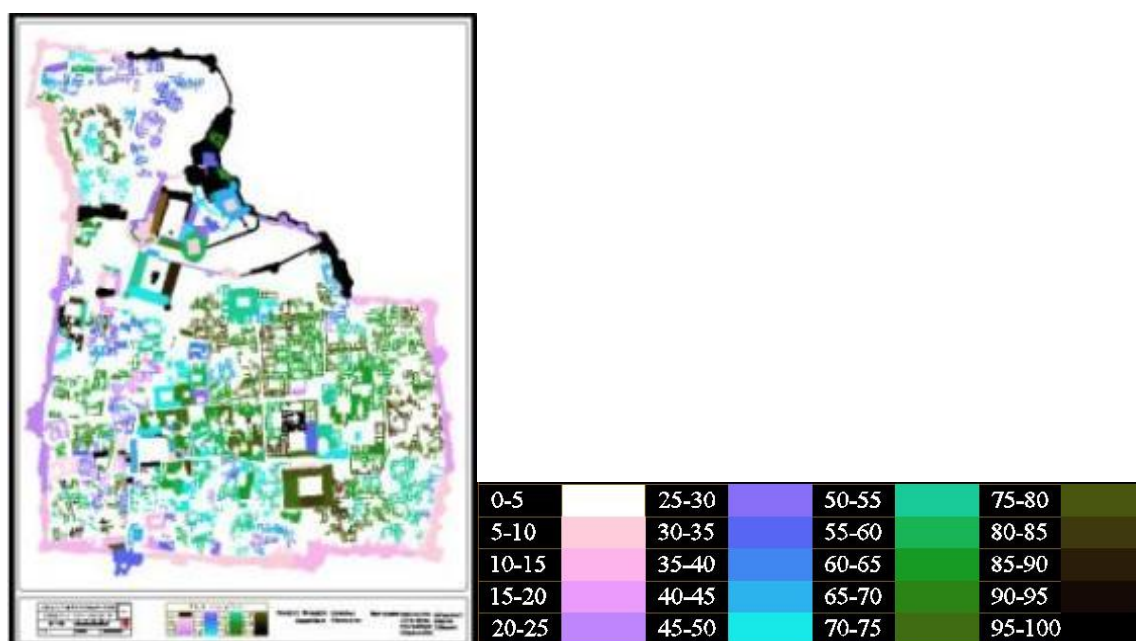


Figure 36 Demolition percentage in Bam Citadel, by Keramatfar (2005)

3.1.3 Structural damage descriptions

For describing and comparing the relative damage levels sustained by monuments after the earthquake, two standard guides are used in Iran that could be referenced here:

- Code 2800: Iran Building Design Code for Earthquake, third edition in 2008
- EERI^{xxi} instruction: Earthquake Engineering Research Institute, 1994



Figure 37 Horizontal and diagonal cracks after Earthquake, 2003.

^{xxi}The Earthquake Engineering Research Institute (EERI) is a national, non-profit, technical society of engineers, geoscientists, architects, planners, public officials, and social scientists. EERI members include researchers, practicing professionals, educators, government officials, and building code regulators. The objective of EERI is to reduce earthquake risk by advancing the science and practice of earthquake engineering; improving understanding of the impact of earthquakes on the physical, social, economic, political, and cultural environment; and advocating comprehensive and realistic measures for reducing the harmful effects of earthquakes. It is located in Oakland, USA.

Table 1 contains a description of each damage state and corresponding description of damage in historical adobe building from EERI 1994.

Table 1 *Standard damage states, [57]*

Damage state	EERI description	Comments on damage to historical adobe buildings
A None	No damage, but contents could be shifted. Only incidental hazard.	No damage or evidence of new cracking.
B Slight	Minor damage non structural elements but probably could be reopened after cleanup in less than one week. Only incidental hazard.	Pre existing cracks have opened slightly. New hairline cracking may have begun to develop at the corners of doors and windows or the intersection of perpendicular walls.
C Moderate	Preliminarily non structural damage but there could be minor, non-threatening structural damage. Building probably closed for 2-12 weeks.	Cracking damage throughout the building. Cracks at the expected locations (openings, wall intersections, slippage between framing and walls). Offsets at cracks are small. None of the wall sections are unstable.
D Extensive	Extensive structural and non-structural damage. Long term, closer should be expected, due either to amount of repair work or uncertainty of economic feasibility of repair. Localized, life-threatening situations would be common.	Extensive crack damage throughout the building. Crack offsets are large in many areas. Cracked wall sections are unstable. Vertical support for the floor and roof framing is hazardous.
E Complete	Complete collapse or damage that is not economically repairable. Life-threatening situations in every building in this category.	Very extensive damage. Collapse or partial collapse of much of the structure. Due to extensive wall collapse. Repair of the building requires reconstruction of many walls.

3.1.4 Damage typologies

It is important to understand the relative severities of the various types of damage as they relate to life safety and the protection of historic building fabric. By doing so, priorities for stabilization, repairs and retrofits can be established for each type of damage. If a particular damaged area or component of a building is likely to degrade rapidly if not repaired, then that damaged element assumes higher priority than others that are not likely to deteriorate. If damage to a major structural element, such as a roof or entire wall, increases the susceptibility of collapse, then higher priority is assigned because of the threat to survivability. If damage that could result in loss of a major feature, such as a wall, compromises the historic integrity of the entire structure, it is more critical than damage that would result in partial failure, but no loss.



Figure 38 Cracks, crashing and collapse after Bam Earthquake, 2003



Figure 39 Crashing part of the faced and bracing, 2005

The following table, Table 2, provides details of the life-safety and historical-fabric concerns for each of type of damage. As noted in the table, some damage types are usually not serious, but they may become serious if the structure is subjected to greater loads, a load of longer duration, or repeated earthquakes-particularly when no remedial repairs are carried out.

In most situations, different types of damage do not act independently, but rather in combination. In fact, several of types of damage are actually caused by other types. In some cases, the specific relation-ships among different types of damage are simple, while in others they may be extremely complex.

Table 2 *Damage typology and status of the building [57]*

Structural damages	EERI description	Life safety and historical fabric concerns
Out of plane damage Gable-end wall failure	Gable-end walls suffer severe cracking that often leads to instability. They are tall, poorly attached to the building, have large slenderness ratios, and carry no vertical loads. These walls are highly susceptible to collapse	Collapse of gable-end walls is a serious life-safety threat and causes extensive loss of historical fabric.
Out-of-plane damage Flexural cracks and collapse	Flexural cracks begin as vertical cracks at transverse walls, extend downward vertically or diagonally to base of the wall, and extend horizontally to the next perpendicular wall. The existence of cracks does not necessarily mean that a wall is unstable. Walls can rock without becoming unstable. After cracks have developed, the out-of-plane stability of a wall is dependent on the slenderness ratio, connection to the structure, vertical loads, and the condition of the wall at its base.	When walls only develop cracks and stabilized at the top to prevent over-turning, this damage type is not severe. Many load-bearing walls in extensively damaged adobe buildings were stable throughout the Northridge earthquake. In the case of overturning, the life-safety danger is serious because not only do the walls collapse but the roof or ceiling structure may also collapse.
Out-of-plane damage Mid-high cracks	Long, tall and slender single-wide walls or long, tall double-wide walls with no header courses interconnection the widenesses are susceptible to mid-height horizontal cracking from out-of-plane ground motion.	Damage represented by mid-height horizontal cracking is not serious in and of itself. However, the potential for much greater damage is significant.
In-plane damage	Classic X-shaped or simple diagonal cracks are caused by in-plane shear forces.	In-plane shear cracks generally do not constitute a life- safety hazard. Nevertheless, this type of damage can cause extensive damage to the walls and the attached plaster, which may be historic. When large horizontal and vertical offsets occur at these cracks, repair costs may be significant and loss of historical integrity can result.
Corner damage Vertical	Vertical cracks can develop at corners in one or both planes of intersected walls.	Life-safety hazard is minimal. The collapse of an entire corner can occur when vertical cracks occur in both plants of a corner, resulting in loss of historic fabric and costly repair.
Corner damage Diagonal	Diagonal cracks that extend diagonally from the bottom.	Life-safety hazard is minimal. Slippage can occur along diagonal cracks that slant downward toward a corner. If

		much vertical slippage occur, the wall may be very difficult to repair, compromising historical integrity.
Corner damage Cross	A diagonal crack extending from the bottom corner can combine with a diagonal crack from the top corner forming a wedge- shaped section.	Life-safety hazard is minimal. A complex pattern of cracks can lead to significant offsets of sections of the walls. Damage may be difficult to repair if these offsets occur, compromising historical integrity.
Cracks at openings	Cracks often begin at the tops of the doors and openings and propagate upward vertically or at a diagonal. Cracks can also develop at the lower corners of windows. These cracks may be caused by in-plane or out of plane motion.	Life-safety hazard is minimal. The cracks that occur at the tops and bottoms of openings are typically not severe except as they affect the plaster over and around the cracks, which may be historic.
Damage at intersection of perpendicular walls	Perpendicular walls can separate from each other and become damaged by pounding against each other.	Life-safety hazard is minimal, unless other problems occur as a result of this damage. Damage to historic fabric is minimal, unless historic rendering spall.

- **Out of plane wall damage**

Adobe walls are very susceptible to cracking from flexural stresses caused by out of plane ground motions. The cracks caused by out of plane flexure usually occur in a wall between two transverse walls (Figure 40). The cracks often start at each intersection, extend downward vertically or diagonal to the base of the wall, and then extend horizontally along its length. The wall rocks back and forth out of plane, rotating about the horizontal crack at the base. Cracks due to out of plane motions are typically the first type of damage to develop in adobe buildings. Out of plane cracks develop in an undamaged adobe wall when peak ground accelerations reach approximately 0.2g. The principal factors that affect the out of plane stability of adobe walls are as follows:

- Wall thickness and the slenderness ratio
- The connection between the walls and the roof or floor system
- Whether the wall is load-bearing or non-load-bearing
- The distance between intersecting walls
- The condition of the base of the wall



Figure 40 Out of plane walls, remain following the earthquake in 2003.

The condition of the base of an adobe wall may also affect its out-of-plane stability. The following conditions lead to out-of-plane instability or increase susceptibility to overturning: basal erosion, which reduces the bearing areas; excessive moisture content, which reduces the strength; and repeated wet-dry cycles, which may also weaken the adobe.

- **In plane shear cracks**

Diagonal cracks are typical results of in-plane shear forces. The cracks are caused by horizontal forces in the plane of the wall that produce tensile stresses at an angle of approximately 45 degrees to the horizontal. Such x-shaped cracks occur when the sequence of ground motions generates shear forces that act first in one direction and then in the opposite direction. These cracks often occur in walls or piers between window openings.

The severity of in-plane cracks is judged by the extent of the permanent displacement that occurs between the adjacent wall sections or blocks after ground shaking ends (Figure 41). More severe damage to the body with a vertical displacement, that is, when the crack pattern follows a more direct diagonal line and doesn't "stair-step" along mortar joints. Diagonal shear cracks can cause extensive damage during prolonged ground motions because gravity is constantly working in combination with earthquake forced to exacerbate the damage.



Figure 41 In-plane cracks, after the earthquake in 2003

- **Corner damages**

These kinds of damages happen at the corner of buildings due to the stress concentrations that occur at the intersection of perpendicular walls. Instability of corner sections often occur because the two walls at the corner are unrestrained and therefore the corner section is free to collapse outward and away from the building. Vertical cracks at corners: vertical cracks often develop at corners during the interaction of perpendicular walls (Figure 42) and are caused by flexure and tension due to out-of-plane movements. This type of damage can be particularly severe when vertical cracks occur on both faces, allowing collapse of the wall section at the corner. Diagonal cracks at the corners: In-plane shear forces cause diagonal cracks that start at the top of the wall and extend downward to the corner. This type of crack results in a wall section that can move laterally and downward during extended ground motions. Damage of this type is difficult to repair and may require reconstruction.



Figure 42 Cracks in the corner

Combination with other cracks or pre-existing damage: a combination of diagonal and vertical cracks can result in an adobe wall that is severely fractured and several sections of the wall may be susceptible to large offsets or collapse.

- **Cracks at openings**

Cracks occur at window and door openings more often than at any other location in a building (Figure 43). In addition to earthquakes, foundation settlement and slumping due to moisture intrusion at the base can also cause cracking. Cracks at openings develop because stress concentrations are high at these locations and because of the physical incompatibility of the adobe and the beam lintels.

Cracks start at the top or bottom corners of openings and extend diagonally or vertically to the tops of the walls. Cracks at openings are not necessarily indicative of severe damage. Wall sections on either side of openings usually prevent these cracks from developing into large offsets. However, in some cases, these cracks result in small cracked wall sections over the openings that can become dislodged and could represent a life-safety hazard.



Figure 43 Cracks and crash at openings

- **Intersection of perpendicular walls**

Damage often occurs at the intersection of perpendicular walls. One wall can rock out of plane while the perpendicular in-plane wall remains very stiff. Damage at these locations is inevitable during large ground motions and can result in the development of gaps between the in-plane and out-of-plane walls or in vertical cracks in the out-of-plane wall (Figure 44). Damage may be significant when large cracks form and associated damage occurs to the roof or ceiling framing. Anchorage to the horizontal framing system or other continuity elements can greatly reduce the severity of this type of damage. Damage at the intersection of perpendicular walls is normally not

serious from a life-safety perspective. However, in the same way that corner damage occurs, adjusted walls can become isolated and behave as freestanding walls. When they reach this state, the possibility of collapse or overturning is greatly increased, and a serious life safety threat can arise. In addition, if significant permanent offsets occur, repair may be difficult and expensive.



Figure 44 Cracks and collapse at intersections

3.2 Erosion

Erosion or decay is another main reason for the damages in Bam Citadel. There is not any precise research with respect to how long the lifetime is of an adobe structure after repair. But it is clear that after a very short period of time the surfaces are damaged if there is no maintenance and repair, as deterioration has shown in Figure 45. Mud walls are very delicate and sensitive to moisture, humidity, temperature and wind; the decay always depends on the environmental conditions like humidity, air quality, deposits of the soil, and presence of water and temperature. Rapid changes in climate exacerbate matters and accelerate decay due to the crystallisation of salts, and the extent of basal erosion can be increased by abrasive action of wind and sand, burrowing by insects or animals, and plant growth.

The major difference between the behaviour of adobe and that of the other masonry materials, such as brick or stone, is the dramatic reduction in strength when adobe becomes wet. Brick and stone can become saturated and still retain a large proportion of their strength, whereas long before adobe has reached saturation, its compressive and tensile strengths may have been reduced from 50% to 90%, Keramatfar (2005). This reduction in load-carrying ability can result in material that can fall even under normal loads.



Figure 45 Erosion in adobe structure and remains

When moisture causes strength reduction to occur, adobe at first starts to deform slowly, and the rate increases as the adobe becomes wetter. A bulge at the base of an adobe wall is most often a sign of this settling or slumping. Repeated wet-dry cycles can also reduce the strength of the adobe significantly. When the clay component of the adobe repeatedly cycles from a moist to a dry state, the bonding between the clay particles and the other constituents of the adobe breaks down, which leads to a weakened material even after the adobe has dried.

It is not necessary for an adobe wall to be wet at the time of an earthquake for water to have been a primary cause of failure. The lowered strength of water-damaged adobe results in a wall that is especially susceptible to damage or collapse. Spilling of adobe or

cementations stuccos can result from the combination of the earthquake motion and a weakened bond between the adobe material and the surface rendering. If an entire wall section becomes wet or the adobe had been weakened by wet-dry cycles, the wall could fail suddenly.

3.2.1 Wind

It is a dynamic action, which causes acceleration to the structure (same as earthquake). The intensity of the forces produced is related not only to the intensity of the acceleration, but also to the natural frequencies and capacity of the structure to dissipate energy. There are three kinds of wind in Bam area:

- The prevailing wind in the summer blows from the north, the other seasons it is from the west; the average speed of wind during winter is 8 m/s.
- Dusty winds (Figure 46) blow from the south in the summer, while favourable winds blow from the north. On hot days, if warm air or dust does not accompany the winds, they will not cause any problems. However on cold days if the temperature drops below 16 degrees, the winds will be undesirable, and if it drops to lower than 5 degrees centigrade, they will be very unpleasant.
- The sand storms with speeds of 130 km/h, which cause the surface evaporation and mechanical abrasion.

Generally wind in the Citadel is a very main factor in the decay of the surfaces, but the effects of the earthquake are more intensive.



Figure 46 Seasonal sand wind in Bam area, [48]

3.2.2 Temperature

Temperature affects the resistance of materials to physio-chemical decay. Daily and seasonal alterations in air temperature and the corresponding cycles of swelling and

contraction may create or increase previous cracks that can trigger or accelerate deterioration, Croci (1998). The average temperature in Bam is 22.6 degrees centigrade.

The temperature has risen as high as 46.6 degrees in the summer and fallen to 9 degrees below zero in winter. However, the average high temperature in Bam is 39.5 degrees and the average low temperature is 4.9 degrees centigrade. There is an annual average 8 days of frost, and the longest period of frost 24 days was in 1972. Therefore, we can say that in Bam the winters are very short and moderate, while the summers are long and hot.

3.2.3 Rain and humidity

Water interacts with the constructions mainly in the form of rain, snow, ice and ground water and as we have seen, contributes to the moisture content of masonry in different

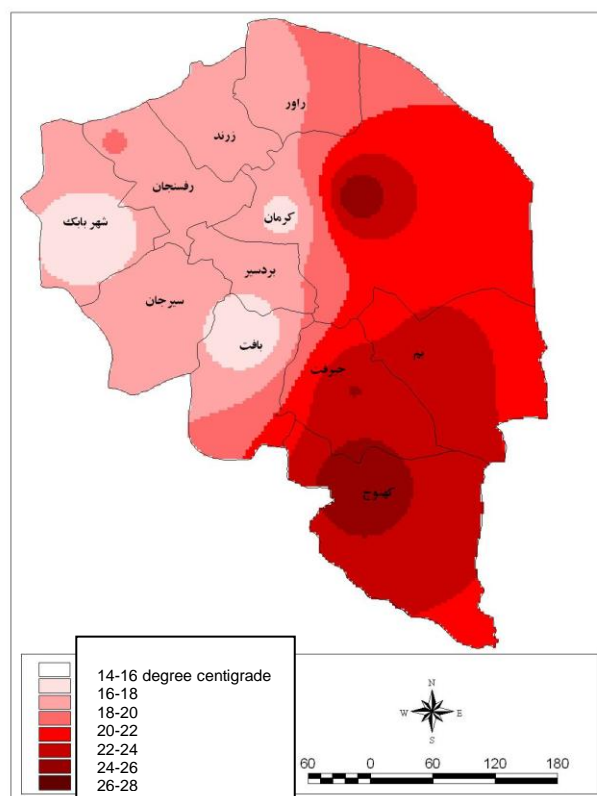


Figure 47 Temperature in Kerman Province, [50]

ways. Rain and snow, whether flowing over the surface or penetrating deeply into the structure, generates changes in porous materials such as masonry, plaster, and wood. Ice is another cause of decay, especially when it penetrates existing cracks, which are then gradually widened and deepened; this process happens seldom and is not serious in Bam region. But the main cause of the serious damage is seen on the surfaces where rainwater is easily able to penetrate the cracks produced by earthquake. Because the Citadel is located in an arid area, the ground water (capillary action) does not play an important role in damage.

The statistics acquired on rainfall in Bam are as follows:

- Annual average of rainfall: 64.1 mm
- Average highest daily rainfall: 15.4 mm
- Maximum number of rainy days per months: 3 days

The conclusion is that the level of rainfall in Bam is very low indeed; the problem is the duration of rainfall is very short but intensive, and thus damages the façade and edges in a short time.

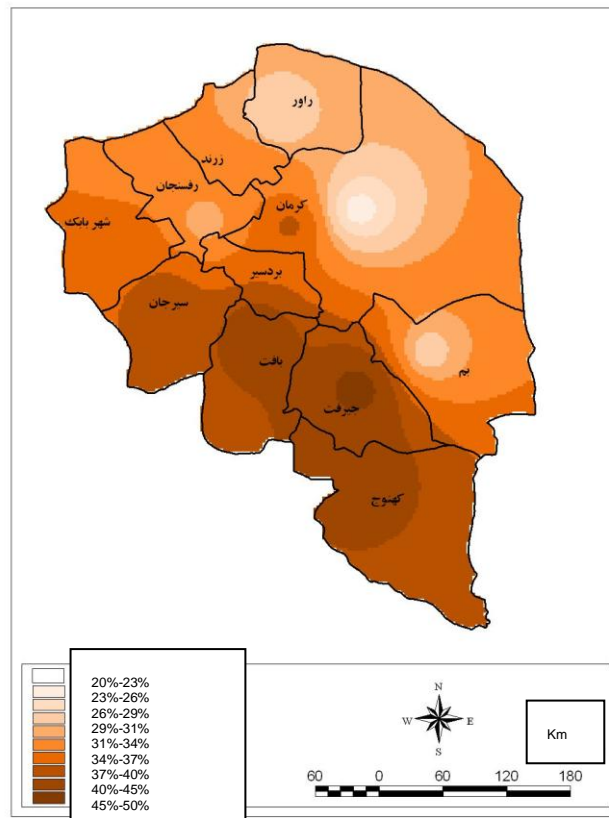


Figure 48 Relative rainfall in Kerman Province, Climate Report (2005), [50]

The amount of the sunlight in Bam is as follows:

- Annual average sunny hours: 3173 hours

Minimum and maximum sunny hours during the cold periods of the year:

- Minimum number of sunny hours during the month of March: 212 hours
- Maximum number of the sunny hours during the month of January: 345 hours

Water is the most serious non-seismic threat to adobe buildings in areas of both high and low seismicity. It can damage the adobe walls by actually eroding away portions of the wall and by reducing the strength of the adobe material.

Basal erosion, the disintegration and loss of a portion of an adobe wall at its base, can be caused by:

- Condensation of water vapour present in the air, bringing with it the pollution contained in the atmosphere
- Rain; by leaking through roofs and other surfaces
- Surface water; splashing up against the base of the wall
- Water being drawn up into a wall by capillary action and then diffusing to the wall surface to evaporate

Regardless of the cause of the basal erosion, the result is that the area of the wall available to carry the loads imposed on it is reduced. When the loads exceed the compressive strength of the material, failure occurs. It is also conceivable that a wall could become sufficiently unstable to be subject to overturning if enough material is eroded from one face of the wall.

When it rains in Bam two events happen:

- The thickness of the walls decrease (especially at the top)
- The moisture at the base weakens the wall and weak plane can develop. The upper section of the wall can then slip and collapse along this plane; the adobe at the base of the wall will have weakened and it will appear that the wall has slipped along this plane and collapsed.

3.2.4 Biological damages

Generally biological pollution is caused by deposits of soil containing moulds and insects, and the mechanical action of roots. The acids contained in the excrement of birds, particularly pigeons, produce physio chemical corrosion, while the excrement itself is a source of bacteria that can act as a fertiliser for vegetation. In the citadel the most important reason for the rest of the damages come from termites, Figure 49. The temperature and climate are such that the following kinds of animals and insects could be harmful termite, rodent, and snake.



Figure 49 Termite in the Bam Citadel

The lack of green plants inside the Citadel means that the effect of the insects is minimal. Termite effects on adobe structure were studied^{xxii}. Tensile elements which were inserted on the higher level of the wall were prevented from the termite attack. The reports show that termite has found in a few parts of the citadel not in Sistani House. The treat of the termite in different environment and on a few material were tested. According to the result wooden surfaces and clay mortar mixed in higher proportion of straw are more exposed by termite than the dead and dried palm fibres. Termite damaged a ten year old door of the house but it has not been any damages on reinforced adobe in the Sistani House yet, [14].

3.2.5 Human

There are two kinds of human damage in the Citadel; the one caused by usage or by war and the one caused by an incorrect intervention:

- Mistakes in design and performance; without using the engineering knowledge of restoration and neglecting the dynamic behaviour of the structure, a very invasive crash happened in the stable, Figure 50.



Figure 50 Collapse because of neglect of the engineering calculation for the buttress, [53]

- Absence of connection between the load-bearing parts plays a substantial role in reducing the degree of collapse in the earthquake, Shad (2008). Croci in his book has emphasised both lack of scientific knowledge and lowering of the strength as important factors in intensifying the erosion of historical buildings, Croci (1998).
- Changes and replacement in management cause varying the priorities in a restoration project, especially when there is not any regulation or legislation preventing the same. Political challenges are always a serious threat for cultural heritage and for Bam Citadel.

This part ends here, as the subject of this research is wide and not relevant to my thesis.

^{xxii} For more information, see the minutes, correspondances and reports of Bam Project at Fakultät Architektur Lehrstuhl Tragwerksplanung, Technische Universität Dresden, November and December 2008 & March and April 2009.

3.3 Comparison of erosion and earthquake

It is a comparison of the natural lifetime of a structure and the condition when disasters like the earthquake of 2003 happened. There are sudden changes occurring constantly throughout the universe, but such events are noted in history for their effects on mankind rather than as disasters, [41]. Randolph Langenbach has an article in which he effectively explains the differences between the earthquake and erosion; he says that earthquakes are unique among natural disasters because they come with very little or no warning, [40].

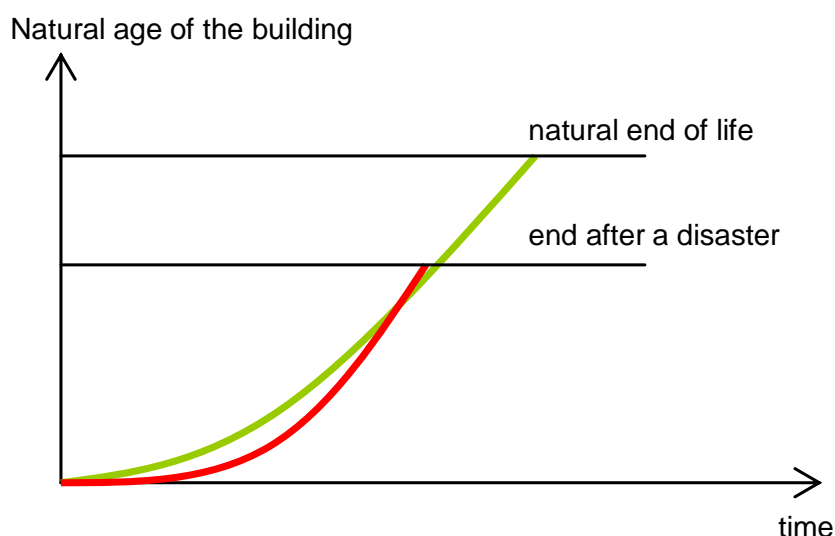


Figure 51 Erosion and sudden disaster

Decay or deterioration is an alteration of material that usually leads to a reduction in resistance, increased brittleness, porosity and a loss of material that usually begins from the outside and works inward; it is mainly related to physical or chemical actions. However, every building is designed with a more or less consciously predetermined life expectancy. This may vary from decades to centuries, depending on rapid evolution of factors such as functionality, convince, maintenance costs and so on^{xxiii}, Croci (1998). In a disaster, the natural lifetime of a structure dramatically decreases and it is faced with an end that may happen after centuries in normal situation, as has been shown in Figure 51.

^{xxiii}This concept is implicit in the formulation of modern codes in which safety coefficients and probability the critical situation will arise, at prefixed in relation to a certain life expectancy for the structure.

4 Intervention plans

In this part, the aim is to analyse and describe how an optimum decision could be made about intervention in a valuable historical site, which has already experienced a huge earthquake and will be faced with next earthquake in the near future. At first and according to the previous chapters, for any case there are three important parameters which should be considered for an accurate decision, as shown in Figure 52; the values and significance of the building, the new usage and function of the building after restoration and the damage level of the building both in the past disaster and future risks; all three items are very important. Depending on the case, the priorities and, therefore, the usage of the techniques and methods may vary.

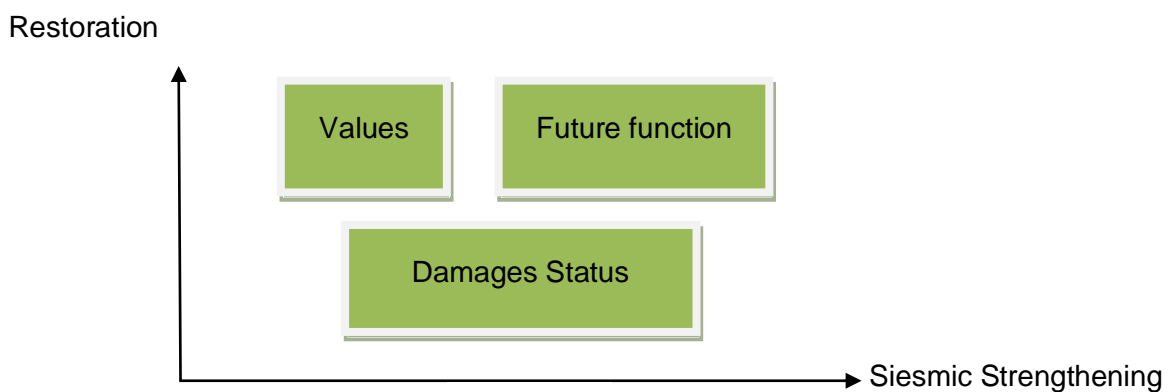


Figure 52 Three main items to consider when making a decision

4.1 Seismic strengthening strategies

4.1.1 Preventive restoration; minimum level of intervention

The three following kinds of interventions have been done to keep the remains; it should not be considered just as a secondary activity but should have an overall plan, covering both periodic and exceptional operation. Here, the question is how damaged buildings can be protected with this strategy after the earthquake in 2003 in Bam, and if buildings or monuments can survive just by a minimum level of intervention. It seems that the measures will not be able to cover the future damages in the next earthquake in Bam. The next question is whether the speed of deterioration and the earthquake time history allows us to follow these kinds of maintenance instead of an intensive restoration or not. EU-INDIA, [10], is an interesting research about that and has pointed to the following classification for adobe structure:

- Preventive maintenance: a detailed maintenance programme is laid-out in order to ascertain the conservation of the present condition of the building in the long term. Preventive maintenance should be carried out using historical or traditional practices (refilling of the mortar losses, substitution of deteriorated individual parts).

- Preventive surveillance: a monitoring programme is undertaken to gather additional information on the response of the building and to assess the maintenance of its condition in the long term.
- Preventive repair: in the case of damaged structures, repair may be executed to recover (partially or totally) the strength capacity of the building. The damage is repaired using traditional or historical techniques and materials. No strengthening is actually implemented.

By the way, EERI 1994 also offers this strategy for buildings located in low seismicity areas. It is also applicable in high seismicity areas in the case of structures showing satisfactory seismic resistant qualities. Repair may involve the recovering of the continuity across cracks or separation may cause large discontinuities, local substitution of deteriorated individual blocks, unreinforced repointing or local improvements of the material strength. It can be applied to Bam Citadel, but after a comprehensive restoration and reconstruction.

4.1.2 Structural survivability, restoration; moderate intervention

A light strengthening is implementing discrete (concentrated) strengthening using light, non-invasive mechanical devices, produces no alteration of material properties and only a limited alteration of the global structural properties, [10].

Techniques are such as tying, strutting, prestressing, and stabilizing by means of devices. Local improvement may be also considered. This approach may be aimed to prove the optimal solution in terms of cost-benefit analysis, the cost being the loss of cultural value, the benefit the gain in seismic resistance. In low to medium seismicity areas, the strategy may provide a very satisfactory level of seismic response. In high seismicity areas, light strengthening may in some cases provide only a partial improvement. The acceptability of “seismic improvement” (where applicable) should lead normally or preferably to light strengthening solutions, even in high seismic areas; it is interesting to note that reversibility in the adobe building has another meaning, because in most of the parts, the units have already been replaced and changed to keep the utility of the structure. Then authenticity, in the adobe buildings, refers to the form, material, dimensions, and the units but not to the originality of the adobe bricks. Adjusting this description to the measurements of the Citadel, either the restoration or reconstruction of the building with traditional methods, or with a moderate intervention, is an effort to protect the continuity of the structure; all of these procedures are not reversible.

4.1.3 Public safety, reconstruction and providing function for the building

EU- INDIA has classified the strengthening methods to two categories, each of which depends on the level of the upgrading. To provide the continuity between two parts, new and old, requires a specific engineering plan. If either a ten percent of the damage exists or a total collapse happens, the strengthening method is irreversible, invasive and maybe with maximum intervention to provide a reliable situation for people; generally in this case the cost is the second priority:

- Extensive strengthening partial upgrading: includes extensive operations affecting a large part of the building. The technologies use are distributed in a smeared (continuous) way across significant volumes or parts of the structure. The operations involved may be irreversible and invasive to significant extent. The strengthening implemented produces an alteration of the material and mechanical properties of a large number of the elements or of the entire structure. The structure may be forced to work in a modified way with respect to its original design and resisting mechanisms. The strengthening is also mobilized by permanent or frequent actions (gravity, wind). The

techniques are such as enlargement (backfilling), reinforcing, continuous confinement, local tying, stitching, extensive improvement (injection), and might include actions at the level of the foundation (e.g. micro-piling). In the case of partial upgrading, these operations are undertaken to cause only a partial, but very significant, improvement of the seismic response.

- Extensive strengthening, full upgrading: techniques similar to those mentioned above are used to achieve the safety level required by a seismic regulation for a modern building in the same location.

4.2 Specificity of design

There is not one solution applicable to a wide number of structures. Each monument is a unique case showing particular construction, structural features, its own material, actions experienced and specific problems. Solutions can not be standardized and must be conceived specially for each building. The process leading to the conception of a solution must take into account the status of the construction, historical and cultural values, physical and mechanical features and the new designed function the; the resistance of the structure, the existing damages and the threats also are to be based on a final decision both from structural and architectural points of view.

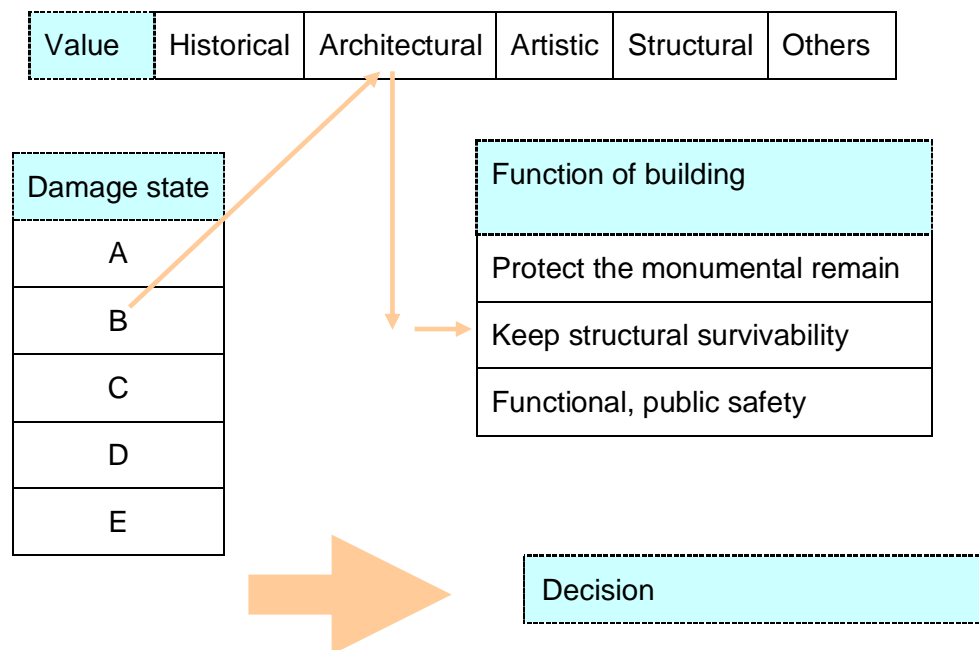


Figure 53 Three main items to make a decision

Furthermore, there are no general methods leading to satisfactory solutions. Not only the solution itself, but also the method used to drive it, cannot result from all-purpose strategies.

Whatever the approach used to reach an optimal solution, it completely depends on understanding of the building and its problems. The design of the intervention must be based on knowledge about the structural nature of the building, the real cause of the

alteration and the need for additional safety. Historical significance of the building and its cultural context is necessary to define as well. The knowledge gained through the previous phases of the study (survey, diagnosis, safety assessment) is finally to be invested in the design of adequate strengthening or repair actions.

In the following diagram (Figure 53), there is a chart, which shows how a restorator can decide according to the items.

4.3 Design requirements for interventions

4.3.1 Respect for structural authenticity

Monuments are not only valuable from artistic or geometrical points of view but also they constitute a structural achievement. They are important because they still carry out their resisting mission and keep on enduring loads, winds and earthquakes; they are a living and persistent proof of the skills of their creators and builders. A proper restoration of monuments must focus on preserving the original condition of the structure. If repair or strengthening work is needed, it should be the minimum possible alteration. This is not only applicable to the geometry and materials but also to the mechanical and structural response (the nature of the structure and its resisting mechanisms is also to be preserved).

4.3.2 Minimum impact

Interventions causing only a reduced impact on the original structure should be undertaken, provided that they are enough to warrant the required safety level. After considering possible solutions, providing the required level of safety, the one causing minimal alteration should be selected.

4.3.3 Structural safety

In conventional structures (not belonging to the cultural heritage), seismic retrofit is primarily applied to achieve public safety, with various levels of structural and material survivability determined by considerations related to the importance of the buildings, among which are:

- **Public safety:** The goal of public safety is to protect human life, ensuring that the structure will not collapse upon its occupants or passers-by, and that the structure can safely exist.
- **Structure survivability:** the goal of structure survivability is that the structure, while remaining safe for exit, may require extensive repair (but not replacement) before it is generally useful or considered safe for occupation.
- **Structure usability:** the aim of the structure usability is to prevent from diminishing its utility, although it may be necessary to perform extensive repair or replacement of components in preparation for the next major seismic event; this is typically the safety level required for the fire fighting stations, public safety (police) command centres, and the like.

4.3.4 Compatibility

The material and the technical devices used for repair or strengthening must be compatible with the original one.

- **Chemical compatibility:** ancient material should not experience any form of chemical deterioration when in contact with the new material or with substances delivered by them.

- Rheology compatibility: new material should not experience rheological phenomena causing possible damage (such as cracking) to the existing material.
- Thermal compatibility: new materials or mechanical devices should not behave too differently from the originals when subjected to environmental thermal variations.

4.3.5 Durability

The safety of the structure can be compromised by the loss of efficiency of the strengthening. Lack of durability leading to the decay of the new material can, in turn, convey damage to the original parts.

4.3.6 Specific requirements for urgent remedial operations

In some cases, the appreciation of an intensely damaged condition in a structure after the effects of earthquakes or any other catastrophic event may lead to the implementation of an urgent remedial measure to prevent further deterioration or a possible collapse. By definition, an urgent remedial operation will be laid-out in a very short time without the possibility of carrying out detailed investigations or studies and will normally have a provisional character. A more perfect solution, more adequately adapted to the problems of the structure and more carefully designed will normally substitute the one initially implemented. Because of this provisional character, urgent remedial operations must comply with some specific conditions. Urgent operations should normally be devoid of any form of intrusiveness and should not only be removal but even fully reversible. The removal of the provisional strengthening must be fully viable, and it must be possible to dismantle it under controllable conditions.

4.4 Analysing the different strategies and decisions in seismic areas

Accepting the concept of improvement implies the possibility of a widespread choice between possible minimal and maximum interventions. The minimal one is related to all the operations consisting of maintenance or minor repairs. The maximum one can be associated to a full upgrading of the structure to ensure its capacity to resist in a future earthquake, with very limited damage. It is related to the newest progress in science and technology.

4.4.1 Strengthening solutions based on seismic improvement

The earthquake to be considered for this purpose should be the one defined by the national seismic code for the location of the structure, or even higher depending on the importance of the building. The role of the designer is to select a level of improvement contained within these two extremes.

It is very difficult to have a model that has been adjusted to a real situation. It is a very complicated equation, which contains many kinds of variations. Rather than thinking in a continuous way, it will be more practical and realistic to consider just a limited (discrete) number of possibilities. In practice, the designer should suggest a number of different possible solutions (S_1 , S_2 , S_N) based on different techniques or characterized by their different cases. For each solution, an attempt should be made to determine the improvement of the seismic response and the loss in cultural value. By arranging the solutions according to their seismic upgrading capacity, a bar diagram similar to that of figure 48 will be obtained.

A diagram of this kind is useful to help determining solutions with an adequate cost/benefit ratio. For example solution S_4 and S_7 provide higher seismic upgrading with a lower cost for those other solutions. As in the case of Figure 54, the diagram helps to visualize a certain group of solutions for which significant seismic upgrading is possible at a very limited cost (solutions S_1 to S_4) and among them a solution producing the best relationship between cost and benefit may be also identified.

The optimal level of improvement might be decided through the consideration of a cost-benefit analysis, where the cost is the loss of cultural value and the benefit is the improvement of the seismic response. This analysis, however, is difficult to carry out because both variables (loss of cultural value and improvement of seismic response) are difficult to quantify in an objective way. Besides, both the cultural value and upgrading efficiency are multidimensional and complex variables which, in fact, cannot be summarized in a single scaled parameter.

The relationship between seismic upgrading and loss of cultural value can be presumed to vary according to Figure 55, [10]. In this case, seismic upgrading will cause limited loss up to point O; however, further improvement beyond limited by O will cause a very significant loss.

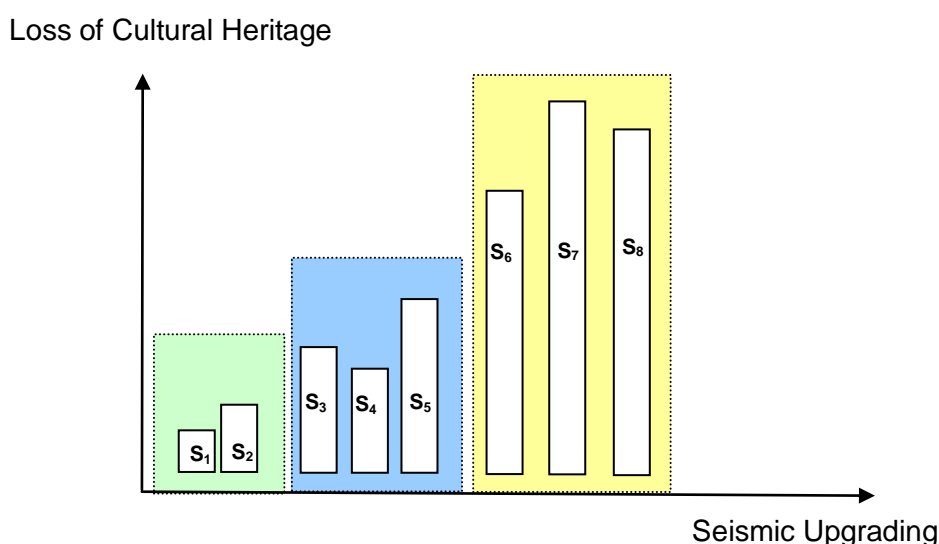


Figure 54 Classification of possible solution $S_1... S_8$ in different categories depending on the extent of the transformation caused [10]

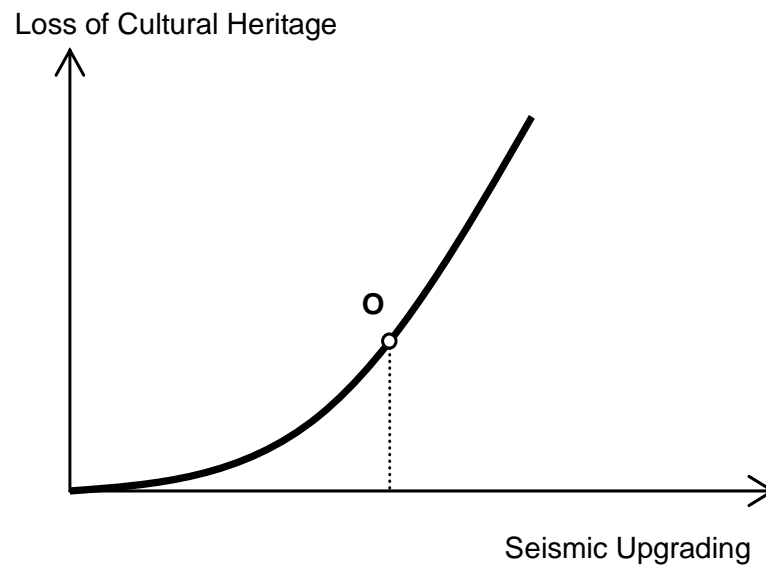


Figure 55 Possible relationship between seismic upgrading and loss of cultural values caused by intervention, [10]

As reference mentioned for other structures, the diagram may show a different profile, moreover, different expected upgrading techniques might produce different diagram shapes.

It seems reasonable to select a level of improvement contained within the origin and limit O; furthermore, it seems also reasonable to prefer a level of improvement close to the limit O as a way of obtaining maximum benefit in terms of strengthening upgrading while still keeping the loss of cultural values within acceptable limits.

4.4.2 Selection of the strengthening solutions based on acceptable damage

The selection of the optimum upgrading solutions can be based on the minimization of the possible losses caused by the earthquake. In the case of the monuments, the losses to be included are:

- The cultural loss which may be caused by damage or destruction produced by the earthquake in the immovable heritage (structure and immovable contents).
- The loss that the seismic event may cause in the form of injuries to people or casualties and in terms of cultural loss in the movable heritage stored inside the building.

The strengthening strategy to be implemented should be oriented to minimize the cost associated with both types of losses. However, these are costs of a very different nature and cannot compare or be included in a single variable. In the present guidelines, no attempt is made to integrate both in a single decision-taking procedure. Instead, they are

considered and linked to the decision-making procedure separately as described in the following sections. In the procedure proposed the selection of the strengthening strategies is based on the evaluation of the potential immovable cultural losses. The aspects related to human safety and movable heritage are considered after the selection of a possible strengthening strategy with the purpose of validating the use intended for the building.

It is important to make a clear distinction between the types of damage meant by the implementation of the strengthening and the one potentially caused by the earthquake. The strengthening will be obviously designed not to cause any deterioration to the fixed artistic heritage but may include actions of irreversible and invasive character (insertion, injection) in the structure. The potential damage due to the earthquake (including deformation, cracks and even partial or total collapse) can destroy the artistic heritage.

4.5 Acceptable damage

The conventional objective of seismic upgrading of normal buildings lays mostly in public safety. Public safety is also one of the aims of the seismic upgrading of the monuments. The aim is to ascertain the stability of the building during earthquake and thus preventing unacceptable risks to people. As for modern buildings, a certain degree of damage is acceptable. The budget allowed public safety and that for maintaining cultural heritage must change when an earthquake occurs. The cost of rebuilding and repairing after an earthquake necessitate spending on the same. Three different situations can be envisaged, at least, regarding the amount of acceptable damage in monuments:

4.5.1 Acceptable damage linked to structural integrity

Some damages, including deformation and cracks, are acceptable. In general, damage to occur should comply with the following conditions:

- Damage should be repairable using traditional or historical techniques for repair or maintenance (substitution of a limited number of stones, refilling of joints).
- Additional or irreversible damage should be acceptable to a very limited extent.

The cost of loss in immovable cultural value caused by the damage due to the earthquake must be smaller than the corresponding cost caused by a more heavy and invasive strengthening designed to prevent this damage.

4.5.2 Acceptable damage linked to public safety and movable contents

The need to avoid injuries or casualties in buildings that normally host large amounts of users or visitors, and avoid losses of significant movable heritage, which normally is present in architecture heritage buildings, should lead to seismic upgrading. This would prevent any kind of damage that can compromise the safety of people. Even in these cases, certain damage might be acceptable (some cracks deformation) provided it does not cause significant risk to people. For instance, limited cracking and deformation may be acceptable, provided that they do not compromise the stability of the buildings.

4.5.3 Acceptable damage linked to the integrity of fixed artistic heritage

The case of buildings containing a very valuable and fixed artistic decoration requires another approach. In these cases, the possibility of accepting certain damage is limited by the possible deterioration that even small cracks and deformation may cause to the artistic contents.

4.6 Selection of solution

The selection of a possible strengthening strategy should be determined from the consideration of the aspects mentioned; seismicity, structural design, state of conservation, new function and with notice to the level of acceptable damage.

Two different conditions, to be simultaneously complied with, are proposed in order to select an adequate strengthening strategy.

The first proposed condition addresses the requirement for a seismic upgrading preventing unacceptable losses or damage. In short, the losses caused by the design earthquake should be limited to the acceptable damage:

4.6.1 Condition 1

Losses due to earthquake in strengthened building < Acceptable damage

The terms in the above condition should include the damage or losses caused in both the structure and fixed artistic heritage (frescoes, decoration) existing in the building. That way, the equation is applied also for the case in which the main aim of the seismic upgrading is preserving the integrity of existing fixed artistic heritage. Condition 1 is intended to provide a minimum requirement of seismic upgrading. Figure 56 illustrates the application of this condition. A possible relationship between the potential cultural loss and risk is compared with the corresponding curve for structure upgraded according to different strengthening solutions S_1 , S_2 , and S_3 . All the solutions cause a cost for even null risk C_{01} , C_{02} , C_{03} due to the alteration of the structure meant by their implementation. In turn, all the solutions are meant to improve the response of the structure (and thus to reduce the potential losses) to a certain extent.

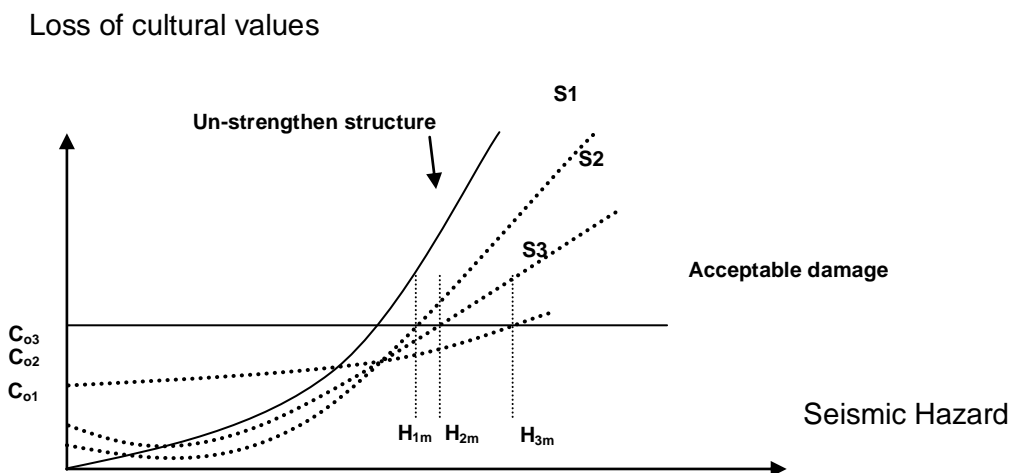


Figure 56 Possible relationship between hazard and cultural loss for different seismic upgrading solutions S_1 , S_2 , S_3 . Upper hazard levels associated to the different solution, [10].

According to condition 1, a certain solution S_i causing upgrading effect, should be only used for seismic hazard levels above the value H_{in} , where the corresponding curve intersects that of the unstrengthened structure. For any solution, a sort of minimum seismic hazard can be determined, below which the solution should not be used. A second condition is introduced with the purpose of limiting the losses caused by the implementation of a seismic strengthening. It is proposed to limit the possible cost in cultural values caused by the strengthening operation itself to the possible costs or losses that could be caused by the earthquake on the structure in its un-strengthened condition.

4.6.2 Condition 2

Cost of implementation < losses in unstrengthened buildings due to the earthquake

In other words, the cost of the implementation of the strengthening should never be larger than the potential losses caused by the earthquake. Figure 57 illustrates the application of condition 2. An acceptable damage level is set up in order to determine the best strengthening strategy. The level of acceptable damage does not depend on the seismic hazard; it is essentially derived from the characteristics of the structure and its possible artistic contents. The intersection of the horizontal line describing the acceptable damage with curves corresponding to a possible solution S_i will provide a limit H_{im} for the maximum seismic hazard, for which this solution is suitable. The combination of conditions 1 and 2 will lead to determination of a degree of acceptance, in terms of seismic hazard (H), for any possible solution, $H_{in} < H < H_{im}$.

Loss of cultural values

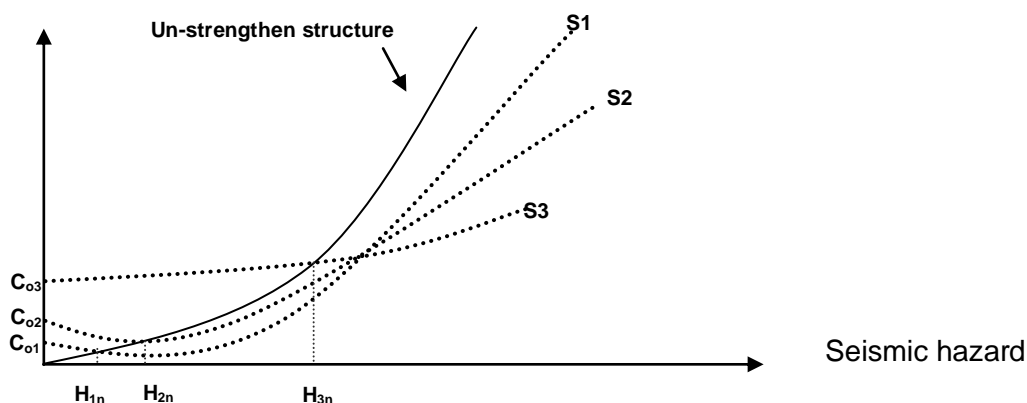


Figure 57 Possible relationship between hazard and cultural loss for different seismic upgrading solutions, [10].

Among the acceptable solutions for a seismic hazard H (the ones complying with the above equation), the one showing the stricter H_{im} limit is preferable because it will normally cause the lesser C_{oi} cost. A solution for which the limited H_{im} equals the seismic hazard H would be an optimal one, causing the lesser necessary cost C_{oi} .

This criterion is intended to work also for historical buildings with severely limited acceptable damage due to the existence of fixed artistic heritage. In these cases, the artistic heritage is to be preserved intact (or almost), which requires a very low structural

damage on the strengthened structure in the case of an earthquake. Conversely, it will be acceptable to cause a certain loss of cultural values on the structure by implementing significant (and structurally altering) strengthening.

For a construction of this kind, the diagram relating cultural loss and seismic hazard will look like the one in Figure 57, with the more restrictive curve to limit the acceptable damage and comparatively larger initial loss caused by the implementation of the strengthening.

5 Expected outcomes

5.1 Bam Citadel in the future

Since 1966, Bam Historical Complex has been designated as a National Heritage Site and has been under repair and conservation since 1972. The management plan has been provided with policies, goals and activities since 1993. According to this plan, the following items were expected to be done before the earthquake in 2003, [55]:

- Obtain more precise data about original core and processing of the construction during the historical lifetime of the Citadel and present it in drawing, photos and text.
- Follow the above with two main activities; organizing the site of Bam Citadel and the related zone for research and investigation by experts, students and professionals and conveying the value and other significant factors of the complex both to the researcher and to tourists.

The main aim was to repair the site adequately so that the architectural plan was understandable, whereas the façade would be kept intact as much as possible to showcase the historical layers to visitors. In this regard this document suggests that the Main Walls, the alleys, squares, urban facilities and valuable dwellings, and public buildings should be under repair and restoration.

This document also emphasizes the holding of professional conferences (two International Urban and Architecture conferences were held in Bam Citadel before the earthquake in 2003), training activities in the Citadel, and establishing some service places for public information, a museum and restaurant for visitors.

The measures during these years were a very primitive kind of restoration, utilizing only the traditional skill of the local masons according to the archaeological investigation. New technology and engineering knowledge have been neglected, in fact, being faithful to the shape and forms and trusting to the local knowledge and skill of the masons caused problems during the unexpected earthquake on 3 December 2003, [69].

The second Comprehensive Management Plan was written with the cooperation of UNESCO and Universities of Iran on 25 January 2010, [58].

According to both plans for Bam Citadel before and after the earthquake, there is an important cultural function. Especially on one hand, the ceremonies that keep Bam Citadel alive and on the other hand the opportunity for local people to practice their own traditions in the mosques and other holy places in Bam Citadel.

5.2 Lessons from history and last restorations and repairs

The following diagram shows the cycle of destruction and repair in Bam Citadel; war occurred and, after conquering a local ruler, a peaceful status resulted on average, every 100 years, [38]. But on the other hand all these repairs happened to improve the situation of settlement and trade. Later it was for the civil purposes and before becoming abandoned in 1864, it was considered neither a significant nor a cultural heritage property, Figure 58.

It seems that all the maintenance to be done by local masons when they felt themselves in secure situations and the invasive interventions has been ordered by the victorious local rulers.

There has definitely been a remarkable difference in the maintenance and conservation since Bam Citadel has been considered a significant historical property. The historical periods of Iran since there have been written documents are:

Seljukid Empire (1037–1194)
 Khwarezmid Dynasty (1077–1231)
 Ilkhanate (1256–1353)
 Muzaffarid Dynasty (1314–1393)
 Chupanid Dynasty (1337–1357)
 Jalayerid Dynasty (1339–1432)
 Timurid Empire (1370–1506)
 Qara Qoyunlu Turcomans (1407–1468)
 Aq Qoyunlu Turcomans (1378–1508)
 Safavid Empire (1501–1722/1736)
 Hotaki Ghilzai Dynasty (1722–1729)
 Afsharid Dynasty (1736–1802)
 Zand Dynasty (1750–1794)
 Qajar Dynasty (1781–1925)
 Pahlavi Dynasty (1925–1979)
 Islamic Revolution (1979)
 Provisional Government (1979–1980)
 Islamic Republic of Iran – present

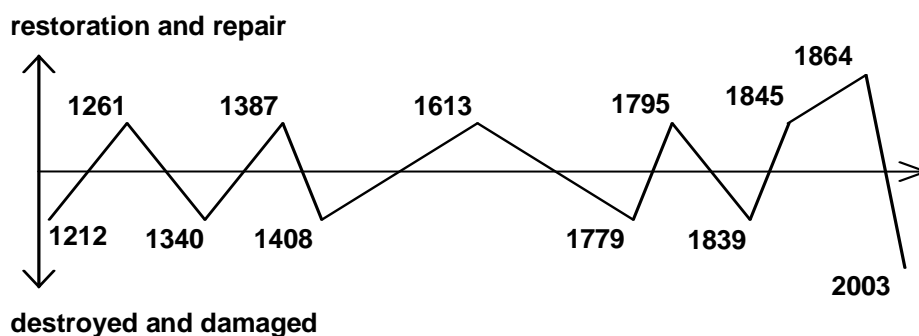


Figure 58 Cycling of destruction and repair in Bam Citadel

5.3 Effects of previous restorations

Table 3 shows the dates of deterioration and repair in the Citadel, Karimi (2005):

Table 3 *Deterioration and reconstruction according to the history*

Year (Hijri)	Year (After Death)	Situation
609	1212	destroyed
660	1261	reconstructed
741	1340	destroyed walls
789	1387	reconstructed
811	1408	destroyed
1022	1613	reinforced and rebuilt
1193	1779	destroyed
1210	1795	rebuilt
1255	1839	destroyed
1261	1845	repaired and restored
1281	1864	abandoned

These dates show that:

- According to the historical references the longest period of time for repair was 205 years and the shortest was 6 years.
- Some written historical texts exist about the history of war in the Citadel an average of 67.1 years for repair and restoration out of 672 years of the lifetime of the Citadel, since 1212 up to 1281.

Considering that:

- The terminology of the historian about describing the repair and restoration, and the amount of damage to the records is not very precise and therefore does not quantify the data.
- For two long durations -205 and 166 years- I could not find any references.

The International Institute of Earthquake Engineering and Seismology (IIEES) has classified earthquake history in Iran into two periods of time: Pre-Islamic and After-Islamic Important earthquakes. Figure 59 shows the historical earthquakes and the active faults in Bam Area:

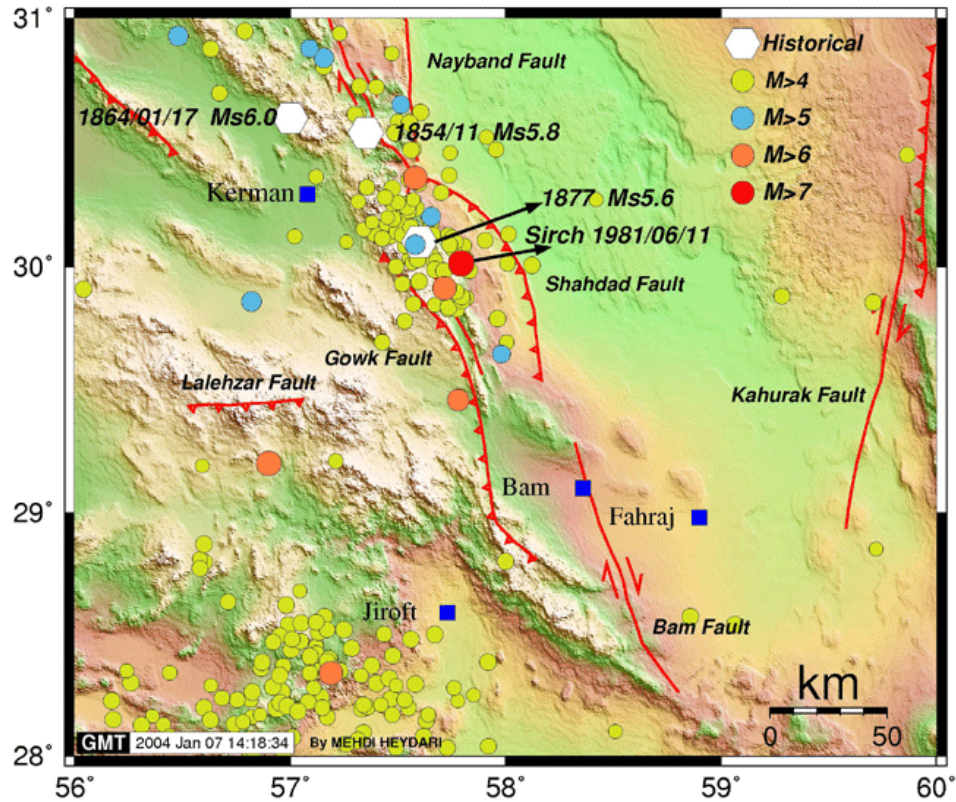


Figure 59 Magnitude of historical earthquake in Bam Area, [65]

According to the Code 2800, [6] , Bam is classified as a risk area for earthquakes; whereas the preliminary magnitude estimated as $M_s=6.5$. IIEES^{xxiv} has studied aftershocks (Figure 60); about 100 aftershocks happened there, [66]; for more information consider attachment number one. There were three aftershocks with $M_s>4$ and the shocks were recorded at least about one month after main earthquake on 26 December 2003.

^{xxiv}International Institute of Earthquake Engineering and Seismology.

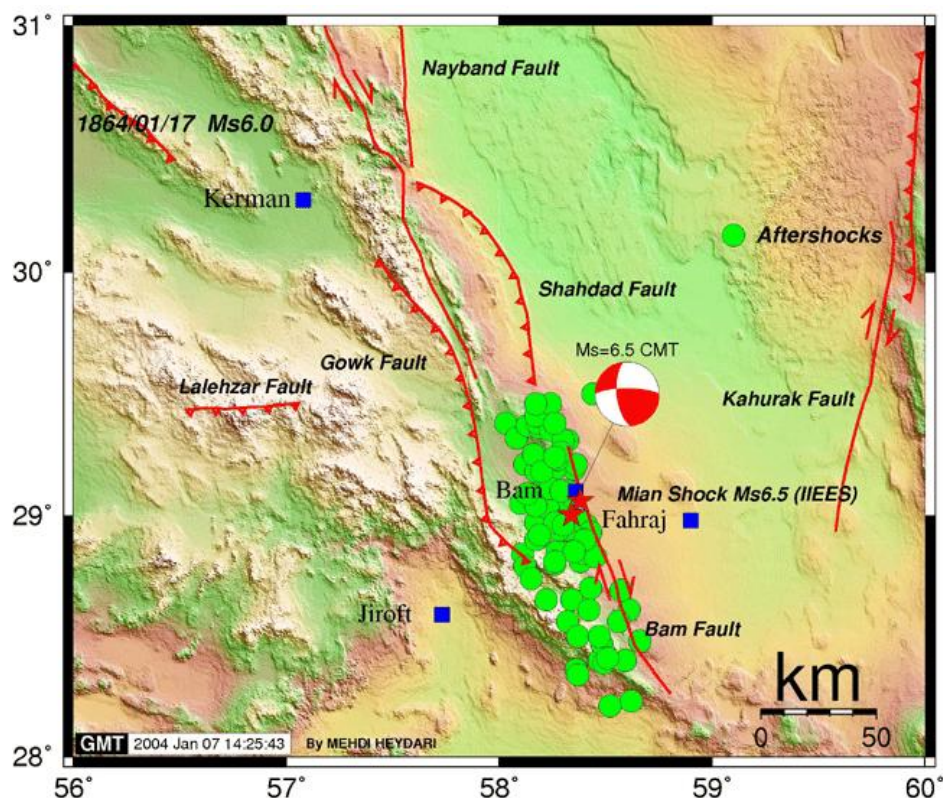


Figure 60 Aftershocks in Bam area after the main earthquake 2003, [66]

Zare M.^{xxv} has a report on the primary investigation of the seismic area and has studies about the Bam fault. According to his report there is not any precise document about the historical earthquakes in Bam, he claims, the survival of ancient Bam Citadel proves, [70]. Table 4 indicates to the seismicity of the region of Bam, within 100 Km from the City of Bam.

Table 4 Seismicity of the Bam region, within a 100 km distance from the city of Bam, [67]

Date			Time			Coordinates								
Y	M	D	HH	MM	SS	Lat.N	Lon.E	FD	mb	Ms	Mw	Efa	Ref	Reg
1948	07	05	13	53		29.460	57.780	0	5.9	6.0	.0		Amb	Gow
1962	09	29	06	54	00	28.290	57.480	83	5.5	.0	.0		N.US	
1964	05	11	06	07	38	28.220	57.390	73	5.3	.0	.0		N.IS	
1964	08	27	11	58	39	28.160	58.830	50	5.1	.0	.0		N.IS	
1976	11	13	10	12	36	28.250	57.340	62	5.0	.0	.0		ISC	
1981	06	11	07	24	25	29.895	57.718	30	6.6	6.0	.0	*	ISC	Gol

^{xxv}Dr. M. Zare has done the primary investigation on seismic area for Bam earthquake; he is the assistant professor at International Institute of Earthquake Engineering and Seismology or IIEES.

1981	07	28	17	22	23	29.987	57.770	11	5.9	7.0	.0	*	ISC	Sir
1981	10	14	09	12	39	29.900	57.758	43	5.2	.0	.0		ISC	
1982	10	15	02	53	55	28.280	57.398	83	5.0	.0	.0		ISC	
1983	01	31	18	56	53	28.919	57.318	133	5.0	.0	.0		ISC	
1984	10	11	05	09	27	29.539	58.030	48	5.1	.0	.0		ISC	
1986	07	25	10	08	09	28.068	57.303	69	5.2	.0	.0		ISC	
1989	11	20	04	19	04	29.880	57.721	18	5.5	5.7	5.9		ISC	South
1998	06	10	08	30	16	28.227	58.507	113	5.0	.0	.0		ISC	

Most of the earthquakes damaged the buildings, destroyed the villages and killed some people. In 1981, two earthquakes happened in Kerman province, the first one happened 11th June and the specification shows $M_s=6.8$ and $m_b=6.1$; about 1071 persons died and 4000 persons were injured. This earthquake also had vertical movement, [68] [71] .

The next one happened on 28th July and $M_s=7.1$. It was the strength of the earthquake in Bam area, in which 1300 died, 915 injured person and about 25,000 people lost their houses, [68] [71].

With this history, it is easy to understand why people could not trust the adobe building as a construction material and their needs for building with the material, which could survive earthquakes after 26th December 2008.

5.4 Next earthquake in the Citadel

The question, which comes to mind, is when the next earthquake will happen. Perhaps it is an important fact that, in Iran, we always live between two earthquakes. The earthquake, which has already happened; and one, which will occur sometime in future. Definitely the answer is very difficult.

Seismic hazard maps, which have been prepared by IIEES, indicate the earthquake hazards of Iran the forms of iso-acceleration contour lines, and seismic hazard zones. According to this map, the highest acceleration contours encompass the North Tabriz fault zone, North of Tehran, the Dasht-e Bayaz Fault, etc. The maximum mean acceleration in the vicinity of these tectonic elements is predicted to be around 0.45g for a return period of 475 years and 0.3g for a return period of 75 years, Figure 61, [64].

In this map, two regions have been considered with the least acceleration. One includes a narrow band, which has a NW-SE trend and extends from Urumiyeh to Isfahan. The other is in the central Lut zone in eastern Iran, which is close to Kerman province, [67]. The maximum acceleration values for both of these regions are less than 0.2g and 0.35g for return period 75 and 475 years, respectively.

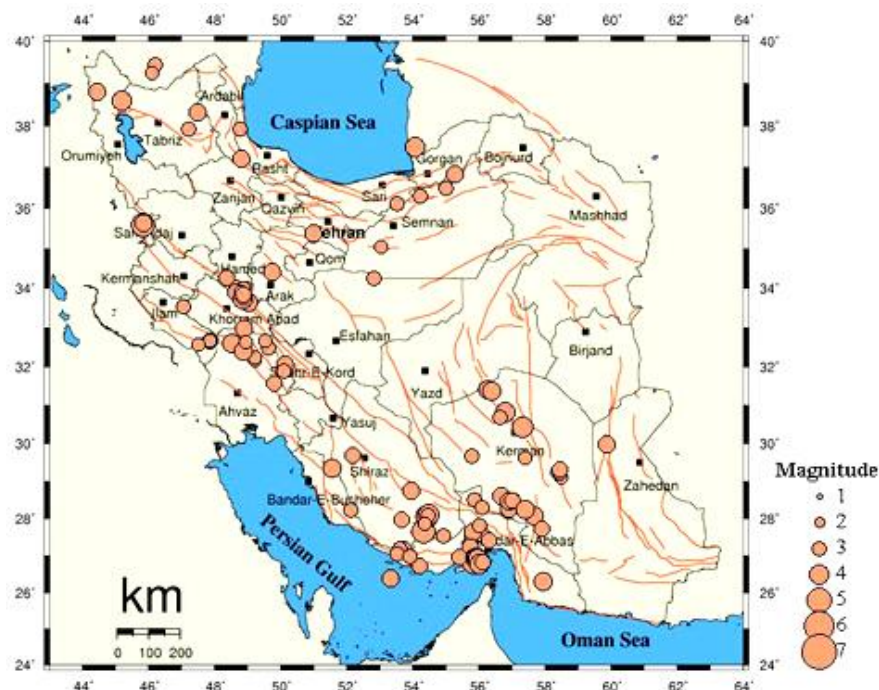


Figure 61 Magnitude earthquake in Iran, [67]

5.5 What engineering codes recommend

The only code for calculating the earthquake loads in Iran is Code 2800. It is necessary to add an appendix to the engineering code, because of the following reasons, [6]:

- In the 3rd chapter, in the definition of masonry building, it says that adobe buildings are not considered in this category, [49].
- The traditional buildings are divided to two kinds: weak ones and reinforced ones. Adobe buildings in Bam Citadel are in the first group and this code recommends that all of them be strengthened with timber, steel, concrete or a combination, Parvini & Shirazian (2009).
- In the first chapter No 3-2-1, recommends that it must be provided precise regulations for adobe buildings in far arid area Parvini & Shirazian (2009).
- In any case, the presumable acceleration in related calculations should be more than 2/3 of the code Parvini & Shirazian (2009).
- The classification of the buildings in this code is according to importance, form, and structural system. It can be used in Bam Citadel because three important factors for Bam Citadel could be: significant, stability, function and safety. According to these four items, I have classified the buildings inside the Citadel.

As a result, this code rejects the structure for all kinds of earthen buildings as a structure, which can be used in seismic areas.

5.6 Required procedures in analytical theory

The analysis of historical masonry construction in the citadel is a complex task. Firstly, limited resources have been allocated to the study of the mechanical behaviour of masonry, which includes non-destructive in situ testing, adequate laboratorial experimental testing and development of reliable numerical fields. Secondly and most

important, the difficulties in using the existing knowledge are inherent to the analysis of historical structures. Usually, salient aspects are:

- Geometry data is missing.
- Information about the inner core of the structural elements is also missing.
- Characterization of the mechanical properties of the materials used is difficult and expensive.
- Large variability of mechanical properties, due to workmanship and use of natural materials.
- Significant changes in the core and constitution of structural elements, associated with long construction periods.
- Existing damage in the structures unknown.
- Regulations and the codes are non-applicable.

Masonry is a complex composite material made of units and mortar. The mechanical behaviour of masonry has generally this salient feature: very low tensile strength. This property is so important that it has determined the shape of historical constructions.

Common idealizations of the behaviour used for analysis are elastic behaviour (with or without redistribution), plastic behaviour and non-linear behaviour. Non-linear analysis is the most powerful method of analysis, able to trace the complete response of a structure from the elastic range, through cracking and crushing, up to complete failure, [2]. It is possible to include the construction sequence in the analysis. The effects of previous applications of loading and the way the intensity of loads are applied yield different results. Different types of non-linear behaviour may be combined, namely, physical (related to the non-linearity of the material), geometrical (related to the fact that the point of application of loads changes with the increase of actions and structures buckle [28] and [29].

5.7 Needs in historical sites in Bam

According to the upper investigations for the using of the optimum method for conservation of adobe buildings:

- The acceleration of the earthquake should be considering at least 2/3 of the 2800 code.
- The maximum acceleration values are less than 0.2g and 0.35g for return period 75 and 475 years, respectively.
- 75 years and 475 years could be suggested also as the duration of time for different types of durability for the repair and restoration in the citadel.
- The lifetime of an adobe building may have been determined by considering the return period of the earthquake.

6 Design process

6.1 Lifetime of buildings in general and of historical buildings

There is a proper time for any repair; before and after that time the building incurs some loss for. Professor Raimund Herz has a very interesting graph about the lifetime of a building, which called “Badenwannenkurve”, Figure 62:

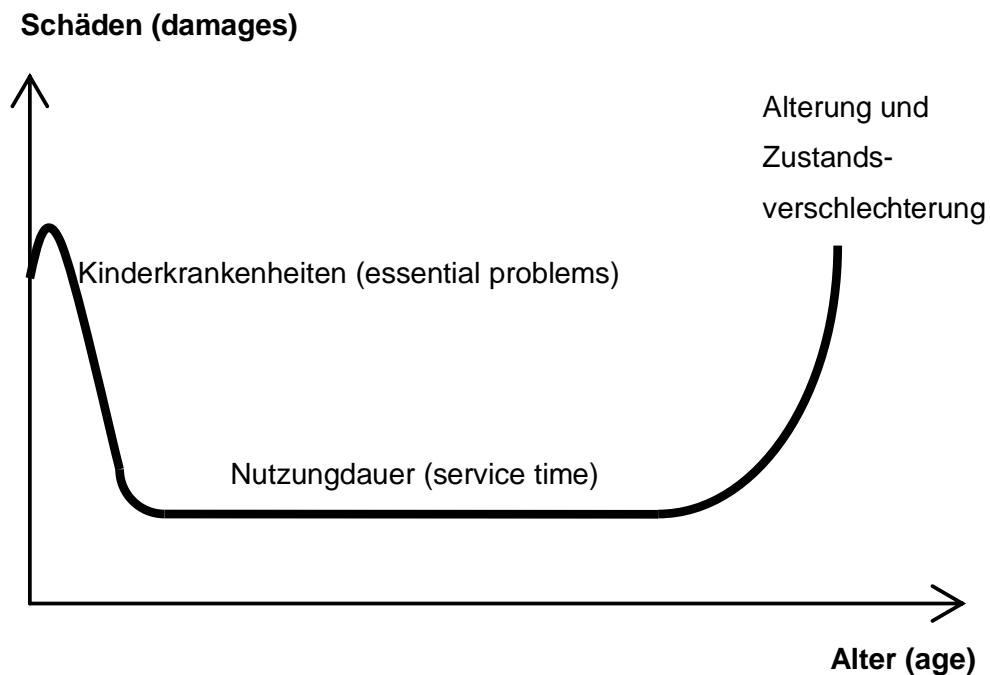


Figure 62 BadenWannenkurve, [18]

This figure is only for damages caused by erosion, time passing and associated function. How can it be after the disasters or after a collapse? According to that idea, I suggest curve Figure 63 for the cycling of the destruction and restoration: during a lifetime the historical buildings faces essential problems, service time and deterioration or hazards. Some restoration and repairs have been done in the buildings.

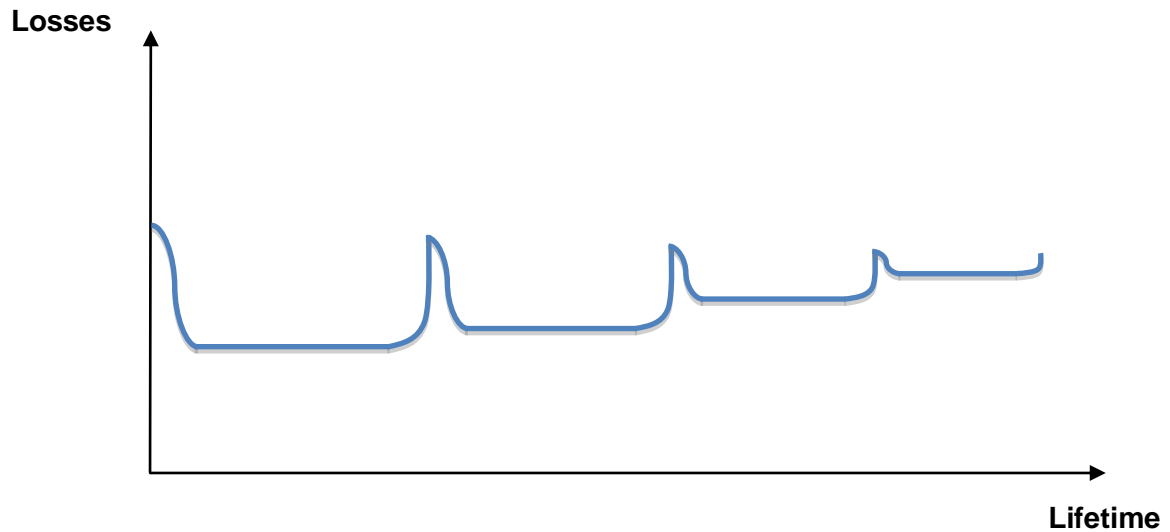


Figure 63 Lifetime Loss in a historical building

6.2 Designing for earthquake severity

The probabilistic assessment of the seismic hazard in Iran involves the likelihood, magnitude, location, and nature of earthquakes that might have damaging effects in the region or at the site, and estimating the peak acceleration of the ground shaking. The earthquake records in Iran include:

- The pre-historic and historical seismicity data
- Instrumental seismicity data (1900-1997)
- Seismic sources of the historical and instrumental earthquakes, rate of activity and fault interaction.

There are 2 main kinds of earthquakes in the seismic code for Iran:

Design earthquake: According to the Code 2800, this earthquake can happen every 50 years and the probability of it is less than 10%. In this case the return period of the earthquakes is considered one time every 475 years.

Probabilistic ground motion analysis was made for sites located throughout the region on a 0.25*0.25 grid and drawing seismic hazard curves. The defined zones were rated as very high hazard, high hazard, moderate hazard and low hazard. The approach and results of hazard analysis shows that the least acceleration contours are expected in two regions. One includes a narrow band that has a NW-SE trend and extends from Urumiyeh to Isfahan. The other one is in the central Lut zone in Eastern Iran. Corresponding maximum acceleration values for both of these regions are less than 0.2g, and 0.35g for return periods of 75 and 475 years, respectively.

Peter C.F. Bekker^{xxvi} has researched about modelling of lifetime performance in building. His work is related to the consequences that are reflected by loss of performance with the passing of time. He has studied two performance models, namely, a deterministic model and a statistical model. According to his research in both cases a characteristic lifetime arises at the point in time when total average performance consumption per year is reduced to a minimum. This finding leads to characteristic properties of an appropriate distribution model that reflects the loss of performance transition process. According to his research, the change of the distribution density, expressed as elasticity, is related to its hazard function of time, regardless of its form.

In fact in the following step, it is tried to model the quantity of performance consumption per year.

6.2.1 Performance consumption and deterministic model

In this model, it is assumed that there is not any event, which could suddenly destroy the building, such as an earthquake, bombing or other natural disasters. In this regard the total consumption, expressed in units of performance, is represented by the following equation, [4]:

$$C_{(t)} = I + M_{(t)} \quad (1)$$

Where:

$C_{(t)}$ amount consumed in time interval (0,t), function of t.

I initial investment in performance

$M_{(t)}$ Maintenance quantity spent or set aside to compensate for a decreasing probability of survival in time interval (0,t), function of t.

t Lifetime

As Becker says, this is a general model as I and $M_{(t)}$ will differ for different categories/populations, of building objects, materials, identical parts or components. If we derived from variable t :

$$d C_{(t)}/dt = C'_{(t)} = m_{(t)}$$

$m_{(t)}$ =maintenance provision at point t in times as a function of t , from $m_{(t)}=0$ where $t=0$. And $m_{(t)}$ increasing with time until an acceptable limit is attained. There is a general power function model used for $M_{(t)}$.

$$M_{(t)} = a^{-1} (b \cdot I) \cdot t_a$$

Which b is average maintenance fraction of I , dimension (time span) $^{-a}$; its size depends on building design, applied materials, using characteristics and environmental conditions, and a = exponent depending on circumstances; for $a=2$, $M_{(t)}$ is a parabolic function as frequently assumed.

Then $m_{(t)}$ will be the maintenance requirements per unit of time could be shown as the following equation:

$$M_{(t)} = (b \cdot I) \cdot t_a^{-1}$$

^{xxvi} He is the former Professor of Industrial and Structural Engineering, Deurne, Netherland.

It will be a linear function when $a=2$.

Becker defines the “average performance consumption” per unit of time with the following equation:

$$Y_{C(t)} = (I/t) + m_{(t)}$$

In this equation I/t and $m_{(t)}$ have controversial proportion. If $a=1$, $Y_{C(t)}$ is represented by a U-shaped curve. In order to establish the relationship that minimizes $Y_{C(t)}$ at $t=t^*$ it is necessary to differentiate equation with respect to the single independent variable and to set the first derivative to zero.

$$d Y_{C(t)}/dt = Y'_{C(t)} = -t^{-2} I + b \cdot I(a-1) \cdot t^{a-2} = 0$$

Then t^* will be:

$$t^* = (I/b(a-1))^{1/a}$$

These two latter equations are practical tools with respect to the lifetime performance. For example: if $a=2$ and the aimed $t^*=50$ years for normal houses in this case, the

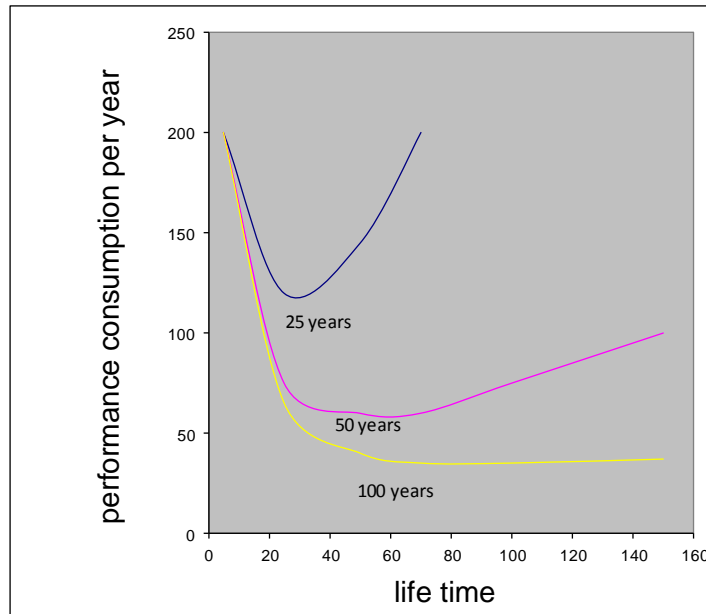


Figure 64 Lifetime variable t in years, deterministic model

average maintenance fraction becomes $b=0.0004$ years in time span t^*-2 . I governs the inclination of the relevant linear maintenance (p.a.)-curves, in these cases for $a=2$, Figure 64.

This equation is indicated to the building as a whole, and is independent from the parts or components.

6.2.2 Performance consumption and statistic model

In this model the assumption a continued decision-making process by deliberating between the termination of the old state of performance and the probability of survival of the new state as obtained after maintenance (repair, replacement, restoration or

renovation). Becker uses the following equation to show this deliberative decision making process, resulting with a robust probabilistic equality, Becker (2005).

$$I \cdot F_{(t)} = M_{(t)} \cdot S_{(t)}$$

$F_{(t)}$ = cumulative probability of termination of the given (old) state as a function of time variable t

$S_{(t)} = 1 - F_{(t)}$ = probability of survival in a new state

According to $C_{(t)} = I + M_{(t)}$ then:

$$Y_{C(t)} = I / S_{(t)}$$

$$\text{And } Y_{C(t)} = I / \{t \cdot S_{(t)}\}$$

What is the difference between the two equations in two models?

The first one refers to one single object, whereas the last one refers to the population of similar objects. The curves from both models are similar but not identical, and they attain to a minimum at $t=t^*$ if their parameters are adjusted to purpose.

Probability density function or “pdf” are shown in the following Figure 65.

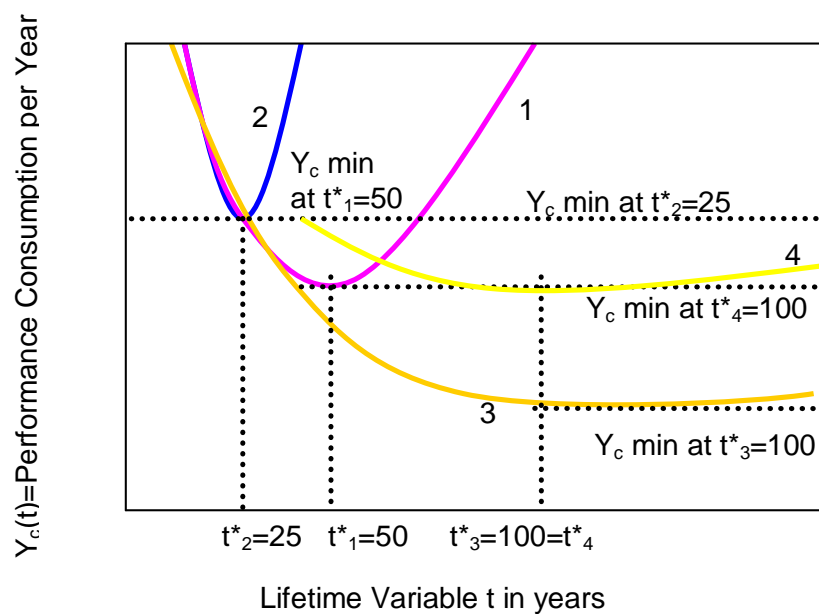


Figure 65 Graph of statistic model in equation $Y_{C(t)} = I / S_{(t)}$, Bekker (2011)

6.2.3 Probabilistic implications

Bekker (2011) believes that loss of performance is a hazardous transition process of a stochastic nature. If we accept it, then we could say that the following equation could be used:

$$S_{(t)} = \exp[-H_{(t)}] \quad (2)$$

The first derivation of $S_{(t)}$ is:

$$dS_{(t)}/dt = f_{(t)} = h_{(t)} \cdot \exp[-H_{(t)}] = h_{(t)} \cdot S_{(t)}$$

Where:

$H_{(t)}$ the integrated hazard function of time variable t , no matter what the mathematical form may be

$f_{(t)}$ Probability density function (pdf), and

$h_{(t)}$ hazard rate function, which is the first derivation of $H_{(t)}$

As we already mentioned t^* or the characteristic lifetime is the point at which $Y_{C(t)}$ is reduced to its minimum. Therefore, it is necessary to differentiate the equation with respect to the single independent variable t and to set the first derivative to zero:

$$dY_{C(t)}/dt = Y_{C(t)} = \{ -t_2 \cdot \exp[-H_{(t)} + t \cdot 1 \cdot h_{(t)} \cdot \exp[-H_{(t)}]] \} = 0$$

If t is substituted with t^* , the characteristic lifetime becomes:

$$t^* = 1/h_{(t^*)}$$

Becker says that this is a remarkable result indicating that t^* is equal to the reciprocal of hazard rate, $h_{(t^*)}$, regardless of its mathematical form, 2005.

Esteban, in 1986, classified the probability density function in terms of an elasticity which shown in the following equation:

$$\Pi_{(t)} = 1 + t \cdot f'_{(t)} / f_{(t)}$$

In this formula $\Pi_{(t)}$ is elasticity and $f'_{(t)}$ is the first derivation of density function $f_{(t)}$.

This equation is used in terms of hazard function $h_{(t)}$ as shown in the following, Bekker, (1991):

$$\Pi_{(t)} = 1 + t \{ h'_{(t)} - [h_{(t)}]^2 \} / h_{(t)}$$

$h'_{(t)}$ is called "transition intensity", which is the first derivation of the hazard rate.

Berkker, in 1978, established the validity of the most appropriate candidate for the Weibull distribution, comprising the following basic hazard functions in the following equations:

$$\text{Integrated hazard: } Hw_{(t)} = (t/\mu)^\beta$$

$$\text{Hazard rate: } H'w_{(t)} = hw_{(t)} = \beta/\mu\beta \cdot t^{\beta-1}$$

$$\text{Transition intensity: } h'_{(t)} = \beta(\beta-1)/\mu\beta \cdot t^{\beta-2}$$

Where

μ = size parameter in the same time units as t , and

β = dimensionless shape parameter of a Weibull distribution

$$\text{then } t^* = \mu \{ \beta - (1/\beta) \}$$

For $\beta=2, 4$: $t^*=0.7071\mu$ and for $2 < \beta < 6$, which is frequently found in practice. Generally, $t^* \approx 0.7 \mu$ is a fair approximation for that range.

After substituting $hw_{(t)}$ and $h'w_{(t)}$, the elasticity of a Weibull distribution becomes as shown in following equation:

$\Pi_{(t)} = \beta\{1 - Hw_{(t)}\}$ and thus: $(1/\beta) \cdot \pi w_{(t)} = \{1 - Hw_{(t)}\}$

Bekker explains that this equation indicates that the rate of change of $\{1 - Hw_{(t)}\}$, labelled as the relative performance, is in the interval $(t, t+dt)$, equal to the elasticity $\pi w_{(t)}$ times a constant quantity $(1/\beta)$.

By replacing t^* in integrated hazard equation we could figure out that:

$$Hw_{(t^*)} = \{\mu \cdot B - (1/\beta)\} \beta / \mu \beta = 1/\beta$$

This result is directly related to the coefficient of variation vw of a Weibull distribution is depended only on β .

For $\beta > 1$, $vw < 1$ and for $\beta=1$ (exponential distribution), $vw = 1$.

The distribution fits for many but not regularly cyclic attacks, such as hot/cold, wet/dry, and stress cycles, extreme weather conditions, and all kinds of accidental and catastrophic events, Becker (2005). These events are independent of distinct underlying failure process characterized by distinct parameters. Apart from the events as meant here, the exponential distribution may be the appropriate model for all durable (conserved) buildings, parts and components.

With shape parameter $\beta=1$, the exponential distribution is a special but important case of a Weibull distribution and results in the following hazard functions in equations:

Integrated hazard: $HE_{(t)} = t / \mu$

Hazard rate: $h = 1 / \mu$, time independent, thus constant

Transition intensity: $h' E_{(t)} = 0$

With replacing $h E_{(t)} = 1/\mu$ and $h' E_{(t)} = 0$ then the elasticity of an exponential distribution becomes:

$\pi_{(t)} = \{1 - HE_{(t)}\}$; which is a linear function of time variable t .

The characteristic lifetime appears to be as shown in equation:

$$t^* E = \{1/h E_{(t)}\} = \mu$$

As they are shown on the curves Figure 64 and Figure 65, $Y_{c(t)}$ are more or less progressively inclining after passing the characteristic lifetime. This is caused by the maintenance need to compensate for all loss of performance with the passing of time. From an operational point of view however the owner(s) and/or user(s) attempt to keep the average performance consumption per year on a minimum level as attained at $t=t^*$. This strategy implies horizontal constant $Y_{c(t)}$ -curves for $t > t^*$. The consequences can be investigated by analysing the relative performance as formulated $(1/\beta) \cdot \pi w_{(t)} = \{1 - Hw_{(t)}\}$.

This relationship is illustrated in Figure 66 for Weibull shape parameter $\beta=1, 2, 3, 4, 6$.

Time variable t on the x-axis is expressed in fraction of size parameter μ in order to achieve a result whereby the graph represents a complete range of lifetimes from short to even millenniums when this should be meaningful. This depends solely on the size of μ . Figure 66 covers not only population of building objects as a whole but also populations of identical parts or components e.g. roofing tiles and masonry, Bekker (1994).

The left y-axis indicates the Integrated Hazard $Hw_{(t)}$, which increases as time progresses. The right y-axis indicates the relative performance $\{1 - Hw_{(t)}\}$, which decreases as time passes from 1 to zero and ultimately to negative.

All curves intersect at co-ordinate μ , where $Hw_{(t)}=1$, regardless of the value of β . Therefore, in every case the probability of survival is as follows: $S_{(t=\mu)} = \exp(-1) = 0.3679$,

as indicated in the graph. Because of spatial limitations, the y-axis is cut off on top at $H_{w(t)}=1.5$; thus, $S_{(t)} = \exp(-1.5)=0.2231$.

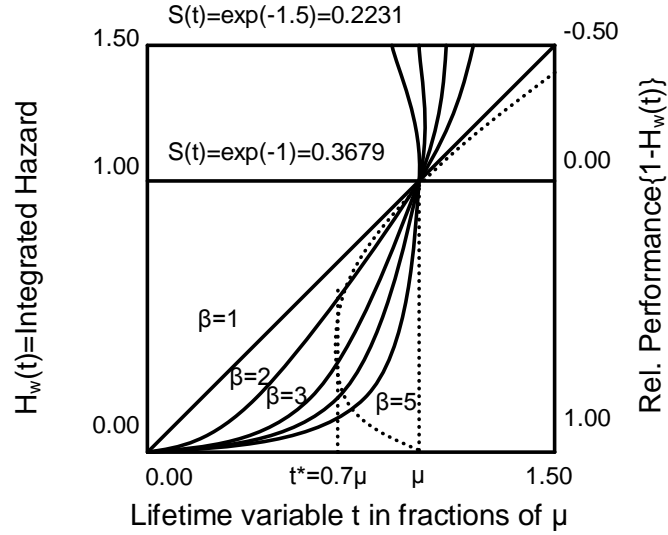


Figure 66 Graph of integrated hazard and relative performance, Bekker (2011)

An arbitrary point on an arbitrary $H_{w(t)}$ -curve is considered with co-ordinates t on the x-axes and $H_{w(t)}$ on the y-axes. The area under, and on the right side, of that curve is the non-performing or depleted part, labelled as $D_{(t)}$. The total area of the rectangle is t times $H_{w(t)}$, thus $t\{H_{w(t)}\}$ is dimensionless. Over and above that curve remains the performing area, labelled as $P_{(t)} = t\{H_{w(t)} - D_{(t)}\}$. The depleted area in the interval $t=0$ and t is shown in Equation (23):

$$D_{(t)} = \int_0^t H_{w(t)} dt = \int_0^t (t/\mu) \beta dt = \{1/(\beta+1)\} \cdot t \cdot \{H_{w(t)}\}$$

$$P_{(t)} = t \cdot \{H_{w(t)}\} - 1/(\beta+1) t \{H_{w(t)}\}$$

The ratio between the depleted and performing area becomes as shown in following equation:

$$R_{(t)} = \{D_{(t)} / P_{(t)}\} = 1/\beta$$

It is necessary to note that $1/\beta$ is not only the reciprocal of the Weibull shape parameter β , but it is also equal to integrated hazard $H_{(t^*)}$ when $t=t^*=\{1/h_{(t^*)}\}$, as found in upper equations.

Once again, the pertinent significance of the characteristic lifetime is hereby convincingly demonstrated. It is also shown that the Weibull distribution is the only one that has the characteristic hazard-based properties expressed by the above equations, Bekker (2011).

As a matter of course, distribution parameter β results from the real world and can not be changed retrospectively. This is the reason why $2 < \beta < 4$ is frequently found in practice when the underlying failure process generates a unit-modal Weibull core distribution.

As Bekker has calculated, the average minimum performance consumption per year, denoted by $Y_{C(t)}$, is attained at $t=t^*$ in each case. From a practical point of view it is most likely that the owners and users will attempt to continue the functional operations at that minimum average level. However, this annual quantity is insufficient to compensate for all loss of performance, which leads to degradation as time progresses.

However, the probabilistic deliberative process as formulated before continues to be decisive for maintaining the performance, whether required or not.

Bekker also has concluded that the survivors within the remaining part of the original population up to every weighing moment are segregated into two actions:

- Maintained/ upgraded to the required performance state.
- Not or insufficiently maintained leading to performance degradation and finally to termination.

He also mentions that the first action is decisive for those objects, which are predestined to become, sooner or later, the status of ancient, cultural or architectural heritage. This is elaborated in the statistical approach set forth in the following section, which is summarized in the following part by Bekker (2011).

6.2.4 Conclusion: A three component distribution concept

This title has been borrowed exactly from Bekker's research; I find it very interesting for determining and analysing lifetime in cultural heritage buildings.

The loss of performance process is at the same time a most effective selection process, known from the evolution theory as "survival of the fittest". That process leads to an autonomous way, to a subpopulation within the original population. This subpopulation is, as it were, predestined to survive because its conservation is regarded as valuable.

Obviously, the objects within an ancient subpopulation are durable, which is expressed by a large t^* and consequently, by a relative low annual average performance consumption.

As a hypothesis, it may be posed that if $Y_{C(t)}$, as represented by equation $Y_{C(t)} = 1/\{t \cdot S_{(t)}\}$, is approximately equal to the annual conservation consumption (on average), the required performance is accomplished on the condition that accidental and catastrophic events are excluded. Nevertheless, rebuilding in whole or in part is always an option when damage may occur, such as through extreme weather conditions, fire, earthquakes, war, terrorism, flood, explosions, and town reconstructions, to which an exponential distribution applies.

Bekker in 1991 has concluded that the original population contains two subpopulations of which the loss of performance process fundamentally differs from that related to the main part of the population. This autonomous segregation process leads to a three components distribution model.

He tested the proposed distribution model based on 119362 well documented discarding data of the entire dwelling stock built in Netherland from before 1800 to 1976. Through an elaborate statistical analysis, a three components (composite) Weibull model Figure 67 was indisputably shown to exist. As a matter of fact, the Weibull core distribution has two truncated tails, Figure 67.

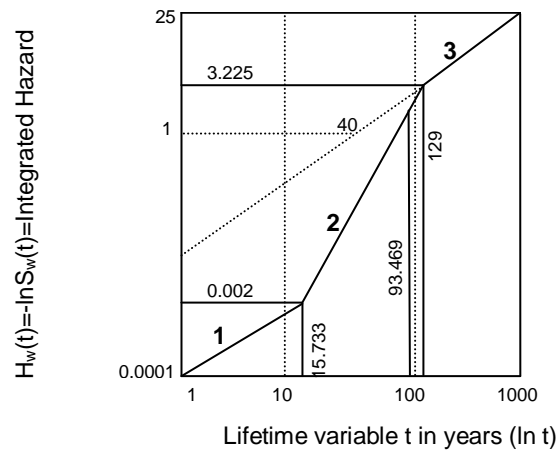


Figure 67 Graph of the integrated hazard model of a three- component Weibull distribution, by Bekker (2011)

The left tail, from $t=1$ to $t=16$ years, reflects the early segregated subpopulation. This tail is the one of an exponential distribution.

The tail on the right clearly emerged for all discard data from $t > 126$ years onwards, which is a reflection of the subpopulation containing ancient dwellings only or, at least, conserved and saved dwellings, regardless the reason of maintaining the required performance. This indicates to an exponential distribution for the subpopulation.

The data after $t > 176$ were lacking for an indisputable finding because conservation excludes an obsolete state of performance.

Bekker has concluded his article with a three component Weibull distribution for dwellings in the Netherlands, which are based on the data obtained by a sophisticated statistical analysis. It would be interesting to have a summary from his research and results here:

The figure starts at $t=1$ year when the probability of survival $Sw_{(t)} = 0.9999$, very close to 1 or hundred percent.

There are 3 lines in this graph:

- Line 1: the time limitation is $1 \leq t \leq 15.733$ years. An exponential distribution with parameter $\mu_1 = 7,843$ years, which implies practically no loss of performance. At $t = 15.733$ years, the probability of survival is $SE_{(t)} = \exp\{-(15.733/7,843)\} = 0.998$, which is still close to 100%. The segregation effect, while apparent is very low during phase 1 of dwelling's service life.

- Line 2: the time limitation is $15.733 \leq t \leq 126$ years. A Weibull core distribution with parameters $\beta = 3.547$ and $\mu_2 = 93.469$ years. Just how perfect this core distribution fits to the more than 100,000 discarding data is shown by the coefficient of termination, $r = 0.993$, which is very close to 1. The size of β_2 and μ_2 incorporates all loss of performance, also the consequence of a slight probability of an accidental or catastrophic event. At the point of $\frac{1}{2}$, $t = 15.733$ years, the probability of survival in common is needed:

$$SE_{(t)} = Sw_{(t)} = \exp\{-(15.733/7,858)\} = \exp\{-(15.733/7,858)3.547\} = 0.998$$

- Line 3: from $t=129$ years onwards: an exponential distribution (on the condition of conservation of the remaining population) with parameter $\mu_3=40$ years. At the point of partition 2/3, $t=129$ years, the probability of survival in common is:

$$SE(t) = Sw(t) = \exp\{-(129/40)\} = \exp\{-(129/40)3.547\} = 0.045$$

The point is when conservation is secured, only accidental and catastrophic events can/will disturb the required performance. The probability of such an event is one average for ancient dwellings in the Netherlands during a time span of $\mu_3=40$ years. Note that the risk of performance loss between $t=1$ and $t=15.733$ is extremely low, $\mu_1=7,843$ years, because new buildings are, generally speaking, much less sensitive to the risk of accidental and catastrophic events and their consequences on loss of performance.

The cultural and architectural heritage belongs to the subpopulation discussed in this research^{xxvii}. According to the Weibul model and also the time history of the earthquake in Iran, for Bam Citadel two period of time is suggested; 10 years for preventive maintenance, 50 years for survivability of the structure and 100 years for public safety.

^{xxvii} For more information about the subject of deterioration, testing and conservation in building, please review to Prof Luigia Binda's articles. I don't indicate specifically because I have read many of them, but did not use them in this chapter.

7 Evaluation

In this chapter the case studies in Bam Citadel are evaluated and analysed; the method, technology and measures will be explained as following:

7.1 Case Study 1 in Bam Citadel; Tower No. 1

7.1.1 History

According to the references, the rampart, beside the north western part of the wall dates back to the pre Islamic period, Figure 68. The structural collapse has shown the pattern of the skeleton as it has been built up and widened throughout the history of the City, whose dating still remains uncertain, but that presumably is to be imputed to the Sassanid period, 224–651AD. Archaeologists believe that the collapse caused the loss of the vertical stratifications of the walls, realized in the last four centuries (Qajar, 1789–1925 AD reconstruction and Safavid, 1501–1736 AD, enlargement), [37]. Some architectural elements of former configurations of the Tower remain visible, as a result of the uncovering caused by collapses such as niches, closed vaults, under walled arches, or arched windows for the positioning of the archers of defence.



Figure 68 Tower No. 1, before earthquake in 2003.

7.1.2 Definition of the plan

The main wall includes 48 towers the first of which is in the south western corner of the wall and named Tower No. 1. It is part of a massive rampart. The mud-brick wall built on a thick mud brick base has a height of 6 to 7 m. It is located at the southwest corner of the third surrounding wall of the city of Bam Since the earthquake of December 2003, the wall has lost most of the volume that had resulted from interventions of restoration and enlargement over the centuries The present dimensions along the two walls running north-south and east-west 3.5 m lower than they are in the plan, along the two north-south and east-west directions. The former thickness of the Tower, even if it can be defined by examining the present configuration, varies, reaching maximum values of

about of 6-7 m. The detailed configuration of the tower before the earthquake is not known. The real depth of the foundation is not visible because of the existing debris.

7.1.3 Values

The value of Bam Citadel can be attributed to its close proximity to the main entrance of the area. The entrance provides a striking first impression of the Citadel. This is one of the first virtual architectural elements that can be seen at first glance. Part of the surrounding wall is architecturally significant and a discovery of 1177 pieces of glazed pottery found in the debris of the wall are archaeologically significant. Diversity of the historical layers is distinguished and provides opportunity for the researchers to find out information about the history of construction and restoration. Diversity of the adobe bricks is notable. The bricks are not homogeneous. An example of homogenous bricks is 36x36x8 cm, 25x13x8 cm, and 22x22x7 cm, as seen during the in-situ survey.

7.1.4 Reports of damages after earthquake

Most of the structure at the top of the tower was completely damaged, Figure 69. In this case, anyway, the typical state of structures had been enlarged with the making of walls, all in mud brick, but of different thickness and size of the elements. Juxtaposed along vertical or sub-vertical planes, they were deeply enlightened. The most recurrent failure phenomena were, in fact, related to kinematics of progressive and retrogressive slide of the different walls on the back standing structure in site, and of toppling and rolling down the slope. It can be seen, particularly on the front North of the Tower, the slide displacement of a brick block of about 1.5-2 m³, with a slide displacement of around 1.5 m. The configurations of the bricklayers of parts of the structures were visible too, as direct consequences of the distortive action of the seismic shock. Fractures of remarkable dimensions fully show the progressive detachment of further portions of the south wall [37].

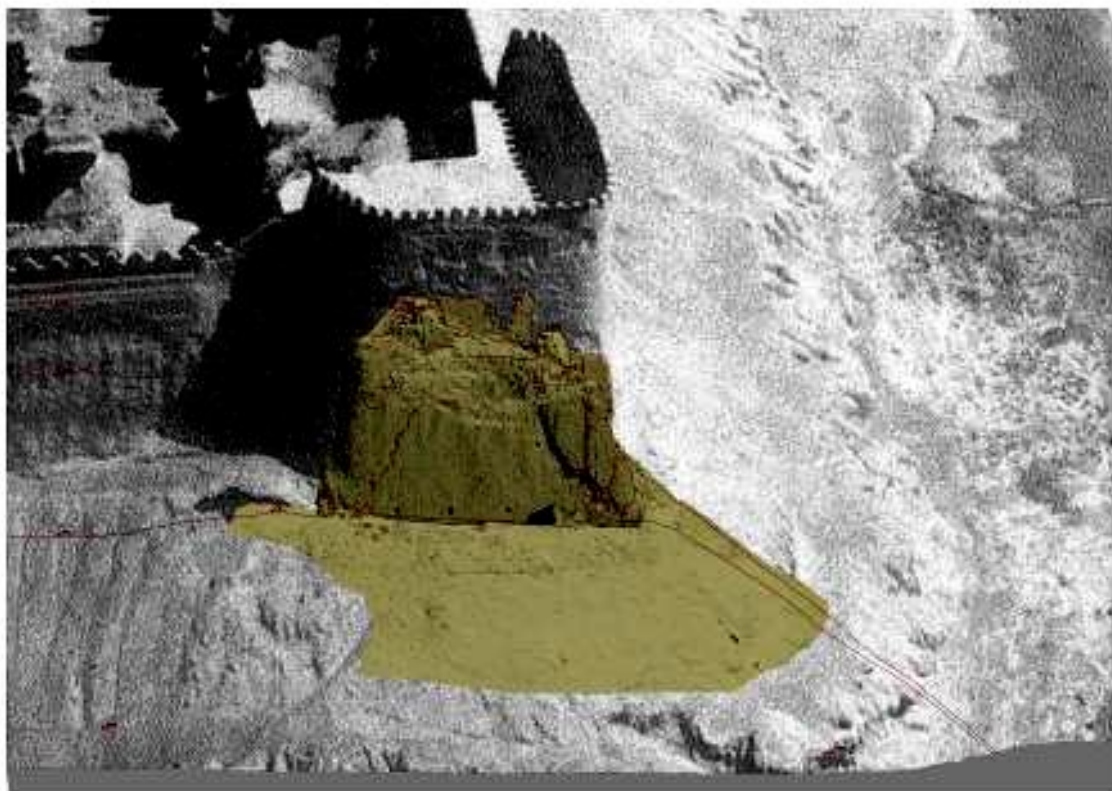
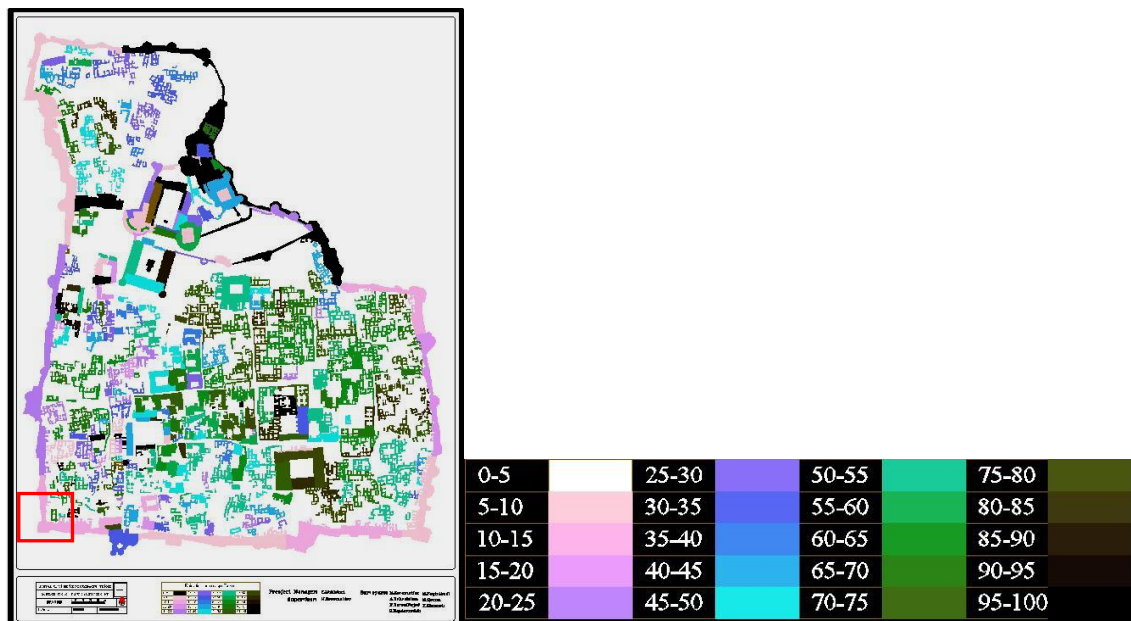






Figure 69 About 20% of Tower No. 1 was destroyed, [39] and [37]

7.1.5 Challenges and solutions

- A review on the system of the structure, [37]:

Table 5 *Repair and restoration of Tower No. 1*

Structure	System	Photo
Original, 1965	Masonry, adobe walls, the whole building was built at once, with a predecessor building at the same place having been demolished.	
After restoration 1973	Restoration and repair of the damaged parts, the traditional methods used and the connection between old and new layers are weak.	
After earthquake 2003	The remains after the earthquake consisted of very short walls and foundation. Other parts collapsed or crashed and with deep cracks are on the top of the openings or corners.	
After restoration 2007	Structural intervention with the assumption that the new and old layers join together as an original situation; a level of intervention is applied to provide safety during the next earthquake.	

- Decision after earthquake: Following the earthquake in 2003, an Italian delegation from the Ministry of Cultural Heritage together with experts from the Civil Defence Department travelled to Iran to provide qualified technical collaboration during the post-earthquake phase.

The Italian collaboration project during the post-earthquake phase was progressively configured, starting from the results of the reconnaissance site visits carried out immediately after the earthquake on 26 December 2003 and carrying on through to the end of 2006. This length of time was necessary to reach an adequate understanding of the problems in the urban situation, as modified by the earthquake, and to agree with the local authorities the issues to be dealt with.

The final decision was to keep separate the two restoration/consolidation and seismic improvement phases, in order to ensure the stability of the structure and to present the new intervention on the façade. With regards to the results of the restoration/consolidation work and the final treatment of the surfaces, following the performance of the seismic improvement work, the aim is to highlight the stratigraphy situation encountered. Only small integration work will be carried out, as necessary, to make the main construction phases more easily legible and to consolidate the less stable elements.

The analysis carried out in this respect showed that it was impossible to reach acceptable conditions by using traditional materials and techniques, without significantly affecting the structure (e.g. it could be “sown together” with palm trunks, but they would be very difficult to insert and it would be invasive). For this reason, a structural consolidation system trial was considered using innovative materials, but still commonly used in building and restoration works.

The design, as it has been conceived, leaves open the possibility to carry out subsequent reintegration work and, in particular, enables, in accordance with the local culture and traditions, to also re-propose the completed image of the structure if required.

- Technology concept: The aim of the work carried out over the years has always been to conserve the material consistency of the tower, which for this reason, has been the subject of regular reintegration work. The analytical study of what may be directly observed in situ has highlighted the main mechanical damage suffered by the structure and defined the state of conservation of the main surface areas. The study of the inside of the tower was temporarily suspended, as it was totally obscured by the rubble resulting from the earthquake. The analysis result of numerical modelling showed for both load combinations: self-weight+SN earthquake and self weight +EW earthquake, the incremental pseudo-static analysis pointed out the inability to achieve equilibrium conditions for the structure. This is due, for the characteristics assigned to the seismic action, to the overcoming of the shear strength on the surfaces of discontinuity, and to the consequent triggering of collapse kinematics like the toppling and sliding of some building volumes not adequately linked to the rest of the structure. The stress level induced by the self-weight alone, instead, results were contained within acceptable safety borders.

- The methodological-operational approach was as follows:
 - Initial reconnaissance analyses based on the “direct reading” of the structure in order to highlight its peculiarities at a macroscopic level
 - Local recognition of documents, photographs and images of the tower
 - Survey of structure, photo-maps and three-dimensional model
 - Reconstruction study of the main construction phases of the structure, carried out by direct observation and interpretative drawings
 - Analysis of the state of conservation

- Archaeological investigations
- Reconstruction of the structural behaviour model for Tower No. 1
- Conservation and seismic improvement work design.
- Principle adopted from charters and codes: For the study of the types of bricks, reference has been made to the samples taken and analyzed in the local laboratory in accordance with the scientific set up defined by Technische Universität Dresden.

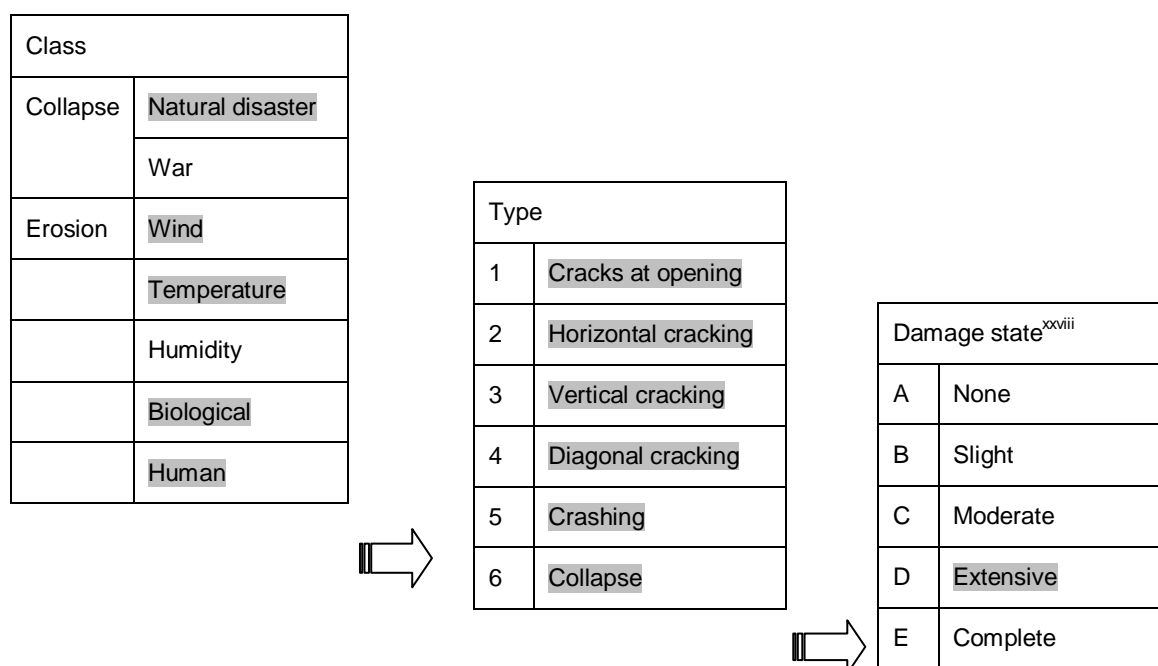
Structural analyses have been performed with reference to the Italian Technical Regulations and Standards for the masonry and concrete works both for static and seismic dynamic load conditions [37].

In particular, with regard to the seismic improvement issue, consideration has been given to the recommendations made during the International Workshop in April 2004, in which it was deemed worthwhile to plan work which dealt with that aspect.

- Theoretical types of intervention:

Classification of the damages for determining the level of safety:

Table 6 *Approach and the rest of intervention plans in the Tower No. 1*



^{xxviii} For understanding the state of damages, please review Table 1, Standard Damage.

Proposed level of intervention	Maintenance	Restoration	Reconstruction	Rebuild	Reproduce
	preventive	Decoration	-	-	-
	repair	Partial	partial	partial	partial
	-	Complete	complete	complete	complete

Loss of cultural heritage

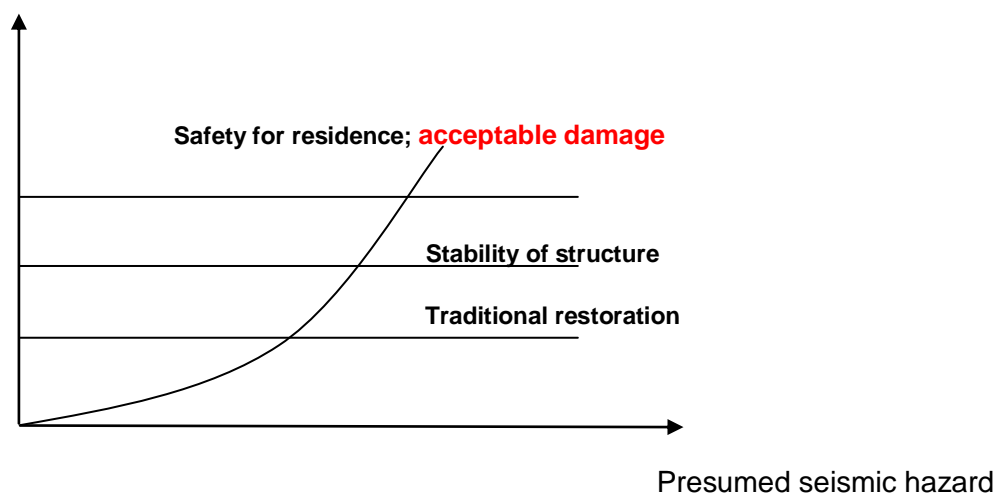


Figure 70 Level of intervention in Tower No. 1

7.1.6 The brick dimension and properties assumption

In general, it was possible to identify the simultaneous presence of the following construction techniques:

Adobe, vaulted structures, mixed masonry (adobe and Chineh), mud bricks, finishing with Kaghel. With regards to the logic to be adopted in the design of the work, taking into consideration the situation documented by the above-mentioned studies and the need to integrate certain sectors of the tower to enable an adequate stability to be achieved, it was considered worthwhile using a brick compatible in terms of grain size and mineralogy, density and load strength, but with predefined dimensions (30x30x10 cm). This brick has positive aspects in terms of its modular possibilities and to reduce the weight with a thickness suitable to support a structure with limited reinforcement, functioning as a block. In addition, the reduced elasticity should guarantee a greater compatibility with the materials in-situ, integrating them with any adjoining walling.

The glass fiber bars were inserted inside the wall horizontally and vertically and the new and old parts joined by drilling and injection of the mortars [37].

The use of materials already in production were proposed for the inner face of the tower (lower sector), which, due to their high load strength, were suitable for the formation of valid supports for the unstable zones.

Assumption of the modelling was as following:

Masonry

Characteristic compressive strength:

$$s_k = 4.27 \text{ MPa}$$

Normal elasticity modulus:

$$E = 5000 \text{ MPa}$$

Poisson's coefficient:

$$\nu = 0.2$$

Fiberglass ties

Characteristic tensile strength:

$$\sigma_{VTR,K} = 750 \text{ MPa}$$

Characteristic shear strength:

$$t_{VTR,K} = 140 \text{ MPa}$$

- Numerical Model of the Tower

The stress-and-strain state induced by the gravitational strengths and by the seismic action has been determined through a FEM analysis on a three-dimensional model of the structure of the Tower that, with good approximation, reflects the actual geometry of it. Particularly, the model was composed of two types of elements: "brick" FE, with which the building volumes and the filling loose material set on the inside of the Tower were modelled; "link" FE, used to simulate the mechanical interaction of the interfaces or discontinuity among the volumes themselves. On the same geometric model of the Tower two analyses were performed: a non linear pseudo-static analysis, aimed to the evaluation of the safety limit of the Tower in the present situation and a response-spectrum dynamic analysis directed to the dimensioning of the possible structural interventions of consolidation and seismic improvement. The solving of the structural model was performed through the FEM numerical code SAP 2000 by Computer and Structures Inc., [37].

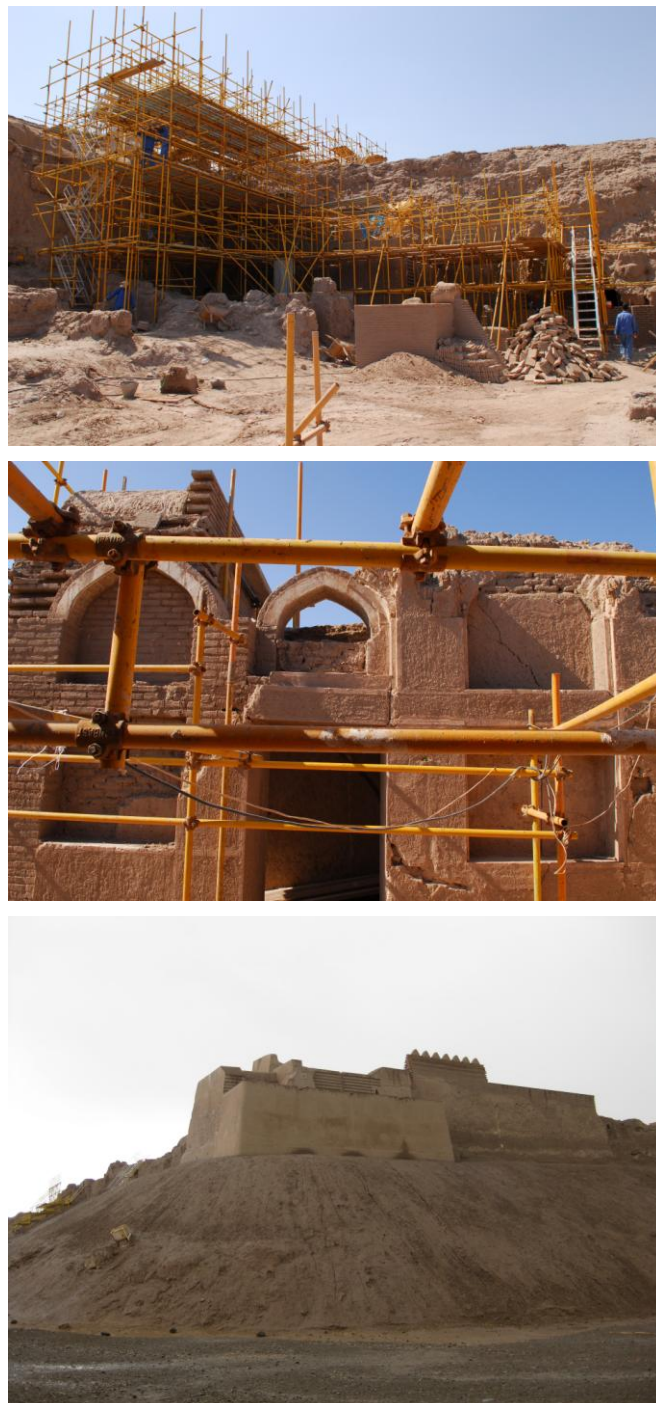


Figure 71 Restoration work for Tower No. 1

Table 7 *A general view from documentation to performance in Tower No. 1*

Performance	lack							
	uncompleted			✓				
	completed					✓		✓
Risks								
	considered					✓		
Design	maintenance							
	stability							
	safety	✓				✓		
Calculation	lack							
	uncompleted							
	completed					✓		
Analysis	lack							
	uncompleted				✓		✓	
	completed		✓	✓		✓		✓
Field works	lack							
	uncompleted				✓		✓	
	completed	✓	✓	✓		✓		✓
Documents	lack	✓						
	uncompleted				✓		✓	
	completed		✓	✓		✓		✓
		historical	archaeological	architectural	functional	structural	geological	material

Table 8 *SWOT Table after the last restoration in Tower No. 1, 2007*

Strength	<p>Integration with the environment</p> <p>Reconstruction of one of the main monuments in the Citadel</p> <p>Adapting a new technological method for adobe building</p> <p>Reliable public safety level</p>
Weakness	<p>High cost technology</p> <p>Depended and imported technology</p> <p>Invasive intervention</p>
Opportunity	<p>A repair to the level of public safety</p> <p>Training the local worker for this new technology</p>
Threats	<p>Side effects of the glass fibre bars inside the wall</p> <p>Next earthquake</p> <p>Erosion</p> <p>Lack of permanent management</p>

7.2 Case Study 2 in Bam Citadel; Pyambar Mosque

7.2.1 History

There is not any information about the history of Pyambar Mosque in the historical references. Only a few plans from the previous restoration before the earthquake 2003 were found. According to the plans, the last intervention before the earthquake had happened in 1990. Even so, the primary archaeological theory indicates his mosque was part of a bigger mosque such as the Jaame-Mosque south east of the Citadel. More documents and records are needed to approve this theory, [47].

7.2.2 Definition of the plan

Pyambar Mosque is located in the western part of the Citadel near Bazaar and has sustained more of a loss resulting from the earthquake than any other parts of the Citadel'. The access to the single monument could be possible by the north entrance from Bazaar alley on the south, east and west. Because of the far distance between Bazaar and Jaame-Mosque, in the past this small vestry was regularly used to pray by the traders and passengers. However, the erratic parts in the process of fabric design have evolved in the area this special instance survived its original state during the past years.

Another theory says that it might have been used by the passengers and traders who were accommodated at the location of the mosque, close to the Caravansary and Stable. To approach the precise evolution, some more investigation is needed.

7.2.3 Values

The value of the Citadel can be attributed to three features:

- Location of the mosque in relation to buildings like Caravansary and neighborhoods like Bazaar
- Architecture - unique to small mosques in arid areas
- Heritage - it is respected and considered spiritually relevant by local people

7.2.4 Reports of damages after earthquake

Through the earthquake, all the western part of the structure collapsed and, as mentioned before, more than 85% of the structure was destroyed Figure 72. The thick column which suffered less damage transferred the gravity loads to the ground; the domes in Pyambar Mosque collapsed completely and the main central column survived although it incurred a large number of cracks on the bottom. The failure pattern in Pyambar Mosque rules as the main key for engineering restoration plan of the monument. The status of damage of the building is shown, the typical shear cracks and out of plan failure in main walls and general collapse that caused by bending moments that reached the capacity of the domes.

7.2.5 Repair history

There is no precise report regarding the previous restoration of the mosque, neither since the last restoration before the earthquake in 2003, nor from the years before. There are few pictures of the restoration in 1990.

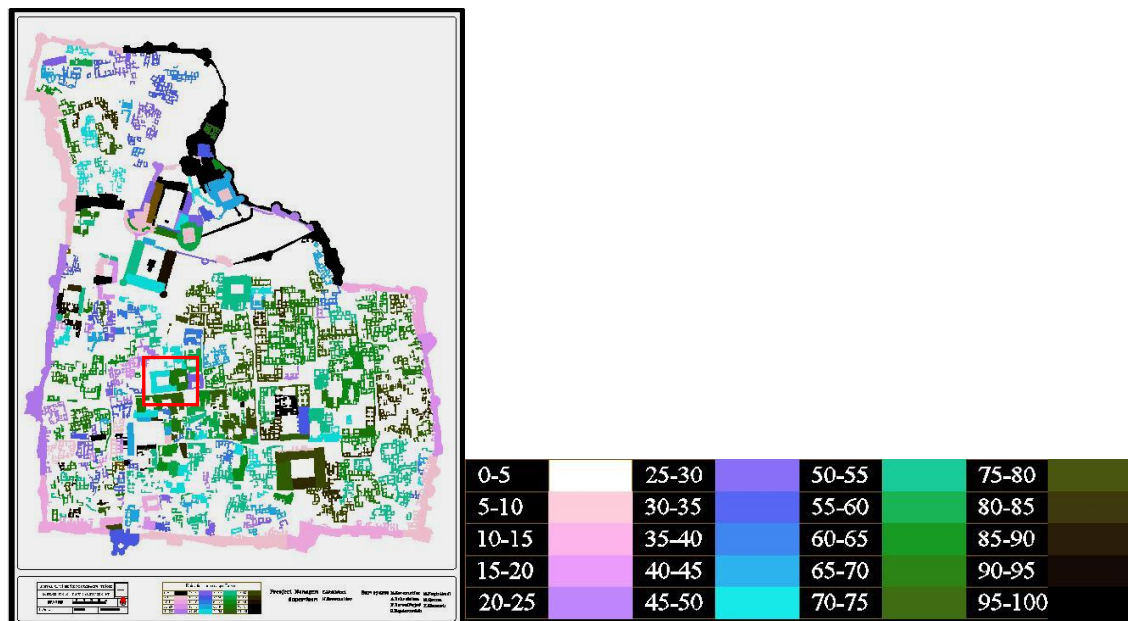
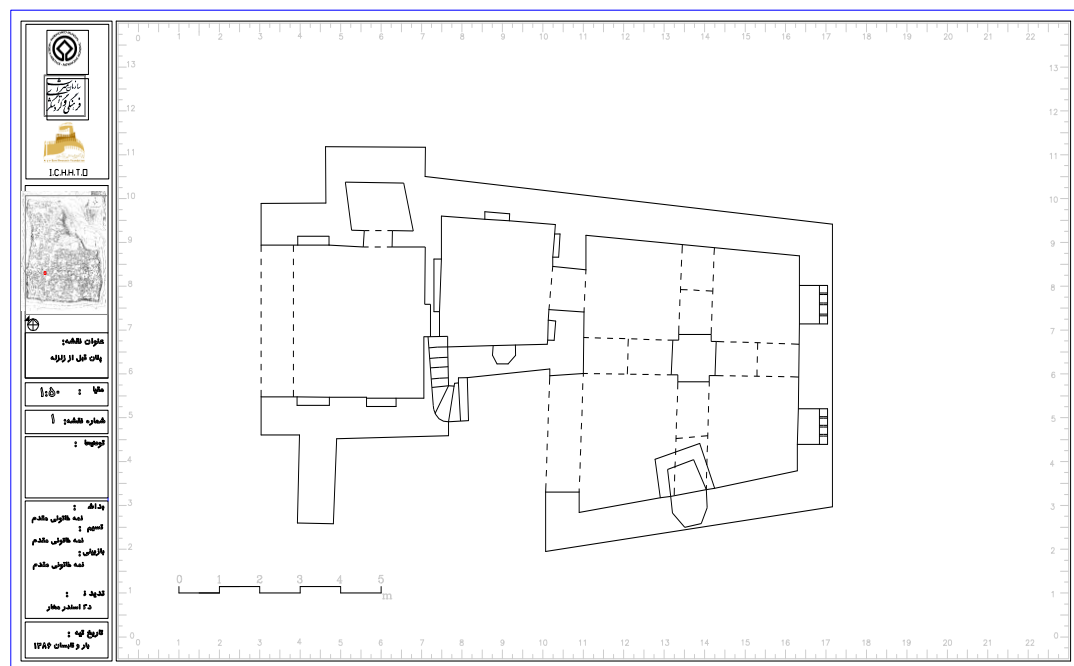





Figure 72 Top: More than 80% of the western part of Pyambar Mosque has been destroyed. It is that part which collapsed during the earthquake, [39]. Bottom: Restoration plan after the earthquake, [39] and [47].



7.2.6 Challenges and solutions

- A review on the system of the structure:

Table 9 *Repair and restoration of Pyambar Mosque*

Structure	System	Photo
After restoration 1990	Restoration and repair of the damaged parts, the traditional methods used and the connection between old and new layers were weak.	
After earthquake 2003	The remains after the earthquake consisted central column. Other parts collapsed or crashed dramatically.	
After restoration 2009	Structural intervention with date fibres. New and old adobe parts were joined together with the tensile elements.	

7.2.7 Decision after earthquake

The main measures for the restoration plan of Pyambar Mosque were based on two elements, [47]. First, the reinforcement experiences with pilot projects in Bam Citadel after the 2003 earthquake, and second the traditional methods that were based on the previous experiences in Bam Citadel particularly with respect to the earthquake load as a destructive lateral load on the structure. The restoration plan of Pyambar Mosque

includes four main parts - documentation, damage status, restoration, rehabilitation as following:

- Structural Appliances

The main key in the restoration plan of Pyambar Mosque is based on strategies that make the monument strong enough as a public building against the upcoming earthquakes; the introduced tensile element is called “Siess” and was inserted inside the walls and domes of the mosque. Siess is made of palm fibre, natural available material, which is very cheap and easy to work with. For anti – termite processing some recommendations are planned and relevant to provide a shear effect on the elements, some specific production will be applied.

- Lateral Load

The Lateral load made by the earthquake caused major failures in the domes and surrounding walls. On the other hand, the continuity in connection between walls and domes has been lost and caused a big failure in the whole structure. The study on failure criteria was provided with a 3-D map of the structure and lead the way to provide the location of the vertical and horizontal tensile elements that are described in the following part.

- Natural Siess material

Siess will be introduced to the structure vertically and horizontally in different forms. The vertical elements will provide any required bending resistance and horizontal elements will act as the elements that provide shear resistance. Figure 73 shows the drilling procedure for inserting vertical elements that will be installed with grout injection, as in this figure is cleared, the vertical elements follows each other in the centre line of the main walls. The maximum distance is around 1.1 m that is reduced to 0.6 m in the compulsory points. The horizontal elements that are provided for shear resistance will be inserted as a mesh form with thin thickness and there are in production line by local producers right now. In 0, the sample of horizontal mesh with a thick element (available on time in the site) is shown; some simple tool is produced for the installation process.

Assumption of the modelling was as following:

Masonry

Characteristic compressive strength:

$$\sigma_k = 4.27 \text{ MPa}$$

Normal elasticity modulus:

$$E = 5000 \text{ MPa}$$

Poisson's coefficient:

$$\nu = 0.2$$



Figure 73 Drilling procedures for inserting vertical Siess elements in the main walls in Pyambar Mosque, [47].



Figure 74 Horizontal Siess were inserted among the layers [47].

- Theoretical types of intervention:

Classification of the damages for determining the level of safety:

Table 10 Approach and the rest of intervention plans in the Pyambar Mosque

Class	
Collapse	Natural disaster
	War
Erosion	Wind
	Temperature
	Humidity
	Biological
	Human

Type	
1	Cracks at opening
2	Horizontal cracking
3	Vertical cracking
4	Diagonal cracking
5	Crashing
6	Collapse

Damage state ^{xix}	
A	None
B	Slight
C	Moderate
D	Extensive
E	Complete

^{xxix}For understanding the state of damages, please review Table 1, Standard Damage.

	Maintenance	Restoration	Reconstruction	Rebuild	Reproduce
Proposed level of intervention	preventive	decoration	-	-	-
	repair	Partial	partial	partial	Partial
	-	Complete	complete	complete	Complete

Loss of cultural heritage

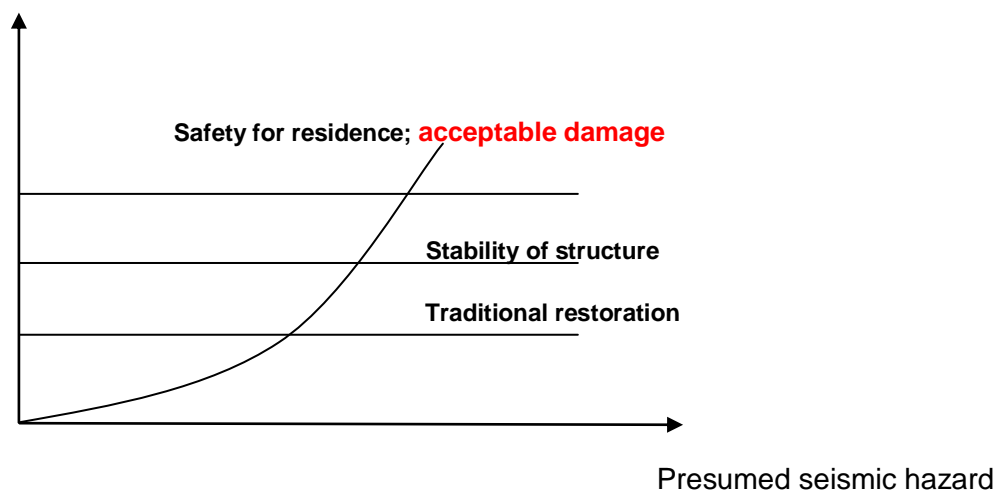


Figure 75 Level of intervention in Pyambar Mosque

7.2.8 Principle adopted from charters and codes

The only existing code, Building Code 2800, doesn't meet the heritage adobe structures. It is a research based project which has been done by ICHHTO.

The most advantages of the Siess elements can be listed as following, [47]:

- being cheap
- available on Bam in every season
- the craftsmen could work with the Siess easily
- flexible materials
- anti-termite (some reports shows its resistance against the termite is around 300 years)
- compatible with adobe and whole structure (colour and mechanical properties)
- keeps the authenticity in advanced level
- provides ductility for the structure

Table 11 *A general view from documentation to performance in Pyambar Mosque*

Performance	lack							
	uncompleted							
	completed			✓		✓		✓
Risks								
	considered				✓	✓		
Design	maintenance							
	stability							
	safety			✓		✓		
Calculation	lack							
	uncompleted							
	completed			✓		✓		
Analysis	lack							
	uncompleted	✓	✓				✓	
	completed			✓	✓	✓		✓
Field works	lack							
	uncompleted	✓					✓	
	completed		✓	✓	✓	✓		✓
Documents	lack	✓						
	uncompleted		✓				✓	
	completed			✓	✓	✓		✓
		historical	archaeological	architectural	functional	structural	geological	material

Table 12 *SWOT Table after the last restoration in Pyambar Mosque 2009*

Strength	<p>Integration with the environment</p> <p>Reconstruction of one of the important heritage monuments in the Citadel</p> <p>Using a natural material and development of traditional technology for adobe building</p> <p>Reliable public safety level</p>
Weakness	<p>High cost technology</p> <p>Depended and imported technology</p> <p>Invasive intervention</p>
Opportunity	<p>To use by public, a repair to the level of public safety</p> <p>Training the local worker for this new technology</p>
Threats	<p>Siess is exposed to termite.</p> <p>Next earthquake</p> <p>Erosion</p> <p>Lack of continues maintenance</p>

7.3 Case Study 3 in Bam Citadel; Sistani House

7.3.1 History

Considering the name “Sistani”, it may go back to the 18th century. The family of Sistani was one of the famous families who lived in Bam. Perhaps the Sistani Family inhabited the building during the Zandiyeh period, [26].

7.3.2 Definition of the plan

The house is located in the middle of the Citadel, between the main gate of the city wall and the entrance to the inner fortifications with the area about 673 m². A little avenue passes by the east of the building. This building has two inner courtyards in the east and in the west, which are bordered in the north by winter rooms and in the south by higher summer rooms. All the outer walls are built without windows, perhaps because of the climate or maybe for security reasons. The former main entrance is located almost in the middle north-south wing of the building and from there you can access the two courtyards by means of a low corridor, [27].

7.3.3 Values

Sistani House was used as a technical office before the earthquake in 2003. It has a strategic importance in the Citadel. On one hand the location provides the possibilities for the experts to protect and control easily, supervising the restoration project every day and on the other hand, because of the number of rooms which could serve the technical team as an office [32].

From the architectural points of view, Sistani House is an individual house because of the form and dimension. It simply shows the characteristic of a Persian traditional house for the upper mediate social level family. It also belongs to the noble classification of buildings; although it is not as large as Mirza-Naeim Complex, it is a very good example of a house in an arid area.

7.3.4 Reports of damages after earthquake

The number of the people who perished or sustained injury during the earthquake was shown in the following table:

Table 13 *Injured people; losses in earthquake 2003, [51]*

No	Position	Numbers	Situation
1	director	1	injured
2	expert	2	died
3	master	4	died
4	workers	10	died

The documents which have been found are listed in this table; it seems that a number of important documents were lost in the earthquake.

Table 14 *Losses of the documents in earthquake 2003, Salari (2008)*

No	Documents	Before earthquake	After earthquake	Damage percent
1	photo	21000 N	17000 N	20
2	map	100 S	50 S	50
3	CD	-	-	-
4	slide	2500	1000	60
5	reports	10	9	30
6	books	500 V	200 V	60

7.3.5 Repair history

In about 1958 first repairs were executed within the Citadel. A comprehensive restoration of the citadel commenced in 1973; there are no written sources or plans which show the original state from the beginning of the house or later applied structural changes. There are some aerial photos from the years 1956, 1981, and 1996 show parts of the house. But just a few photos after the restoration in 1993-95 are available.

Sistani House was used as a technical office before earthquake 2003. During the earthquake 16 persons, who worked in the citadel, died and the head of the project was saved as he stayed under debris.

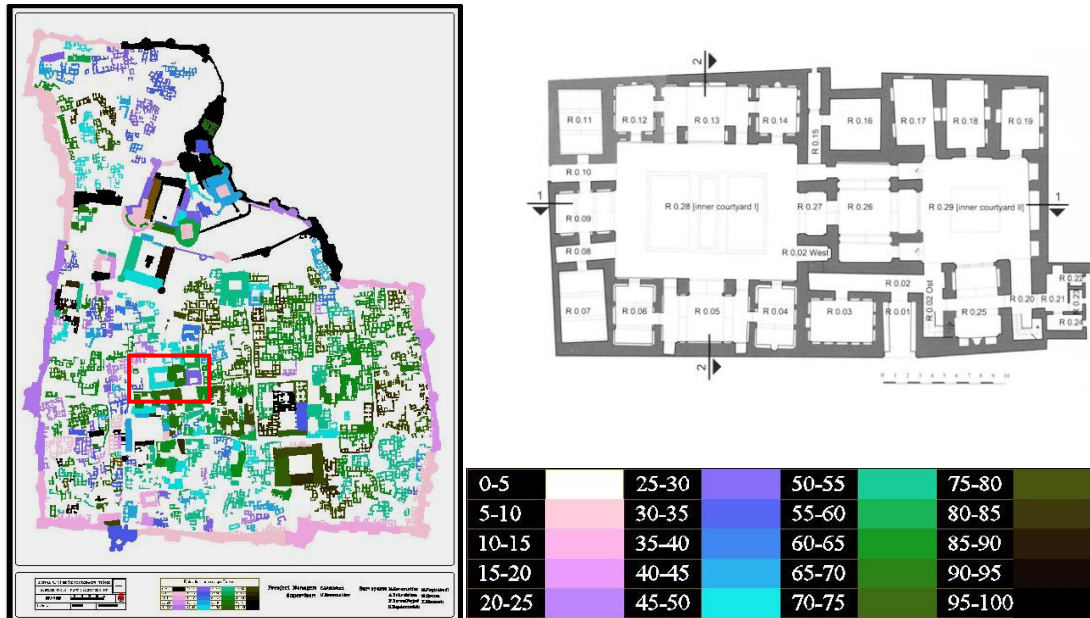






Figure 76 *More than 42.5% of the western part of Sistani House has been destroyed. It is that part which collapsed during the earthquake, [39].*

7.3.6 Challenges and solutions

- A review on the system of the structure:

Table 15 *Repair and restoration of Sistani House*

Structure	System	Photo
Original	Masonry, adobe walls, the whole building was built at once, with a predecessor building at the same place having been demolished.	
After restoration 1973	Restoration and repair of the damaged parts, the traditional methods used and the connection between old and new layers are weak.	
After earthquake 2003	The remains after the earthquake consisted of very short walls and foundation. Other parts collapsed or crashed and with deep cracks are on the top of the openings or corners.	
After restoration 2007	Structural intervention with the assumption that the new and old layers join together as an original situation; a level of intervention is applied to provide safety during the next earthquake.	

- Decision after earthquake
according to the stakeholder decision, two rooms of the Sistani House have been selected as a pilot project. TU Dresden has started with two rooms. Later TU Dresden had a great effort to complete the whole Sistani House. It is now under construction.
- Technology concept

three phases are seen in a study of these two rooms: survey and documentations, experimental investigation and design. The main concept has been based on reconstruction of Sistani House, designed to reach an adequate level of stability of the structure and safety of people and documents.

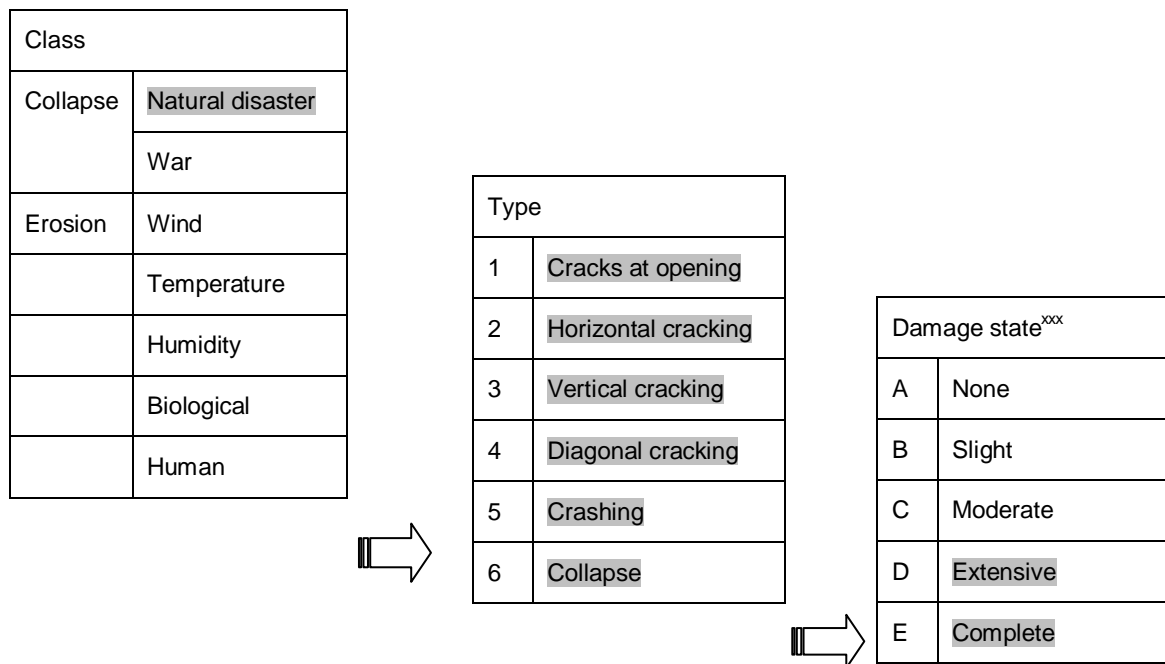
- Principle adopted from charters and codes

There are not any seismic codes for repair and reinforcement of the adobe structure and material. The only existing code is Building Code 2800, which is applied only to steel, concrete and brick buildings. It also supports all the rules for seismic areas in Iran. Then all the previous actions for restoration and repairs only obey the traditional experiences and not the scientific references.

- Theoretical types of intervention

Classification of the damages for determining the level of safety:

Table 16 *Approach and the rest of intervention plans in the Sistani House*



^{xxx} For understanding the state of damages, please review Table 1, Standard Damage.

	Maintenance	Restoration	Reconstruction	Rebuild	Reproduce
Proposed level of intervention	preventive	decoration	-	-	-
	repair	Partial	partial	partial	Partial
	-	Complete	complete	complete	Complete

Loss of cultural heritage

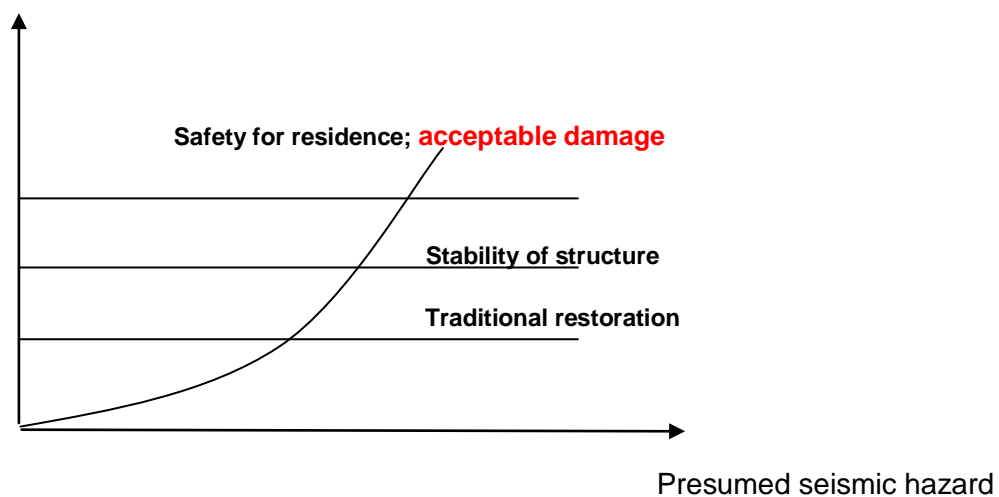


Figure 77 Level of intervention in Sistani House

7.3.7 Properties assumption and test results

Results of the laboratory tests have been done by Jäger & Braun at TU Dresden, (2007), [31]:

- Compression strength:

According to the accomplished tests, generally and for the examined materials, the fibre reinforcement has obviously no influence on compressive strength of the test specimens up to the occurrence of the first crack. The further increase of the compression load shows that the maximum compression strength of the fibre-reinforced cubes is significantly higher than the strength of non-reinforced test samples. A considerable increase of the energy absorption capability under compression due to the fibre reinforcement in the clay can be expected.

The New Mexico Earthen Building Materials Code has offered an average minimum compressive strength of 300 psi; it determined that one sample out of five may have a compressive strength of not less than 250 psi.

- Flexural tensile strength

The flexural tensile strength of the reinforced test specimens is generally slightly smaller than the strength of the non-reinforced test samples. This can be explained by the smaller content of clay due to the percentage of fibres. This reduction of clay results in the decrease of the flexural tensile strength. The load bearing capacity of reinforced test specimens after the first crack and energy absorption due to the fibres could not be determined because of the limitation of the measurement.

- Splitting test

The splitting tensile strength of the fibre reinforced test specimens is generally slightly smaller than the strength of the non-reinforced test samples. This can be explained, according to the measured reduction of the flexural tensile strength, by the smaller content of clay due to the percentage of fibres. The effects of the fibre reinforcement after the first crack and energy absorption could not be measured.

- Abrasive strength

The resistance of fibre reinforced adobe bricks against abrasion proved to be considerably higher than those of non-reinforced bricks. The fibres obviously reduce the attrition of material due to mechanical forces.

- Capillary water absorption

The testing results show that there is obviously no relation between the capillary water absorption of the adobe bricks and the content of palm fibres in the clay. Apparently the production process (soaking time of the clay) of the adobe bricks is more decisive for the speed of water absorption.

- Resistance against weathering

According to the test results, the fibre-reinforced adobe bricks show, on average, a slightly higher resistance against abrasion due to short, heavy rain. Obviously the production process of the adobe bricks (soaking time of the clay) is more important for the weathering resistance of clay bricks.

- Additive kinds

Five kinds of material have been tested:

Sisal, coconut, flax, hemp and palm fibres.

- Amount of the fibers

The test sample also serves as to the determination of the optimal amount of natural fibre in clay so the clay bricks can survive maximum compression and tensile forces; several samples from natural fibers mixed together with the clay. The final proposed mixture is 560g fibre and 35 kg clay or 16% of weight. The size of fibres is 4 cm; a minimum of 10 samples was tested.

- Size of adobe brick

The length of the test unit must be a minimum of twice the width.

- Mortar

The use of earth mortar is allowed if the earth mortar is of the same type as the adobe blocks.

7.3.8 Structural measures and technical methods

- Foundation

Earthen code has suggested a continuous footing at least 8 inches thick and not less than 2 inches wide on each side that supports the foundation stem walls above. All the foundation stem walls that support adobe units shall extend to an elevation not less than 6 inches above the finish grade, Jäger (2007).

According to the excavations there was not broadening of the footing exists. The existence of any former extension of the external wall could not be validated, so the existence of future rooms to the west of the nowadays-appearing west wall could not be proven. The vertical anchors inserted in the wall. These anchors are made of Glass fibres Rods with a diameter of 8 mm that run from the foundations up to the top of the wall. The rods are introduced with a distance of about one meter from each other into the remaining parts of the wall. The vertical anchors are tied to the foundation by a bundle of three rods that are forced apart by a spacer and inserted into a fine concrete. The vertical anchoring system provides on the one hand a strong between the old structure that have survived the earthquake and the newly erected walls in the course of reconstruction. It is planned to cope with strong vertical stress caused by the first seismic shocks.

- Bond beam

A ring beam of 8mm glass fire rods in cob clay is to cope with the shear forces resulting from the vaults of the ceiling.

Bond beams are courses of block constructed with special units designed to receive horizontal reinforcement and grout. These units are used to integrate the horizontal reinforcement with vertical reinforcement bars in a reinforced masonry wall. Bond beams often are placed at regular intervals in the wall to permit placement of more reinforcement than would be possible using bed joint reinforcement. Bond beams can be used in masonry bearing walls--to serve as horizontal members along the top of the walls, tying the walls together. They can be used below a line of bar joists, so that joist anchors can be embedded into the grout of the bond beam. Bond beams often are used as lintels over doors and windows. They sometimes are located at the bottom of walls that span over an opening to make a deep beam. Bond beam reinforcement also can be used for crack control. In this application, there must be a break between bond beams at the control joints in a wall. The area of steel required for bond beams used for crack control should be greater than that required for joint reinforcement. This is because the yield strength of the bars often is slightly less than that of the joint reinforcement and because the walls will undergo greater shrinkage due to the wetting effect of the grout during construction. Moisture from the grout causes the concrete masonry units to expand during construction. The CMUs will shrink as this moisture dissipates over time.

- Drilling

For the repair of cracks in the adobe masonry at the Arg-e Bam, braces designed for cracks in the form of a load-bearing anchor will be used. The brace is inserted by a drilled hole in the adobe masonry work, using shock mounting drilling technology, to prevent any damage to the remaining Adobe masonry. Such is also valid for removal of loosened clay from the drilling process, as the cleaning of the holes. For the determination of an appropriate method of drilling in the securing of different types of cracks, variable drilling methods have been tested for drilling holes varying in

diameter and inclination at an adobe masonry wall measuring 200*125*36.5 cm. Before the positioning of the brace and the filling material can be started, a cleaning of the drilled hole of loose material and drilling the debris is advisable. This can be achieved by the blowing of drilled hole with a hand held, commercial quality compressor or equally with an industrial quality vacuum cleaner. In addition to this, the surface area of the drilled hole should be brushed with a wire brush supplied by the company Hilti, to ensure a better fixing surface. Two kinds of drilling machines have been used in Sistani House, Jäger (2007):

Hilti spiral drill; hand operated with 40mm Diameter and 130cm length. Core drill; hand operated drilling machine, which has differing diameter 3 and 5 cm for dry lancing and air flushing.

- Anchoring

This is used for renovation of cracks in the citadel; the application of tension bearing anchor designed for connecting the two sides of the cracks is planned. The identification of suitable anchor materials and subsequent tension strength testing of the anchor has required the building of two-replica adobe bricks wall measuring 100*100*36.5 cm. Each wall, conserving the wall's thickness, has eight holes drilled with varying diameters(from 3cm-5cm) into which an anchor has been placed and fastened by the chosen grouting material.

Reinforced glass fibre in various designs was chosen for the anchor material and then its appropriateness tested. Glass fibre as reinforcement is chemically stable, inoffensive in the event of vermin attack. It has in comparison to steel reinforcement, a low modulus of elasticity; it is reasonably priced and does not corrode. Four different anchors were chosen for the tension test. For more information see the TU Dresden references, [30] and [31].

- Grouting

It is used for filling the drilled holes; and to grout the cracks and drilled holes with an injection pump. The filling material must be of a consistency that will allow it to be injected where desired. The grouting material would then be injected into the bored hole in the clay. The determination of material properties such as compression strength, bending tensile strength and splitting tensile strength of the test specimens made by the grouting material has been done at the laboratory of the TU Dresden. Different specimens of fine clay, bentonite, kaolin and coarse clay with gypsum and cement have been selected a fluid yet with little material shrinkage, grouting material which is strong. It should be possible to be utilized for a while after being mixed. It should produce a good fixing surface between the brace/anchor and adobe masonry.

For Bam Citadel, a kind of special hand pump has been used. The main advantage of using a hand pump is that the injection pressure is not too high and the risk to destroy the inner structure of the wall is very low. This pump should be controlled by the technician, who is working.

The grout was made only from natural adobe powder, hydrated lime, wallpaper paste and water. It was tested on partial damaged walls in the test laboratory of TU Dresden:

- Natural adobe powder (grain<1 mm), dry bulk density approximately 1.600 kg/cm³
- Lime hydrate as dry powder
- Wall paper paste (methyl cellulose, starch-natural material)
- Water

- Crack filling

In the identification of suitable technology for the cleaning and filling of the cracks, two test samples have been tried. Each has diameters of 75*75*50 cm. The design of this crack in these testing walls was chosen on so that the crack could be enlarged or shrunk as well as completely opened to control the results of the filling tests and to repeat the filling. For the first wall a mortar shot for the clay mortar has been used on the edge area of the crack. On the second wall the outer area of the crack was closed by wedging a quantity of clay in the crack the clay that mixed with natural fibres to ensure an improvement in strength and to reduce the shrinkage. Then the filling material was injected into inner parts with a pump. The grouting material used for the filling in the cracks was the same that has been applied for fastening the anchor in wall one (clay-cement grouting mixture) and wall two (clay –plaster grouting mixture).

- Shaped voids like Niche and Fireplace

Niches: 4 kinds of niches could be recognized; type 1: rectangular niche whose back upper edge is like a coving. Type 2: stands out due to a special emphasis of the upper groin of the niche. The covers of the niche are formed to a coving at the upper end and connected by a straight groin jumping up. Type 3: a pointed arch niche, which was executed. Type 4: a rectangular wall opening like Type 1, whose upper limitation area tapered toward behind, [26].



Figure 78 *Reconstruction of the niche and fireplace in Sistani House*

- Reinforcement

Experimental tests have been done to investigate the pull-out failure force. The bars built 36 cm into the wall, which is the tested anchor length. For standard glass fibre bar $d=8\text{mm}$ was built into drill hole $d=30\text{mm}$. The average maximum pull-out force for clay-cement grout was 9 KN. The numbers of bars for vertical reinforcement is 2 bars, for horizontal reinforcement 8 bars; for vault reinforcement 2 bars, [26].

Table 17 *A general view from documentation to performance in Sistani House*

Performance	lack							
	uncompleted							
	completed			✓		✓		✓
Risks								
	considered					✓		
Design	maintenance							
	stability							
	safety					✓		
Calculation	lack							
	uncompleted							
	completed							
Analysis	lack					✓		
	uncompleted	✓	✓				✓	
	completed			✓	✓	✓		✓
Field works	lack							
	uncompleted						✓	
	completed	✓	✓	✓	✓	✓		✓
Documents	lack							
	uncompleted	✓	✓				✓	
	completed			✓	✓	✓		✓
		historical	archaeological	architectural	functional	structural	geological	material

Table 18 *SWOT Table after the last restoration in Sistani House 2007*

Strength	<p>Integration with the environment</p> <p>Reconstruction of one of the main monuments in the Citadel</p> <p>Adapting a new technological method for adobe building</p> <p>Reliable public safety level</p>
Weakness	<p>High cost technology</p> <p>Depended and imported technology</p> <p>Invasive intervention</p>
Opportunity	<p>To use as an office, a repair to the level of public safety</p> <p>Training the local worker for this new technology</p>
Threats	<p>Uncompleted project</p> <p>Next earthquake</p> <p>Erosion</p> <p>Lack of permanent management</p>

7.4 Case Study 4 in Bam Citadel; Barracks

7.4.1 History

The governor complex consists of the military quarters and comprises the royal stable, the barracks and the residential premises of the army commander. ICHHTO believes that this dates back to the Seljuqid, and part of the Mongol and Timurid era, Behzadi (2004).

7.4.2 Definition of the plan

The Barracks is located at the north eastern end of the citadel. The height is 9 m in the citadel, 15 m lower than the Governor Seat. The total area is 5967 m². The area of the first floor is 1412 m² and at the second floor is 1420 m².

7.4.3 Values

The Barrack is the second largest building inside the Citadel and is also in one of the most important parts of the governor complex building. The historical documents prove that the political events affected the architecture of the building during its lifespan.

7.4.4 Repair history

In 1700 A.D, before being desolated, the citadel was repaired for the last time. Until 1782, people were living in the citadel, [42]; but the last settlement went back to the Qajar period, when the citadel used as a military foundation.

From 1868 up to 1880 was the last restoration for the habitants. It seems that the history of the direct usage of the citadel stopped here and a new period of the citadel's life was started.

Since 1941, the National Organization of Conservation of the Ancient Works had been responsible for Bam Citadel; it was completely uninhabited during this period of time.

It was repaired during 1978-1995 as a historical monument for the first time; most of the measures included the strengthening of the walls, restoration of the eastern part, strengthening the eastern walls and covering the roofs with Kahgel.

1948 The preliminary maps were made (includes the Governor Complex, the Chaharfasl and the Main Tower).

1966 It was entered on the National Heritage List (No.519).

1978 Archaeological excavation was done.

1979 Removal of the soil to know the floors.

1993 Restoration of the eastern part; also Bam Citadel become one of the important projects of ICHHTO.

1994 Restoration and structural supporting of the eastern part.

1995 Isolation of the roofs of the second store from "Kahgel".

Most of the restoration has been done in the eastern part.

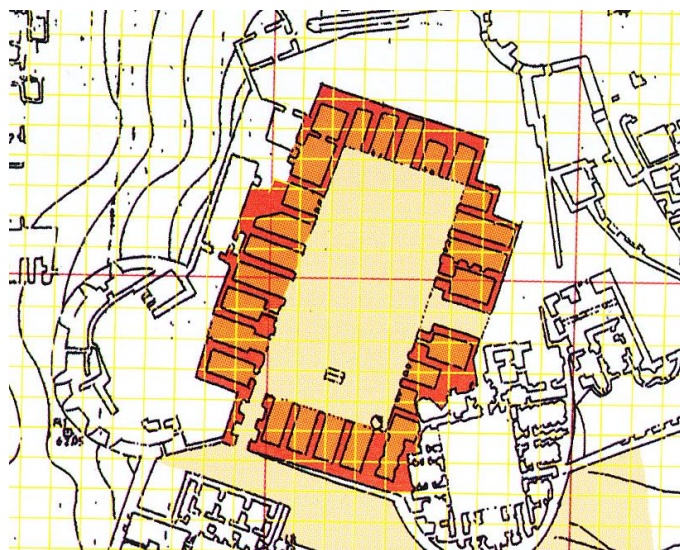
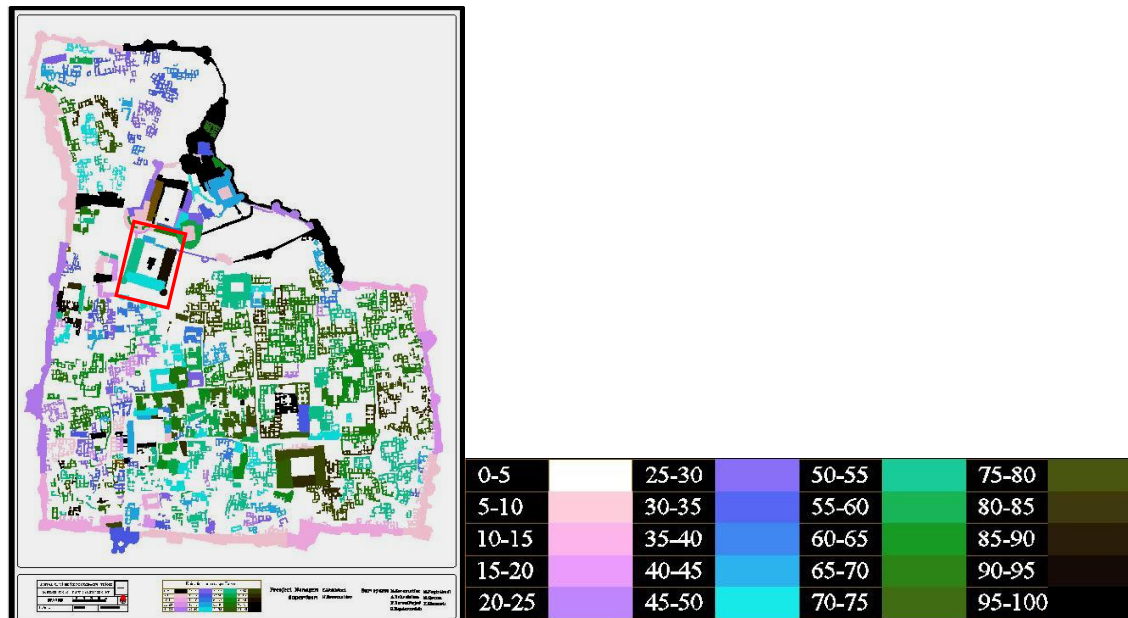






Figure 79 The eastern part of Barracks has been destroyed more than 95%. It is that part which has collapsed during the earthquake in 2003, [39].

Table 19 *Repair and restoration of Barracks*

Structure	System	Photo
Original	It was used as a barracks and as the photos show, the soldiers with the horses stayed there.	
After restoration 1973	Restoration and repair before the earthquake; traditional methods had been applied.	
After earthquake 2003	Most of the repaired parts were collapsed or crashed and deep cracks were seen at openings or between different layers.	
Restoration in 2007	The traditional methods have been applied in the Barracks and in some parts the heavy and weak parts have been removed, replaced and repaired.	

7.4.5 Decision after earthquake

Conservation and restoration of the whole body with consideration of the relation of the building with the whole citadel. In this method, the over weight of the construction removed and renewed by the adobe bricks 20*20*5 and the mortar with clay and more gypsum.

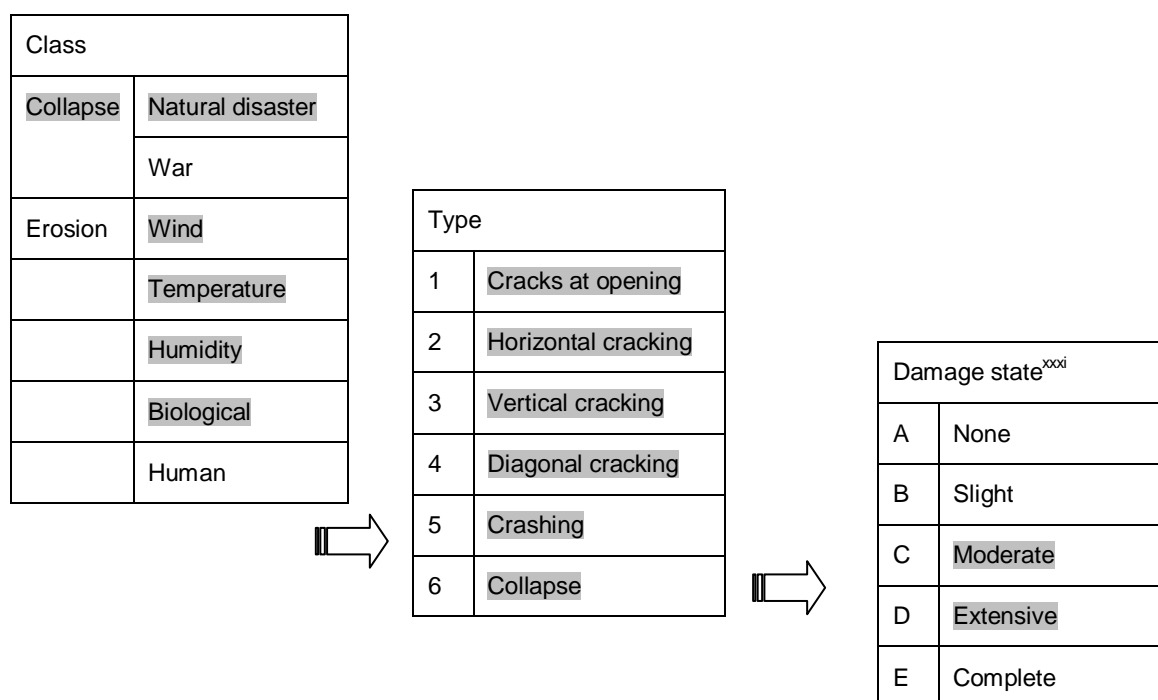
7.4.6 Archaeology

The investigation shows the foundation laid on the rock and built with the bricks 27*27*7, Farahbakhsh & Ejraei (2008), [11].

7.4.7 Technology concept

The concept of the technology follows the traditional methods as used many years ago. It is adjusted to the local potential in making adobe bricks and traditional methods without any consideration of the new to the developed techniques. Theoretical types of intervention, Farahbakhsh & Ejraei (2008):

Table 20 Approach and the rest of the intervention plans in the Barracks



^{xxxi}Table1 explains about the standard damages. Review it to find out the details.

Proposed level of intervention	Maintenance	Restoration	Reconstruction	Rebuild	Reproduce
	preventive	decoration	-	-	-
	repair	Partial	Partial	partial	Partial
	-	Complete	Complete	complete	Complete

Loss of cultural heritage

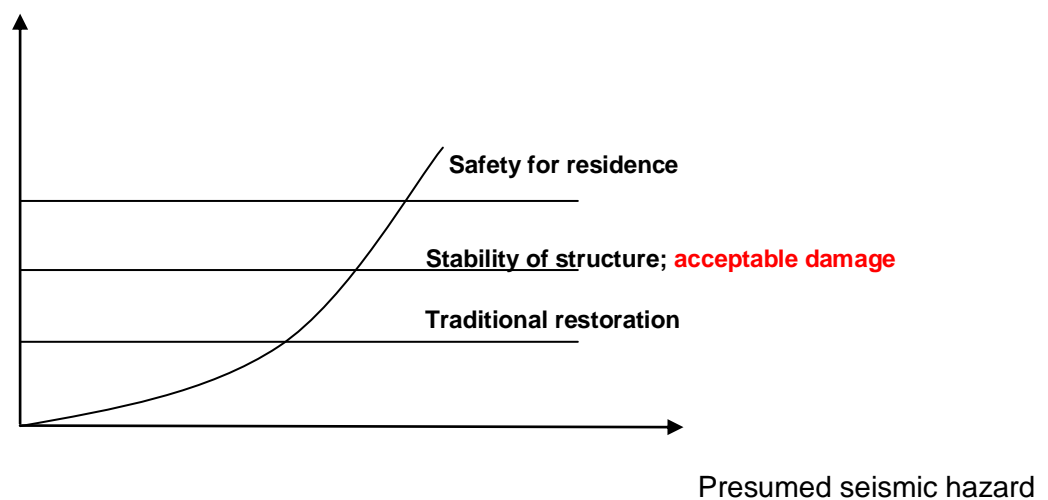


Figure 80 Restoration of the Baracks

Table 21 *A general view from documentation to performance in Barracks*

Performance	lack							
	uncompleted							
	completed	>	>	>	>	>	>	>
Risks	Not considred	>	>	>	>	>	>	>
	considered							
Design	maintenance							
	stability	>	>	>	>	>	>	>
	safety							
Calculation	lack					>		>
	uncompleted							
	completed							
Analysis	lack					>		
	uncompleted		>				>	>
	completed	>		>	>			
Field works	lack							
	uncompleted		>			>	>	>
	completed	>		>	>			
Documents	lack							
	uncompleted		>			>	>	>
	completed	>		>	>			
		historical	archaeological	architectural	functional	Structural	geological	material

Table 22 *SWOT Table after the last restoration, 2007*

Strength	<p>Integration with the environment.</p> <p>Preventive repair of one of the main monuments in the Citadel.</p> <p>Minimum repair to provide structural survivability.</p> <p>Keeping usage of traditional methods.</p> <p>Lightening the roofs and arches.</p>
Weakness	<p>This method is suitable for low-level seismic threats.</p> <p>The connections are still weak.</p> <p>Lack of scientific research and numerical calculation.</p>
Opportunity	<p>To revitalize a main monument in the Citadel.</p> <p>Improvement of the traditional method of restoration.</p>
Threats	<p>A subsequent earthquake</p> <p>Erosion</p> <p>Lack of permanent management</p>

8 Conclusions- Proposed solution

8.1 Management plans before and after the earthquake

The pre-earthquake management plan for Bam Citadel aimed at maintaining the current status as well as enhancing the intelligibility of the entire fabric of the Citadel. Thus interventions varied between preventive maintenance and repair to moderate and entire restoration, as pointed in Figure 81. The latter was reserved for buildings serving touristic or fictional purposes. Generally, restoration before the earthquake was limited to a traditional repair of the damaged areas with new adobes. But the result was not satisfactory, as shown in Table 23.



Figure 81 ICHHTO model of Bam Citadel, the restorations before the earthquake 2003

Most of the interventions before the earthquake were limited to superficial restoration. Only, in case the building was designated to be re-used, some measures of construction were taken. The technical quality of restoration and reconstruction measures proves that earthquakes were not considered a possible threat. The statistics (see references [66], [67], [68], [71]) on earthquakes in the region show that at least in the past hundred years, until 2003 no earthquake had shaken Bam. Both the historical remains of the monuments and particularly the reconstructed parts proved incapable to provide the necessary stability to endure the main shock of the earthquake. The high rate of destruction and the damage patterns after the earthquake 2003 showed that the traditional construction method desperately needs much more careful attention, thorough analysis and scientific upgrading.

Table 23 *Evaluation of the restoration and repair before and the earthquake*

Level of intervention & method of conservation before the earthquake	Location	Demolition percentage% after earthquake 2003, Keramatfar (2008)	Qualification of damages after earthquake 2003	Proposed Level of intervention after the earthquake
Minimum: maintenance	Konari-Neighborhood (Konari Mahalleh)	23.7	C,D	Preventive restoration
Moderate: restoration the architectural plan	Bazar	10-15	C, D	Restoration and reconstruction to protect structural survivability
	Main Mosque (Jame Mosque)	75-90		
	Dwelling in north west	50-95		
	Governor's Complex(Barracks and Seat)	5-95		
	Khaneghah	90-95		
	Western Quarter	30-35		
Complete: reconstruction and to use	Sistani House	40-75	C, D	Restoration and reconstruction to provide public safety
	Stable	45-95		
	Jame Mosque eastern side	75-90		
	Mirza Naeim Complex	35-90		
	Jewish Quarter	85-90		
	Bazar Stores, eastern part	40-45		

After the earthquake a new comprehensive management plan was set up. The first step was to measure the amount of damage to the Citadel and its components. Both the extents as well as the techniques of restoration were chosen according to these results and to the significance of the building.

After the earthquake, the new challenges were discussed, with reference to the conservation theory for historical property on one hand and modern engineering technologies for strengthening the adobe structure from the other hand. It is not always possible to follow all these principles at the same time, because often they contradict

each other. A very important subject to be addressed considering retrofitting measures is the question of reversibility of a measure.

The lifetime of different restoration approaches is another factor playing a very important role on decision making about the level of interventions and the selection of materials, especially in a climate like in the Bam Area, where the speed of erosion is so fast. Practical experiences in Bam offer duration times of different methods. According to this research three periods of time can be considered for different level of intervention^{xxdii}, according to deterministic model 25, 50 and 100 years; and due to the Weibul distribution, 15, 90 and 130 years.

It is useful for engineers to have a time factor for durability, compatibility and reversibility for selected techniques and the material. In the discussion on the choice of restoration techniques though only the code 2800 states a number for a lifetime. Yet this number refers to the lifetime of a newly erected building (50 years) and thus offers no indication whatsoever for lifetimes of different restoration techniques applicable in Bam (or comparable cases). The period of 15, 50 and 100 years are offered for three categories in the following. With a comparison between two models and considering the safety factor 15, 50 and 100 years has been presumed a lifetime of the structure to choose convenient technology and material for restoration and reconstruction.

8.2 Categorizing

Three different categories of buildings to be addressed in the Bam Citadel:

8.2.1 Category 1: Preventive restoration

Category 1 refers to two types of monuments, which are stable enough and the buildings that not functional. Often either the safety is enough or the priority is to keep and protect the authenticity.

The appearance of the buildings in this category is being protected and maintained but they will still be at risk of structural failures and damages during future seismic events. Also due to continuous erosion a permanent monitoring system is needed to avoid worsening of damage. Two examples of this category: The low class dwelling area to the northwest and the former windmill on the Castle hill west of the Second Wall, Figure 82. The Windmill has a stable structure. In either case minor restoration or protection measures are sufficient in order to prevent further degradation. Traditionally these measures are executed by repairing weakened parts or reconstructing an external wall layer Table 24. These measures do not aim at enhancing structural stability, but more at maintaining a given state. This method is being considered a minimum level of intervention by the management plans, before and after earthquake 2003. The 15 years duration could be suitable as lifetime for this kind of restoration.

^{xxdii} Review Chapter 7 of this thesis to consider the different level of interventions.

Table 24 *Level of intervention for preventive restoration*

Requirement	Damage status	Lifetime of restoration
Protection of the authenticity	B	Related to rate of erosion
Structural stability	B,C	Until the next earthquake
Public safety	B,C	Until the next earthquake

Figure 82 *Bam Citadel, left: Ammeh Neshin, right: Windmill*

8.2.2 Category 2: Survivability of the structure

Figure 83 shows three examples of restoration in Category 2. The Barracks on the right has been repaired by completion of the destroyed parts with no enforced adobe bricks according to the traditional methods. With this difference that the layers have been lightened. The middle one is a pilot project realized in a small part of the Stable. The bricklayers in this building were wrapped with the Geogrids; also these grids were put into the horizontal layers of the adobe masonry. The image on the left shows a small storage area that was reinforced with palm tree fibre meshes. All three examples were rebuilt and repaired to re-establish the original form of the structure and – in part – to enhance their stability.

Yet these methods are not based on engineering knowledge and are not proved sufficient stability for the structure avoiding collapse in a hypothetical earthquake. In addition, recognition of historical construction layers will be obscured and the experts will have to face historical ambiguity and archaeological doubt.

Category 2 concludes the monuments that need moderate restoration, moderately invasive and primarily not reversible measures, in combination with possible maintenance/repair operations. These operations are carried out applying traditional techniques, Table 25, and Figure 83.

The solutions corresponding to this category do not cause a significant alteration of pre-existing strength and resisting mechanisms of the structure. In fact the structure is repaired and rebuilt to revitalize the load bearing system. This method generally follows traditional restoration techniques used before the earthquake.

Furthermore structure and the materials are moderately improved with artificial or natural elements and additives. In spite of this improvement these restored buildings are not expected to withstand another seismic event. For that reason, the lifetime of these measures is less than earthquake time history, which according to this research could be considered 50 years.

Table 25 *Level of intervention for survivability of the structure*

Requirements	Damage status	Lifetime of restoration
Protection of the authenticity	C	Related to rate of erosion
Structural safety	C	Until the next earthquake
Public safety	C, D	Until the next earthquake



Figure 83 Applying meshes in Small Storage, Stable, and lightening in Barracks

8.2.3 Category 3: Safety for public

It includes solutions with the implementation of heavily invasive and irreversible techniques. The solutions in this category may cause a significant alteration of the stability of the structure and, in extreme cases, may even convey a partial or total functional substitution of the structure, as seen in Figure 84.

This kind of intervention is necessary for public facilities in the Citadel, e.g. buildings used as offices, stores, teahouse and information centre. These technologies have been verified by test runs, calculation and simulations. Both modern technologies as well as modern materials have been chosen. The example of this method is the Sistani House, in Figure 84, left side. In this project the adobe bricks have been improved with palm tree fibres and the structure was reinforced by vertical and horizontal glass fibre bars. Heavily damaged walls were retrofitted with grouting and anchoring. Table 26 states that the structural remains are not able to bear the load. In this case, especially when the building is under use, the priority is with reinforcement and consequently to provide public safety.

Yet it changes the natural loading system; it is comparably expensive and demands rather extensive technical skills.

Table 26 *Level of intervention for Public Safety*

Requirements	Damage status	Lifetime of restoration
Protection of the authenticity	C, D	Related to rate of erosion and the earthquake damages
Structural safety	C, D	Beyond the next earthquake
Public safety	C, D	Beyond to the next earthquake

The lifetime for this category is considered to be 100 years, according to the history of earthquakes and the two statistic models in chapter 6.



Figure 84 *Bam Citadel, top: Sistani House under restoration 2009, below: Tea-House (Second Gate before the earthquake in 2003)*

9 Recommendations

The earthquake, such as happened in the Bam area in December 2003, destroyed the physical character of the adobe historical buildings, damaged the authenticity of the Bam Citadel and caused adverse economic effects on tourism.

We always face essential questions with respect to the level of intervention in the Citadel; which method of conservation is the best solution for keeping authenticity and how it is possible to prolong the lifetime of the property. It is a fact that the traditional methods of restoration did not succeed during the last huge earthquake. Most of the valuable buildings were destroyed partly or collapsed totally and without a structural science, during the next seismic events, the result will be at least the same seismic damages in Bam Citadel again.

As a task, the decisions with respect to the damaged building in the Citadel could not always follow the conservation policies or the earthquake codes; they may not be adequate for study of the ancient structures; it is a case by case research and has to consider all the problems, needs and future risks. Any solution intended to improve the seismic response of the structure must be carefully analyzed for an adequate balance among the values, the status, and the new function and costs. This research has illustrated 3 different kinds of intervention in the Citadel to prolong the lifetime both in erosion (natural situation) and in the next disaster (next earthquake).

Category 1 provides some preventive instructions like maintenance for the buildings and decreases the speed of erosion and deterioration. It is recommended for all the kinds of buildings in the Citadel, however after a restoration or reconstruction because there are really few buildings with a low level of damages inside the Citadel after the earthquake 2003. According to the classification of the damages, category 2 and 3 supplies structural stability and safety for public with strengthening the structure during the earthquake. The category 2 is suggested moderate level of intervention. It obeys the traditional rules of restoration and reconstruction when the aim is to keep the original system of structure, to improve the structural character of the building, and to let people exit the building during the pending earthquake. It is the minimum of intervention and the stability of the structure is under danger. Category 3 is aimed at protecting human life, ensuring that the structure will not collapse upon its occupants or passersby, and the structure can be kept safely. It concludes all methods of reinforcement like tying, anchoring and injection to join the old and new parts of the structure. Most of the measures may not be reversible but they have to be visible and expose some part as much as possible; as the glass bars and the meshes are visible on the walls and the ceilings in Sistani House.

According to the weak properties and fast rate of the erosion of the adobe structure, the reversibility may not be suitable for a short period of time. Dismantling the structural elements may cause more risks because almost always the original structure suffers from the weak connections between dried mortar and adobe bricks. Durability ensures the structural safety with the glass fibre bars and meshes; the original structure is not threatened by the loss of efficiency of the strengthening because of the long lifetime of the bars.

As Chapter Eight of this research has illustrated 15, 50 and 100 years is the duration that has been considered for any categories. For future researchers, I offer two important items, which are necessary to improve the lifetime of the material; if a longer lifetime for a building is needed, durability of the material could be studied and in this regard the compatibility of the material and the common function with the adobe could be a very interesting research for the future.

Durability: The applied material must be always used according to the lifetime of the historical property. In this regards the time history of the earthquake and compatibility should be noticed. To have precise results about the durability of the adobe structures, the adobe material and mortars, the natural additives, and the elements could be very helpful subjects for future research.

Compatibility: There are three kinds of compatibility.

- **Chemical compatibility:** Corrosion of glass fibres in cement matrices is due to the calcium hydroxide content of hydration products, but low amounts of alkali hydroxides play a considerable role too.
- **Thermal compatibility:** Glass fibre products loose their structural water within the investigated temperature range. In this regard both the environmental temperature and also the temperature of the chemical mix have important roles. To have a good comparison it is good to know that for concrete, this amount is 5-12, for reinforced concrete it is 10, and for stainless steel it is 15.

The question is if the mortar has any interaction with the glass fibres or not?

- **Mechanical compatibility:** the question is why we decided to use this material inside the adobe layers and which kinds of specifications change after that.

Finally, reversibility for adobe historical building is meaningless, while it is impossible to return back to the original situation. Adobe bricks have somewhat of a life force. They are removable and are comparable with human the cell. New technologies are available to prolong the lifetime of the properties, decrease the speed of the erosion and to avoid the collapse of the valuable buildings. It is very important because it brings hope and trust for the local masons and motivates people to protect adobe buildings and other properties with satisfaction. There is still a serious lack of the regulation and code for historical buildings is in Iran, especially in seismic zones like Bam Area.

10 Illustration Credits

Figure 1, pp. 15: www.thetistravel.com/en/iran-map-cities

Figure 2, pp. 16: Photo from archive of recovery project of Bam's cultural heritage. The text has been written on the photo: No 41-5621&41-5622. Department of the Documents, Institute for Contemporary History of Iran, Bam, 1930

Figure 3, pp. 17: Photo from archive of recovery project of Bam's cultural heritage. The text has been written on the photo: No 42-655&42-656. Department of the Documents, Institute for Contemporary History of Iran, Bam, 1930

Figure 4, pp. 17: Photo from archive of recovery project of Bam's cultural heritage. The text has been written on the photo: No S151-10 & 44-2232. Department of the Documents, Institute for Contemporary History of Iran, Bam, 1930

Figure 5, pp. 18: Photo from archive of recovery project of Bam's cultural heritage; the photographer is not identified.

Figure 6, pp. 19: From archive of recovery project of Bam's cultural heritage; the draftsman is not identified.

Figure 7, pp. 20: From archive of recovery project of Bam's cultural heritage; the draftsman is not identified; with considering the similarity of the Farsi fonts with the first management plan of Bam Citadel, probably has been provided between 1979 up to 1990.

Figure 8, pp. 21: From archive of recovery project of Bam's cultural heritage; by Hanieh Banki, restoration expert at Recovery Project of Bam's Cultural Heritage, 2009

Figure 9, pp. 22: Photo from archive of recovery project of Bam's cultural heritage; National Cartographic Centre, www.ncc.org.ir, 1956

Figure 10, pp. 23: Photo from archive of recovery project of Bam's cultural heritage; the photographer is not identified.

Figure 11, pp. 24: Photo from archive of recovery project of Bam's cultural heritage; the photographer is not identified.

Figure 12, pp. 24: Photo from archive of recovery project of Bam's cultural heritage; the photographer is not identified.

Figure 13, pp. 25: Photo from archive of recovery project of Bam's cultural heritage; the photographer is not identified.

Figure 14, pp. 26: From archive of recovery project of Bam's cultural heritage; by Hanieh Banki, restoration expert at Recovery Project of Bam's Cultural Heritage, 2009

Figure 15, pp. 27: Photo from archive of Kerman Cultural Heritage; a photo from a poster; it is not identified.

Figure 16, pp. 28: Photo has been taken after the earthquake in 2003, by Babak Sedighi, photographer at recovery project of Bam's cultural heritage; sedighi.babak@gmail.com, 2007

Figure 17, pp. 28: Photo from archive of recovery project of Bam's cultural heritage; the photographer is not identified.

Figure 18, pp. 29: Photo from archive of recovery project of Bam's cultural heritage; the photographer is not identified.

Figure 19, pp. 30: Photo from archive of recovery project of Bam's cultural heritage; the photographer is not identified.

Figure 20, pp. 31: Photo from archive of recovery project of Bam's cultural heritage; the photographer is not identified.

- Figure 21, pp. 32: Photo from archive of recovery project of Bam's cultural heritage; the photographer is not identified.
- Figure 22, pp. 34: Photo from archive of recovery project of Bam's cultural heritage; the photographer is not identified.
- Figure 23, pp. 35: Photo from archive of recovery project of Bam's cultural heritage; the photographer is not identified.
- Figure 24, pp. 35: Photo from archive of recovery project of Bam's cultural heritage; the photographer is not identified.
- Figure 25, pp. 36: Photo from archive of recovery project of Bam's cultural heritage; the photographer is not identified.
- Figure 26, pp. 36: Photo has been taken after the earthquake in 2003, by Babak Sedighi, photographer at recovery project of Bam's cultural heritage; sedighi.babak@gmail.com, 2007
- Figure 27, pp. 37: Photo has been taken after the earthquake in 2003, by Babak Sedighi, photographer at recovery project of Bam's cultural heritage; sedighi.babak@gmail.com
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- Figure 31, pp. 42: The photo before the earthquake is selected from archive of recovery project of Bam's cultural heritage; the photographer is not identified. After the earthquake is by Babake Sedighi, photographer at recovery project of Bam's cultural heritage; sedighi.babak@gmail.com, 2004
- Figure 32, pp. 43: The photo before the earthquake is selected from archive of recovery project of Bam's cultural heritage; the photographer is not identified. After the earthquake is by Babake Sedighi, photographer at recovery project of Bam's cultural heritage; sedighi.babak@gmail.com, 2004
- Figure 33, pp. 43: The photo before the earthquake is selected from archive of recovery project of Bam's cultural heritage; the photographer is not identified. After the earthquake is by Babake Sedighi, photographer at recovery project of Bam's cultural heritage; sedighi.babak@gmail.com, 2004
- Figure 34, pp. 45: Photo has been taken after the earthquake in 2003, by Mahmoud Nejati, deputy of research at recovery project of Bam's cultural heritage; nejati.office@gmail.com
- Figure 35, pp. 46: Photo has been taken after the earthquake in 2003, by Mahmoud Nejati, deputy of research at recovery project of Bam's cultural heritage; nejati.office@gmail.com
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- Figure 37, pp. 47: Photo has been taken after the earthquake in 2003, by Babak Sedighi, photographer at recovery project of Bam's cultural heritage; sedighi.babak@gmail.com, 2003
- Figure 38, pp. 49: Photo has been taken after the earthquake in 2003, by Babak Sedighi, photographer at recovery project of Bam's cultural heritage; sedighi.babak@gmail.com, 2003

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- Figure 40, pp. 52: Photo has been taken after the earthquake in 2003, by Babak Sedighi, photographer at recovery project of Bam's cultural heritage; sedighi.babak@gmail.com, 2003
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- Figure 42, pp. 53: Photo has been taken after the earthquake in 2003, by Babak Sedighi, photographer at recovery project of Bam's cultural heritage; sedighi.babak@gmail.com, 2003
- Figure 43, pp. 54: Photo has been taken after the earthquake in 2003, by Babak Sedighi, photographer at recovery project of Bam's cultural heritage; sedighi.babak@gmail.com, 2003
- Figure 44, pp. 54: Photo has been taken after the earthquake in 2003, by Babak Sedighi, photographer at recovery project of Bam's cultural heritage; sedighi.babak@gmail.com, 2003
- Figure 45, pp. 55: Photo from archive of recovery project of Bam's cultural heritage; the photographer is not identified.
- Figure 46, pp. 56: Photo has been taken after the earthquake in 2003, by Mahmoud Nejati, deputy of research at recovery project of Bam's cultural heritage; nejati.office@gmail.com
- Figure 47, pp. 57: Climate report, from archive of recovery project of Bam's cultural heritage, Bam, 2005
- Figure 48, pp. 58: Climate report, from archive of recovery project of Bam's cultural heritage, Bam, 2005
- Figure 49, pp. 59: Photo by Christian Fuchs; c.fuchs@winterfuchs.de
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- Figure 58, pp. 74: by Shirin Shad
- Figure 59, pp. 76: website of IIEES, Tehran, Iran 2003

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- Figure 70, pp. 98: by Shirin Shad
- Figure 71, pp. 100: Photo has been taken after the earthquake in 2003, by Babak Sedighi, photographer at recovery project of Bam's cultural heritage; sedighi.babak@gmail.com
- Figure 72, pp. 104: top: Keramatfar, M.: Calculation of the amount of the damages in the earthquake in 2003, in Bam Citadel. In: Annual report of Arg-e Bam research foundation. Resaneh Pardaz-Paygah-e Pazhooheshi-e Bam: Tehran 2008, p. 93. Bottom: Photo from archive of recovery project of Bam's cultural heritage.
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- Figure 74, pp. 107: by Mahmoud Nejati, Deputy of Research at recovery project of Bam's cultural heritage; nejati.office@gmail.com
- Figure 75, pp. 108: by Shirin Shad
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- Figure 77, pp. 115: by Shirin Shad
- Figure 78, pp. 119: Photo by Christian Fuchs; c.fuchs@winterfuchs.de
- Figure 79, pp. 123: Keramatfar, M.: Calculation of the amount of the damages in the earthquake in 2003, in Bam Citadel. In: Annual report of Arg-e Bam research foundation. Resaneh Pardaz-Paygah-e Pazhooheshi-e Bam: Tehran 2008, p. 93
- Figure 80, pp. 126: by Shirin Shad
- Figure 81, pp. 129: Photo by Randolph Langenbach, 2004
- Figure 82, pp. 132: Photo has been taken after the earthquake in 2003, by Babak Sedighi, photographer at recovery project of Bam's cultural heritage; sedighi.babak@gmail.com
- Figure 83, pp. 134: Photo has been taken after the earthquake in 2003, by Babak Sedighi, photographer at recovery project of Bam's cultural heritage; sedighi.babak@gmail.com

Figure 84, pp. 135: Photo from Sistani House, Bam Citadel, by Christian Fuchs; c.fuchs@winterfuchs.de. The old photo (Second Gate and Tea House) is selected from archive of recovery project of Bam's cultural heritage; the photographer is not identified.

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12 Appendix 1, aftershocks in Bam area, [66]

DATE	TIME	LAT-N	LONG-E	DEPTH	mb	Ms	ML	REGION
2003/12/26	01:56:56.1	29.08	58.38	13.2		6.5		BAM
2003/12/26	02:34:20.3	28.98	58.33	15.0			3.8	BAM
2003/12/26	03:06:16.0	28.91	58.32	15.0		5.1		BAM
2003/12/26	03:21:08.7	28.40	58.47	15.0			3.9	BAM
2003/12/26	03:31:21.6	28.36	58.36	15.0			3.4	BAM
2003/12/26	03:37:37.8	28.91	58.19	15.0			3.6	BAM
2003/12/26	03:53:29.7	28.90	58.42	15.0		4.6		BAM
2003/12/26	04:25:51.7	29.03	58.27	15.0			3.6	BAM
2003/12/26	04:51:44.5	28.90	58.37	15.0			3.7	BAM
2003/12/26	09:16:41.6	29.03	58.23	15.0			3.8	BAM
2003/12/26	09:22:29.0	29.00	58.22	15.0			2.8	BAM
2003/12/26	09:25:39.0	29.01	58.28	15.0			3.0	BAM
2003/12/26	09:37:28.4	28.97	58.24	15.0			2.7	BAM
2003/12/26	09:42:48.5	28.84	58.11	15.0			3.2	BAM
2003/12/26	10:00:03.8	28.97	58.17	15.0			3.6	BAM
2003/12/26	14:08:17.0	28.56	58.32	12.0		4.0		BAM
2003/12/27	04:45:47.6	28.65	58.34	15.0			3.5	BAM
2003/12/27	05:42:09.6	28.85	58.27	15.0			3.7	BAM
2003/12/27	06:26:35.1	28.94	58.31	15.0			2.8	BAM
2003/12/27	08:03:16.0	28.65	58.22	15.0			3.2	BAM
2003/12/27	08:10:31.2	29.38	58.03	15.0			2.9	BAM
2003/12/27	09:10:19.8	28.39	58.49	15.0			3.0	BAM
2003/12/27	10:48:36.4	28.50	58.37	15.0			2.7	BAM
2003/12/27	14:10:55.2	29.05	58.10	15.0			2.6	BAM
2003/12/27	15:13:31.1	29.32	58.08	15.0			2.7	BAM
2003/12/28	08:51:58.9	29.09	58.19	15.0			2.5	BAM

2003/12/28	09:25:27.7	28.81	58.38	15.0	3.6	BAM
2003/12/28	10:15:31.5	28.96	58.41	15.0	2.5	BAM
2003/12/28	11:52:25.6	28.84	58.40	15.0	2.5	BAM
2003/12/28	19:00:35.0	28.98	58.37	15.0	2.4	BAM
2003/12/28	19:34:11.6	29.19	58.35	15.0	2.3	BAM
2003/12/28	20:44:03.0	28.21	58.52	15.0	2.4	BAM
2003/12/28	20:53:11.3	28.34	58.37	15.0	2.4	BAM
2033/12/28	23:18:22.0	29.31	58.32	15.0	2.6	BAM
2003/12/29	04:20:33.7	29.21	58.12	15.0	2.4	BAM
2003/12/29	06:45:49.9	28.61	58.61	15.0	2.8	BAM
2003/12/29	07:01:22.7	28.83	58.45	15.0	3.1	BAM
2003/12/29	09:32:51.0	29.37	58.13	15.0	2.6	BAM
2003/12/28	14:56:38.6	28.47	58.48	15.0	3.5	BAM
2003/12/29	13:02:05.2	29.21	58.36	15.0	2.7	BAM
2003/12/29	13:33:51.2	28.80	58.26	15.0	2.4	BAM
2003/12/29	13:49:11.5	29.03	58.23	15.0	2.3	BAM
2003/12/29	14:45:24.2	29.36	58.19	15.0	2.3	BAM
2003/12/29	16:52:06.0	29.50	58.44	15.0	2.5	BAM
2003/12/29	17:37:42.3	28.23	58.62	15.0	2.5	BAM
2003/12/29	13:02:05.2	29.21	58.36	15.0	2.7	BAM
2003/12/29	18:42:14.9	29.38	58.18	15.0	2.3	BAM
2003/12/29	19:15:14.1	29.10	58.32	15.0	2.6	BAM
2003/12/29	20:03:27.2	28.50	58.47	15.0	2.7	BAM
2003/12/29	22:50:17.5	28.79	58.12	15.0	2.6	BAM
2003/12/30	00:53:33.9	29.41	58.17	15.0	2.5	BAM
2003/12/30	07:28:08.0	29.21	58.24	15.0	2.3	BAM
2003/12/30	11:41:56.2	29.22	58.23	15.0	2.4	BAM
2003/12/30	12:15:35.9	29.04	58.17	15.0	2.5	BAM
2003/12/30	12:35:22.2	29.24	58.18	15.0	2.6	BAM

2003/12/30	13:32:18.9	29.19	58.26	15.0	2.2	BAM
2003/12/30	14:23:12.3	29.08	58.34	15.0	2.2	BAM
2003/12/30	20:00:29.3	28.94	58.28	15.0	2.9	BAM
2003/12/30	22:20:54.6	28.48	58.66	15.0	2.6	BAM
2003/12/31	03:14:05.7	29.09	58.13	15.0	2.4	BAM
2003/12/31	07:35:54.5	28.61	58.42	15.0	3.2	BAM
2003/12/31	11:46:21.6	29.31	58.30	15.0	2.4	BAM
2003/12/31	13:30:58.6	29.23	58.27	15.0	2.1	BAM
2003/12/31	13:43:44.3	29.17	58.19	15.0	2.6	BAM
2003/12/31	15:38:01.0	28.97	58.26	15.0	2.5	BAM
2003/12/31	18:49:43.7	29.10	58.29	15.0	3.0	BAM
2004/01/01	05:17:07.1	28.69	58.57	15.0	2.3	BAM
2004/01/01	08:00:30.2	29.11	58.24	15.0	2.3	BAM
2004/01/01	09:14:13.0	29.46	58.24	15.0	2.5	BAM
2004/01/01	10:45:52.0	29.26	58.29	15.0	3.2	BAM
2004/01/01	12:10:47.0	28.56	58.56	15.0	2.4	BAM
2004/01/01	13:45:17.3	29.18	58.17	15.0	3.4	BAM
2004/01/01	14:31:28.3	28.70	58.43	15.0	2.3	BAM
2004/01/02	06:12:12.1	28.93	58.43	15.0	2.3	BAM
2004/01/02	09:49:48.2	29.25	58.16	15.0	2.5	BAM
2004/01/02	13:30:59.2	28.90	58.17	15.0	2.7	BAM
2004/01/02	18:21:20.9	28.41	58.51	15.0	3.3	BAM
2004/01/03	00:39:34.2	28.90	58.40	15.0	2.3	BAM
2004/01/03	04:29:09.9	28.92	58.19	15.0	2.4	BAM
2004/01/03	13:48:01.5	29.46	58.17	15.0	2.5	BAM
2004/01/03	19:50:24.5	29.18	58.20	15.0	3.0	BAM
2004/01/03	22:40:28.4	28.85	58.35	15.0	2.6	BAM
2004/01/04	18:29:23.7	28.96	58.30	15.0	3.6	BAM
2004/01/04	20:43:16.3	28.81	58.26	15.0	3.1	BAM

2004/01/05	06:02:02.5	29.10	58.29	15.0	2.7	BAM
2004/01/05	11:42:56.9	28.74	58.15	15.0	2.3	BAM
2004/01/05	18:34:52.6	29.39	54.34	15.0	2.7	BAM
2004/01/05	20:41:36.8	28.78	58.28	15.0	2.6	BAM
2004/01/06	01:00:28.4	28.83	58.30	15.0	2.1	BAM
2004/01/06	17:49:44.2	29.35	58.24	15.0	2.6	BAM
2004/01/07	11:15:53.0	29.16	58.29	15.0	2.7	BAM
2004/01/09	02:51:28.9	29.23	58.26	15.0	2.5	BAM
2004/01/10	12:58:04.6	28.70	58.45	15.0	2.8	BAM
2004/01/11	05:06:17.3	29.14	58.29	15.0	3.6	BAM
2004/01/12	05:10:24.5	29.20	58.23	15.0	2.4	BAM
2004/01/12	21:07:20.5	29.03	58.31	15.0	2.3	BAM
2004/01/13	00:13:51.6	29.20	58.12	15.0	2.3	BAM
2004/01/13	01:36:59.7	29.03	58.10	15.0	2.5	BAM
2004/01/13	06:45:52.0	29.34	58.39	15.0	2.5	BAM
2004/01/14	02:18:07.0	28.66	58.41	15.0	3.2	BAM
2004/01/14	12:34:21.6	29.25	58.26	15.0	2.4	BAM
2004/01/14	21:50:05.2	29.13	58.29	15.0	2.4	BAM
2004/01/16	04:08:10.0	28.48	58.44	15.0	2.7	BAM
2004/01/16	06:50:14.0	29.23	58.30	15.0	2.2	BAM
2004/01/16	06:53:27.9	28.87	58.45	15.0	2.4	BAM
2004/01/17	02:54:04.0	29.11	58.15	15.0	2.4	BAM
2004/01/20	13:23:05.7	29.34	58.02	15.0	3.8	BAM
2004/01/23	00:35:04.3	29.01	58.19	15.0	2.6	BAM
2004/01/28	13:22:44.7	29.03	58.10	15.0	3.1	BAM
2004/01/28	17:29:40.8	28.94	58.24	15.0	3.9	BAM