

COLLAPSE FROM THE INSIDE-OUT
THE IMPACT OF THE 2003 BAM, IRAN EARTHQUAKE ON THE EARTHEN
ARCHITECTURE OF THE ARG-E BAM

By
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Figure 1: The Arg-e Bam before and after the earthquake. *Before photo courtesy Kerman Province*

ABSTRACT

The Arg-e Bam is a remarkable example of earthen architecture and construction that was heavily damaged in the Bam, Iran earthquake of 26 December 2003. This paper presents the hypothesis that the collapse of the walls was caused largely by a combination of the effects of (1) the additive changes made to the walls, particularly in recent restorations resulting in variations in the density and response to vibrations of different layers of unfired earth construction in the walls, and (2) extensive damage from termites and loss of the cohesion of the clay from degradation and excessive drying out, all of which interacted with the earthquake vibrations of unusually high frequency in such a way that many walls effectively burst from the subsidence of their clay internal cores. Concern is raised about the possibility of similar previously unrecognized risks to other earthen monumental structures from future earthquakes.

INTRODUCTION:
THE CITADEL AND WALLED CITY OF BAM

The Arg-e Bam has been identified as the world's largest complex entirely of earthen construction. Settlement on the site is said to date back as much as 2000 years, with many of the structures and archeological remains that are currently visible dating from 1300 to 1800. Despite its history as a fortified site, all of the battlements, turrets and buildings in the Arg were composed of unfired earth. Unlike many earthen monuments that are clad with brick or stone, the structures in the Arg were entirely composed of unfired earthen construction. The numerous arches, vaults and domes were constructed of sun-dried bricks, often using techniques of construction that avoided the need for structural centering. This construction was of two distinct types – unfired “adobe” masonry, known in Farsi as “*Khesht*,” and built up earth or “cob” construction, known as “*chineh*”¹ (Figure 2) Both types of construction could be found in many of the structures, sometimes in layers where the later work, including 20th century restoration work, would be in *Khesht*, while the original work would be *chineh*.

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Figure 2: *Chineh* wall inside the Arge Bam that was only slightly damaged in the earthquake.

As an archeological site, many of the structures in the Arg were already in ruins prior to the time of the earthquake. The walled town was gradually abandoned in the nineteenth century as people migrated out to houses located in the date palm orchards nearby. Gradually, the houses and public buildings in the Arg fell into ruin through a slow process of erosion of the earthen walls and domes. Only the structures on the rock outcropping continued to be used and maintained as a military base ,until vacated under orders from Reza Shah following the demise of the Qajar Dynasty in 1925 (Figure 3).



Figure 3: Late Qajar Period (19th Century) view showing soldiers in the inner citadel.

Beginning in 1953, the site became recognized as a nationally significant historic site and a gradual process of conservation and restoration began. Most of the restoration work has been carried out over the past 25 years. Some of the ruins in the shadow of the military citadel were restored back into complete buildings. The final step in this restoration process was to plaster the exterior surfaces with a layer of mud plaster reinforced with straw. Most of this modern-day restoration work appears to have been done with square sun-dried bricks, rather than in *chineh*

THE BAM EARTHQUAKE OF DECEMBER 26, 2003

The earthquake that visited upon Bam in the early morning of December 26, 2003, struck with a suddenness and ferocity that bore little relation to its comparatively modest magnitude of 6.5. There have been few past earthquakes to prepare one for the extent of the destruction seen both in the Arg and in the modern town adjacent to it. There was hardly a single building type, ancient or modern, that did not suffer total destruction. Even many of the steel frame buildings constructed over the last decade ended up with their steel frames wrapped into shapes like pretzels on top of heaps of crumpled infill masonry walls and floors. In the case of the ancient Arg, little remained inside its walls of what had been whole buildings that had been restored over the previous half-century. A sea of rubble extended out as far as the eye could see (figure 4 & 13). Even the Governor's House and Tower astride the hill that formed the central symbolic image for the site disappeared, leaving behind ruins that resembled a natural rock outcropping, untouched by human hands (Figure 1). (See Figure 25 for location of sites)



Figure 4 View of the ruins of the Arg-e Bam.

Many engineers and seismologists have pointed to the intensity of the Bam earthquake itself as sufficient to explain much of the damage to earthen structures. The seismograph records show that the vertical component of the vibrations near the site of the Arg was greater than the horizontal component, reaching a level of almost 1g. With such intense vertical vibration, the loads on the earthen walls were rapidly cycled from a loss of their overburden weight to having to sustain double that weight. Because, in general, buildings are designed to carry well more than their own weight, the vertical earthquake forces generally have not been considered to be as dangerous as the lateral forces. However, for earthen construction, when the overburden weight on the walls is reduced or eliminated, the lateral forces can be far more destructive than if there were only lateral motion. In

addition, with vertical forces of almost 1g, the ancient walls were forced to sustain almost double their weight with each cycle. As will be described below, the degraded state of the inner cores of some of these walls may simply have been unable to sustain this momentary additional weight.

Even so, the extent of the collapses in the Arg was greater than one would have expected. There was almost no middle ground. With the notable exceptions described below, almost every structure suffered partial or total collapse into formless piles of rubble. Of those parts that did survive; some structures came through with remarkably little damage.

What occurred to cause all of this damage? Is it explained by the intensity of the shaking alone? In a comprehensive ten-year research project on the seismic behavior and protection of historic adobe building by the Getty Conservation Institute, the researchers concluded that “*It is often assumed that an unreinforced masonry structure (such as adobe or brick) is safe only while it is largely undamaged, that is, if it has not sustained substantial cracking. The usual analysis assumes that once cracks have developed the materials have lost strength and continuity – and therefore the building is unsafe. However, a thick-walled adobe building is not unstable after cracks have fully developed, and the building still retains considerable stability characteristics even in that state.*”² Since it took only a little over 10 seconds for the earthquake not only to crack, but to collapse much of the Arg-e Bam, the Getty project’s important findings on adobe structures clearly were not applicable to this site in this earthquake.

Why did the walls and vaults of the Arg prove to be so unstable? Shouldn’t the structures and ramparts, with their thick earthen walls, have remained standing, even if heavily cracked? Were they simply overwhelmed by the unusually large surface shaking for a 6.5 earthquake, or is this now an unsettling exception to the Getty Seismic Adobe Project’s findings that disproves the rule? In either case, does this mean that the rest of Iran’s most celebrated monuments, many of which are largely constructed of unfired earth, will eventually suffer the same fate?

In spite of the extent of destruction in the Arg (as the ancient walled -city is called), it is important to correct one misimpression that has served to call into question the safe continued use of buildings of unfired earthen construction throughout the world. The news accounts that spread around the world gave the impression that tens of thousands of people died in ancient mud buildings. Instead, almost all of the 30,000 who died in the earthquake were in buildings that were less than thirty years old.³ For five decades prior to the earthquake, the Arg was an archeological museum. At the time of the earthquake, which occurred at 5:26 am, only three people were sleeping in the Arg complex. The two guards sleeping in the gatehouse were killed, but the chief conservator, who was sleeping in the archeology office in the Arg, was rescued from under the rubble. Had the earthquake happened during the daytime, there undoubtedly would have been more fatalities in the Arg, but it is important to note that the massive loss of life from this earthquake was almost entirely the result of the collapse of *modern* buildings – buildings constructed not only of unfired earthen masonry, but also of steel and concrete.

The destruction of earthen and masonry structures in large earthquakes is often accepted by observers as inevitable. Thus, inquiry into the causes of such destruction often stops with the analysis of the lateral forces measured against the capacity of the unreinforced earthen structures without consideration of other factors such as pre-existing pathologies. Yet one important anomaly in the damage distribution in the Arg-e Bam flies in the face of this common assumption – *those structures that had not been recently maintained or restored survived with significantly less damage than did those that had been restored and even strengthened in recent years.* (Figures 2, 5, 11, 18, 22)



Figure 5: This unrestored ancient earthen structure, the Shahrbast Wall, was only lightly damaged by the earthquake despite the height of its unbuttressed earthen walls. Earthquake damage to this archeological ruin is evident only where there is debris on the ground. Notice the height of the walls compared to the figure in the middle distance.

TERMITE DAMAGE IN THE ARG

During the four months that followed the December 26, 2003 earthquake that destroyed much of the Iranian desert city of Bam, much has been said in the international press about the damage to the Arg-e Bam. Nowhere in this coverage, however, was there any mention about *termites*. While attending the *International Workshop on Bam* sponsored by UNESCO, ICOMOS, and the Iranian Cultural Heritage Organization (ICHO) I noticed evidence of an insect infestation in the broken remains of the city's walls. The Iranian archeologists working on the site identified the insects as termites, explaining to me that such termites are relatively common in Iran. In contrast to the archeologists working at the site, few conservation architects or engineers who had come to Bam to observe the damage during the preceding four months that followed the earthquake either noticed or were aware of the existence of the extensive termite infestation of the Arg.

While there is no question but that termites did not *cause* the destruction of the historic Arg-e Bam, the evidence of extensive infestation in the ancient earthen monument was unmistakable (Figure 6). This raises the following question: *Did this infestation contribute to the extraordinarily large amount of earthquake damage?* While it took only 12 seconds for the earthquake to shake this majestic monument down into formless piles of rubble, the seeds of its destruction in this earthquake may have been laid over the many centuries of continuous erosion, decay, and rebuilding that have taken place on the site.



Figure 6: Evidence of termite damage in a wall of the Arg-e Bam showing extensive deposits of frass with insect tunnels.

This question of the importance of the termites as a factor in the earthquake induced collapses was debated during the *International Workshop on Bam*, without arriving at a single consensus. The observation and discussion was, however, valuable in that awareness of this particular pathology has now been increased throughout Iran. In terms of the analysis of the causes of the collapses in the Arg, the discovery of the termites, did serve to focus my own attention onto the nature of the earthen material itself. No longer did it seem adequate to treat this material as a generic material which, in engineering terms, can be assumed to have a certain strength and structural capacity. The earth in the Arg may have been in a seriously degraded state going into the earthquake – a degradation that was largely hidden from view by the subsequent layers of new material and surface earth plastering from the recent restorations – until the earthquake dramatically brought it to attention.

The following observations on the damage to the Arg were made over a brief two-day series of visits to the Arg, during a seven-day period in April 2004 when the *International Workshop on Bam* was held. The following explanations of the causes of the damage are hypotheses based on this rapid survey. Definitive determinations on all of the causes of the damage could not be done during such a short visit, but it is hoped that these observations can help to define areas for further research.

DAMAGE TO THE ARG-E BAM

At first view, the damage to the Arg is so extensive as to defy any attempt to classify or interpret it. The structures were pulverized, often leaving only mounds of rubble at the base of a few remaining standing walls and piers. Few of the walls survived to their pre-earthquake height, and many of those structures that had been fully restored back into buildings were returned to a ruined state with less remaining standing than had existed prior to the last fifty years of restoration work.



Figure 7: The same view of the walls and towers of the inner citadel before and after the earthquake. *Before* photo by Mary Hardy, 2003.

After an exploration of the site, some patterns in the damage began to emerge. These included the following: (1) the circular structures, such as the turrets on the ramparts, fared worse than the long straight walls and rectangular structures (Figure 7); (2) the Governor's House and other structures on the top of the hill were more completely destroyed than were the structures lower down the hill (Figure 1); (3) almost every structure in the Arg that remained standing showed evidence of the onset of damage through the spreading to their walls from the inside-out as evidenced by the preponderance of vertical cracks (Figures 8, 17, 18); (4) most of the earthen masonry domes and vaults in the complex, many of which had been rebuilt in the late 20th century, collapsed. The largest dome in the complex on the icehouse, a structure that was outside of the walled town that had been converted to an auditorium, collapsed as if punched in.



Figure 8: Piers in a partially collapsed section of the Caravansary showing the bursting of the outer layers from internal expansion from the earthquake vibrations.

With regard to interesting examples of surviving structures, one could not help but notice the following: (5) a brick reconstruction of a structure with internal vaults over an ancient water cistern in the center of the stables courtyard (figures 9 & 10) survived with no evidence of even so much as a crack from the earthquake. In aerial photographs taken in 1974, the cistern was uncovered and the current structure is a recent reconstruction in modern fired brick masonry. (6) The outer ramparts on the south, east and west sides of the walled city suffered a great deal of damage, with the loss of their projecting turrets and complete destruction of the top crenellations and walkway, yet the north facing ramparts survived in better condition (figure 18). (7) In the structure known as the ‘Small Caravansary,’ the second level of the side that had a series of buttresses along the outside wall collapsed, whereas the opposite side, which had no buttresses, survived almost intact (Figure 19).



Figure 9&10: Before (November 2003) and After (April 2004) of the same view of the Stables courtyard showing the superstructure over the cistern that was recently reconstructed in fired bricks. *Before photo by James Conlon, 2003.*

Most intriguing and significant, perhaps, are (8), those structures that had been maintained and repeatedly modified and expanded over time (such as the structures of the inner citadel) and those structures that had been partially or wholly strengthened and restored during the late 20th century (such as the outer ramparts and buildings of the lower town) fared significantly *worse* than did those ancient structures – both inside and outside of the Arg – that had not been maintained, modified or restored.



Figure 11: LEFT: Unrestored ruins in the Konari neighborhood of the Arge Bam that survived the earthquake with comparatively little damage. RIGHT: The Shahrbast Wall from above (see also Figure 5).

The unmodified and restored structures included most of those in the north-west section of the walled town known as the “Konari” neighborhood, and also those structures just outside of the Arg to the north-east including the tall “Shahrbast Wall,” (figures 5, 11) located near the icehouse, and the “Khale Dokhtar,” (figure 22) located on the opposite riverbank to the north. Some of these surviving unrestored structures are of considerable size and height, and were undoubtedly subjected to shaking of close to the same characteristics as the rest of the Arg, but they remained standing, except for some smaller parts that broke off. (Even in these few collapsed sections in the Khale Dokhtar and other structures, termites were also in evidence.)

The question that presented itself after these observations was: *Is there any single condition that can explain all of these phenomena?* During the brief study of the site, two unrelated experiences have contributed to my assessment of what may have caused so much damage, in addition to the high frequency vertical earthquake vibrations. One was the discovery of the termite infestations, and the second was the chance experience of the largest aftershock to be felt at the site in many weeks. The aftershock, 3.8 on the Richter Scale⁴, rolled through the site at 7:10 a.m. on the 20th of April. Fortunately that was a day that a small group of us had visited the site shortly after dawn. Standing in the middle of the Arg, the aftershock was felt as a high frequency vertical vibration. It can be described as being like standing on a platform above an engine that was just starting up, but not firing on all cylinders. It lasted only for about four or five seconds. A small amount of dust rose from the complex, but no further damage was sustained.

This vibration was at the opposite end of the spectrum from the kind of earthquake that had, for example, affected Mexico City in 1985 or even San Francisco in 1989. Emanating from directly below the site, rather than from some distance away, the waves caused vertical shaking and vibrated at a high frequency. The earthquake records from the one instrument that was in Bam that was located near the site of the Arg recorded strong vertical vibrations of about 10 hz (cycles per second).⁵ Strong high-frequency vertical shaking alone is capable of causing extensive damage to load-bearing earthen and masonry structures, but there had to be a plausible explanation for the counter-intuitive observation that the unrestored parts of the complex did better than those that had been strengthened and restored. That is where the issue of the termites enters into the picture.

After first noticing the termite bore holes and frass in a damaged section of one surviving rampart wall in the center of the Arg, I began looking for further evidence of the insects. Selecting walls at random, I looked to see if similar insect evidence could be found on other broken surfaces. In every instance, insect damage was in evidence on each of the newly exposed inner surfaces that had been broken open by the earthquake. This evidence consisted of both tunnels into the still standing portion of the walls, and large amounts of frass on the interface between the fallen and standing portions. The earth itself in these areas was extremely friable. There was evidence that the surfaces

between many of the fallen and standing portions of walls had been the interface between earlier and later work. This interface had contained many channels left by the insects that gave access to those tunnels that drove deeper into the (usually) older material that was still standing. (figures 2 & 12)

I have learned since that termites were also common in dwellings in the city, even to the extent that people have avoided using wood for kitchen cabinets and other fittings. Since the earthquake, the termites have been found to have consumed the wood of the front doors and woodwork of the citadel that became buried when the front towers collapsed during the earthquake. (Figure 12)



Figure 12: The Arg-e Bam archeologists, conservators and technicians examining the termite damage on the doors to the Arg recently exhumed from the collapsed tower. *Photo courtesy of Mehrdad Hejazi.*

Termites live in earth and feed on organic material – that is, the same kind of cellulose that is frequently used to reinforce adobe bricks and the earth stucco used in earthen construction. Thus, the concentration of termite passageways in the interface between newer and older construction appeared to have weakened and separated the different layers of construction.

If further research does prove that the termites were concentrated in the interface between zones of construction of different periods, it can explain why the later construction tended to fall off of the older cores of the walls. In addition, once they have perforated the matrix of the earthen wall, the termite tunnels may have contributed to the further drying out of the earth itself, with a commensurate loss of cohesion that comes from an excessive drying out of the clay.⁶

COLLAPSE FROM THE INSIDE-OUT

The termites are only a part of the larger problem of the internal degradation of the walls, but seeing how pervasive the insect tunnels were throughout the ruins did alert me to consider the possibility that the many of the collapses in the Arg may have initiated from failures deep inside the thick walls. As I explored the ruins of the still impressive earthen complex, it was, of course, difficult to come up with a single theory that could explain the nature and extent of the damage. I had expected to experience the kind of damage described by the Getty Seismic Adobe Project with the classic signatures of structural weaknesses inscribed on them: shear “X” cracks, cracks propagating out from the tops of windows and doors, collapsed corners, overturned walls, etc. However, in the Arg, even the usually common diagonal or “X” cracks were relatively rare. It appeared as if the structures had exploded from the inside and crumbled straight to the ground in a scatter of small pieces. Rubble was everywhere. It formed a mat of broken material that in some places was higher than the still-standing remains of the walls and piers. The previously completely restored Grand Mosque, for example, was completely unrecognizable after the earthquake. In the rubble pile, there was even barely enough left intact to discern the outline of what had been its large courtyard (Figure 13).

It was only after having taken in all of the evidence seen in four short visits to the site over a six-day period that a pattern began to emerge. First it became apparent that walls did not crack into a series of larger sections that could rock back and forth as the Getty project had predicted based on the adobe buildings they had studied. Instead, the Arg buildings appeared to have responded to the high-frequency vibrations like unconsolidated earth fill. The study of the situation thus seemed to require a change of discipline – from *structural engineering* to *soil dynamics*.



Figure 13: Ruins of the formerly impressive four-sided courtyard of the Main Mosque, which has completely disappeared from view, leaving only the ritual washing place as the only thing still identifiable.

The more we examined the site, the more compelling this explanation became. In a number of locations there was evidence of lateral spreading of the kind that one would expect to find around the shore of a lake – but in this case it was located on dry ground where historically the surface had been built up to create the level terraces on which the buildings were constructed on the lower hillside. One section of the terrace that supported a building above the stables collapsed altogether, carrying away the front half of the rooms constructed on it (Figure 14). The round turrets appeared to have failed at the bottom, instead of splitting apart at the top as one might have expected. Their seemingly strong walls were simply pushed out at the base, with sections of the upper walls having slid down the rubble with the upper ornamentation remaining as the only recognizable pieces left. As the earthen core in a wall loses its cohesion, then the loose sand and clay material can settle. The spreading forces of this settling earthen material are sufficient to blow out the containing exterior surfaces, leading to the collapse of the wall.



Figure 14: Buildings above the Stables courtyard that collapsed from the lateral spreading failure of the retaining wall and fill beneath.

The aftershock at 7:10AM on the 20th of April provided a palpable sense of what had happened during the main shock. As the records did show, the main earthquake on December 26th was recorded as having a high frequency vibration, particularly in the vertical direction. From the sensation felt during the aftershock, it did feel like the kind of vibration that could cause soil subsidence – much the same way that a vibrator causes freshly-placed wet concrete to flow. The experience then began to explain each of the seemingly disparate and sometimes counter-intuitive phenomena described in the list above.

For example, in the case of (1) the first observation, the particular vulnerability of the circular turrets may be explained by the fact that they had contained large amounts of unconsolidated fill in their bases. One of the few that survived is to the right of the 2nd gate (Figure 15), and it has a timber floor diaphragm with timbers penetrating the walls located beneath the upper windows, with a room, rather than solid fill, below. The absence of the fill, combined with the effectiveness of the floor diaphragm may have been instrumental in holding it together. (Figure 15)



Figure 15 The one of the few surviving turret on the rampart wall of the inner citadel visible on the right has a room in its base. The second floor diaphragm timbers extend through the walls just below the window. By contrast, the turret on the left that has collapsed was filled solid below the level of the room that is visible at the upper level.

In the case of (2) the collapse of the structures at the top of the hill (Figure 1), this seemed to be caused in part because the failure of the retaining walls and fill that had been constructed up from the lower hillside to widen the platform at the top of what had originally been a narrow rock outcropping. (A similar failure can be seen in Figure 14.) The failure of (3) the walls of many of the buildings and ramparts was also consistent with the lateral spreading of the material in the cores of their walls, with the exterior adobe bricks being forced out as manifested by the greater frequency of vertical cracks as compared to diagonal cracks (Figure 8, 16 & 17).

In the case of (4), the collapse of the domes throughout the complex, many simply may have followed their bursting supporting walls to the ground. Others which collapsed inward, like that of the Icehouse, suffered from the effect of the intense vertical vibrations on the soft adobe brick masonry. The momentary doubling of the weight of the domed structures was probably more than they could handle. In the case of the Icehouse, the 1974 aerial photographs provide evidence that the part of the dome that did collapse had been reconstructed after that date, as it was missing in those photographs.⁷



Figure 16: Collapsed round turret on the ramparts at the main entrance to the Arg shows evidence of having burst apart from collapse of internal layers that are composed of construction of different periods.

By contrast to the bursting walls (5), the masonry structure over the cistern in the center of the stables courtyard performed much better despite being of unreinforced masonry. (Figure 9 & 10) Most likely in this case, the walls were of a uniformly solid and bonded masonry construction without a rubble core. The fact that it was constructed of fired brick would have contributed to its strength, but what may even have been more important was the fact that the walls were of a fully cohesive material of uniform density without voids or vertical gaps.



Figure 17: Another view of a collapsed section of at the main entrance where the surface of earlier construction has been exposed underneath. Note the multitude of vertical cracks – evidence of spreading forces on the exterior layers from the compression of the internal solid clay fill.

As for the better behavior of the north-facing ramparts compared to the other city walls (6), the subsurface soil conditions along the riverbank where the wall is located may account for some of this difference because the alluvial soils may have served to damp out some of the vibrations, rather than intensify them, as is often the case with earthquakes where the epicenter is farther away. Further research is needed to determine whether this may be one explanation. Also, like the nearby Konari neighborhood, these walls had not been altered and restored along their tops as much as had the other walls around the Arg. It was the newer restored upper level battlements, walkways and crenellations that consistently suffered the most, possibly because of the different densities and vibration response of the new and old material and the additional weight. (Figure 18)



Figure 18: LEFT: Ramparts on the West side of the Arg showing the spreading failure of the turret and the collapse of the crumbling of the walls. RIGHT: The North-facing ramparts, which were significantly less damaged in the earthquake than the other city walls. Notice that the crenellations are still intact on this one section, the only section where that was observed to be the case.

The second-to-last item (7) is the Caravansary, where the rooms on the second level of the buttressed west side of the complex collapsed, leaving the east side that lacked buttresses largely intact. The buttresses themselves were also damaged, with one collapsing from the crushing of its base. (Figure 19)

The story of this complex became even more interesting when I learned from the old photos that the side that collapsed had been almost completely reconstructed only a few years earlier, whereas the still standing side had mostly survived from antiquity. In aerial photographs of the caravansary taken in 1974,⁸ the domes on the east side were almost completely intact, whereas on the west side they had collapsed. At that time, the buttresses on the west side only extended up to the level of the first floor. As late as 1996 the condition of both sides was similar to 1974, except that the small holes in the east side domes had been fully repaired.⁹

At the time of the earthquake, photographs show that the restoration of the west side of the Caravansary had been completed.¹⁰ The domes had been reconstructed and the west wall and buttresses had been extended up to the roof level. Ironically, in the earthquake it was this newly constructed and fully buttressed side that fell. This was simply one more example of the finding that the areas with the greatest amount of strengthening, reconstruction, or even of continued maintenance were the most heavily damaged.



Figure 19: The ruins of the Small Caravansary show that the domed rooms on along the buttressed wall (UPPER LEFT) have collapsed, while the ones along the non-buttressed wall (UPPER RIGHT) survived. Some of the buttresses themselves are in a state of partial collapse.

All of this evidence taken together seems to point to a phenomenon where those earthen walls that are composed of material of different densities and construction characteristics resulting from their different phases of construction, repair and reconstruction, proved to be more vulnerable to the earthquake vibrations. As long as one perceives of the earthen construction as having a uniform composition, it is difficult to understand why the strengthened and restored walls would fare worse than the unrestored and naturally eroded walls. However, the succeeding phases of construction in the Arg over the centuries had produced walls of a very different composition than that of a newly constructed earthen building.

No longer did many of these walls consist of horizontal layers of earth or sun-dried bricks, and those that did consistently appeared to be less damaged. Instead, through generations of erosion, repair and remodeling, many of the walls had evolved into a series of vertical layers of earth, standing together like books on a shelf without bookends. Each of the different layers was of a different density and cohesion resulting from the different ages, construction characteristics, and degradation. For example, modern *Khesht* (adobe masonry) frequently encased older *chineh* (cob) construction (Figure 17), and the organic material used for reinforcement had rotted or been consumed by insects, leaving cavities and friable earth (Figure 12).



Figure 20: View of a surviving damaged section of wall showing the cracks and separation between different types and vintages of construction that make up the same wall.

Further research is needed on this subject, but it was only after I began to interpret what I saw at the site as the behavior of vertically disconnected unconsolidated earth, rather than as the uniform horizontally bedded earthen construction of the sort analyzed for the Getty project, that a possible explanation for the nature and extent of the earthquake damage began to emerge. Based on the Getty research, the thick walls of the ramparts and main citadel in the Arg of *Khesht* or *chineh* construction would normally be expected to be the most resistant, rather than the most vulnerable as they turned out to be. If the hidden interior parts of the walls are composed of a series of vertical segments, and especially if the inner segments had large voids, crevices, and dried-out unconsolidated fill that lacked connections to the outer layers, the high frequency vibrations of this earthquake could cause the inner older and more degraded portions of the walls to settle. This then could exert a horizontal force from the inside-out onto the outer layers at the base of the structures, causing the walls to collapse, not by tipping over, but by crumbling in place.

In addition, variations in the density and cohesion in the earthen layers in a wall, particularly resulting from different periods of erosion and reconstruction and changes from *chineh* to *Khesht* quite possibly can cause the earthquake vibrations – particularly vibrations in the high frequency range experienced in Bam – to ricochet off of the layers of different densities, causing the onset of damage from the local intensification of the vibrations. Evidence of such behavior can be seen in (figure 20) where the wall began to break out at the interface between two vintages of *Khesht* construction, both of which appear to be pre-20th century. This is a subject in need of further research specific to earthen construction in order to establish if this phenomenon can be explained in this way, but such research may have a significant bearing on the protection of other earthen monuments that have been altered over the centuries. The North and South American adobe structures that were the primary subjects for the Getty research are less likely to be subject to this

phenomenon because they are not of such great age, and thus their walls are more uniformly of horizontally bedded adobe bricks without the many stratifications of different construction in the walls.

This is why the observation of the widespread infestation by termites may turn out to be important. Not only did it appear that the ancient construction in the Arg was perforated by the insects, but that the insects had also succeeded in separating the different vertical stratifications in the walls, and reducing the cohesion of the inner core of earthen material. In a trip to Isfahan after the mission to Bam, during meetings with the professional restorers of several of the historic monuments in that splendid city (figure 21), I learned that termites were also found in the walls during the recent restorations. These professional conservators explained that the damage caused by the termites had to be addressed in the restorations by consolidating the earthen cores of some of the walls.



Figure 21: The Imam Mosque in Isfahan, April, 2004. The inner cores of many of these walls and the walls of other great monuments in Isfahan are constructed of unfired clay.

In contrast to this strengthening work in Isfahan, some of the 20th century restoration work seen in Bam may have aggravated the problem. Clay stucco added before the earthquake was reinforced with copious amounts of straw – a material that appeared in many areas to have been consumed by termites. By contrast, the older reinforcement of shredded date palm tree bark appeared to have been more resistant. Perhaps the termite population inadvertently has been increased in modern times, simply because of this “banquet” of non-resistant straw-reinforced stucco.¹¹

THE RISK TO EARTHEN MONUMENTS

What many people do not realize is that new buildings in any country constructed of modern materials to code are not designed to withstand major earthquakes without damage. For earthen structures, elastic analysis procedures provide little guidance on how such buildings will behave in the post-elastic range. Quoting again from the Getty Seismic Adobe Project report: “*The sole use of an elastic approach can be justified only when there is a known relationship between the level at which yielding first*

occurs and the level at which the structure collapses. In the case of thick-walled adobe construction, there is no clear relationship between these two events. ... While a strength-based analysis can accurately predict when cracks will occur, it cannot provide insight into the post-elastic performance of adobe buildings."

This report makes a very important distinction between what is described as a "strength-based" approach and a "stability-based" approach to seismic upgrading. The report identifies that the current "conventional engineering approach to seismic retrofitting" is a strength-based approach, which is based on increasing the elastic strength of a building's structural system. They go on to explain that for adobe buildings, a "stability-based approach" is more suitable. The objective in stability-based design is to ensure that the structure remains standing long after the elastic range of its structural system has been exceeded. Since the elastic capacity of adobe masonry is low, seismic hazard mitigation of adobe structures depends on maintaining its stability long after it begins to crack.

The Getty Report then goes on to describe the potential that adobe buildings have for "structural ductility" even though they lack "material ductility." The structural ductility can come from the inherent stability that even the cracked adobe walls can have so long as the cracked wall sections remain bearing one on another. This is an important finding that can be used as effective basis for design for many adobe structures that otherwise would be condemned. However, in retrospect, what the Bam earthquake has proved is that, in spite of the thickness of the ancient earthen walls in the Arg, stability was quickly lost after the elastic range was exceeded. The earthquake on 26th December 2003 was recorded to have lasted only 12 seconds, so the collapse of the Arg was almost instantaneous. *Structural ductility* thus was not to be found in the structures of the Arg.

Who could have ever known there was such a risk? The interiors of the walls with their voids and degraded materials were hidden. An engineer doing a structural analysis would normally have based the analysis on measurements of the thick walls without anticipating the effect of the fractured and weakened conditions of their internal cores. Research is now needed to find ways to be able to evaluate such walls as non-destructively as possible, and then to find ways to address the kinds of problems that may be discovered that would lead to their rapid loss of structural cohesion when subjected to earthquake vibrations.

WHY DID THE ARG -E BAM PROVE TO BE SO VULNERABLE?

If the changes to the walls of the Arg over the centuries, and during recent restorations can be proven to be a major part of the cause of its wide-spread collapse, then there are two remaining questions that need to be asked. The first is: *Since the Arg is located in a known earthquake region, why was its construction not more responsive to the threat?* Before answering this question, one must ask whether or not the original construction prior to its alteration and degradation over time was in fact designed to be more resistant. These are both particularly difficult questions because the subject of the inquiry is archaic construction using a limited palette of materials – namely unfired earth with a small number of undressed timber logs – not something that provides much opportunity for modification to resist large earthquake forces.

Earthquake resistance is not an absolute. One must alter one's expectations to reflect what could be achieved in a culture where only unfired earth and a limited amount of timber were available. In the present, expectations of earthquake safety have been shaped by the existence of steel, either as the structural building material itself, or imbedded into concrete, or even when used to reinforce the connections between timbers. The frequent catastrophic failures of modern buildings of steel and concrete, as we have seen in Bam, in the case of steel, and other recent earthquakes in the case of reinforced concrete, notwithstanding, the existence of steel as a building material has raised expectations, making it harder now to recognize pre-modern mitigation efforts.

Traditional construction – particularly in a desert environment – did not have the luxury of an abundance of timber, much less access to modern steel. Much of what could be done was the product of trial and error leading to the evolution of building practices over many centuries. Thus, out of all of the influences on the evolution of construction practices, it is not easy to discern those specifically that are a response to earthquakes. Earthquakes themselves are not always the same. The December 26, 2003 earthquake in Bam was only 6.5, but it was a shallow earthquake with its epicenter located almost directly beneath the Arg-e Bam. The likelihood of being directly above the epicenter of an earthquake is significantly less than being nearby. Thus, it is entirely possible that the Arg had never been subjected to such a high frequency vertical vibration over the prior 2000 years of its history.¹²

The earthquake risk most often analyzed by computing the static equivalent forces on structures, but in this case, the frequency of the vibrations may have been particularly significant. Even a small difference in the location of the epicenter, would have shifted the ground shaking under the Arg away from such high frequency vertical vibrations to a lower frequency vibration with a smaller vertical component. How this may have affected the spectrum of damage in the Arg is difficult to determine, but important to know because it can shed light on the degree to which other monuments are at risk. If high frequency is a large part of the cause of the damage, the odds of a recurrence under other monuments is less than if a broad range of frequencies will cause similar damage.

CONCLUSION

In summary, it appeared to be that the collapse of the Arg-e Bam was largely a result of the internal collapse of the walls resulting from a catastrophic loss of the cohesion of the earth deep inside those walls. The initial impression was that the 20th century restoration work itself performed far worse than the ancient work, but it was not always the newer work that failed *per se*, but the combination of the new and old. In fact, it appeared that the newer work often failed as a result of the internal collapse of the older work on which it was founded.

While it does not explain all that happened, the termite damage is symbolic of the larger issue of the role of time and change in both the science and the art of building conservation. It was only after noticing this infestation that the other aspects of internal wall degradation were revealed as well – the dryness and lack of cohesion of the earthen cores, the decay and insect consumption of the reinforcing timbers and straw, the existence of small and large voids between vertical layers in the walls, and the piles of loose dry sand and clay powder that made up a large proportion of the debris. When all of these elements are put together with the high frequency vertical vibration that was characteristic of this earthquake in particular, the wide-spread collapse of the walls from the inside-out appears to be a plausible explanation for a great part of what happened, including many of the seemingly counterintuitive observations described above.

If, after further research, these explanations are substantiated, it is important then to ask: *what are the implications of these findings not only for the future restoration work in the Arg, but also for the other cultural heritage sites in Iran and throughout the Middle East and North Africa?* If, after a 50 year program of restoration, such a seemingly robust earthen monument can be shaken down in 12 seconds, we need to understand why the kind of post-elastic stability described in the Getty research did not occur. Many of Iran's most splendid monuments are of earthen construction behind their exterior surfaces of carved stone and ornate ceramics. In an earthquake, if the inner layers shift and settle in response to earthquake vibrations, the outward pressure could lead to a blowing out of the walls at their base, causing collapse of the structures. Standard structural retrofit analysis and techniques may neither fully account for this risk, nor mitigate it.

In terms of the future restoration and reconstruction of the Arg-e Bam, and the further restoration of other similar archeological and historical monuments, the earthquake collapse does create a major dilemma in terms of adherence to one of the long-accepted principles of restoration practice – that of preserving in place as much of the original fabric *in situ* as possible. Since the restored parts proved to be so much more unstable in the earthquake than the unrestored parts, the nature of the restoration work now has to be questioned.

More than any other building material, unfired clay can change over time from cumulative effects of the short repeating cycle of erosion and renewal, and also from a gradual deterioration of the hidden core of the walls from rising damp, water intrusion from the top and sides, insect attack, fungal decay, differential settlement, gradual compaction, and gradual chemical or mineralogical changes to the matrix of the material. Although of particular importance when dealing with unfired earth, these causes of deterioration can affect many different building materials.

As observed, there are two basic issues that are specific to earthen construction: (1) the instability that is created by adding new fabric at the base along side and on top of the historical earthen walls such that the combined construction is not horizontally bedded through the entire thickness of the wall,¹³ and (2) the adding of new material of different density, cohesion, and dynamic characteristics from the historical material. What the collapse of the structures in the Arg illustrate is that the repair of walls simply by filling in the gaps created by erosion or degradation can result in a reduction in seismic resistance from both the increased overburden weight, and from the fact that, over time, the wall ends up composed of a series of vertical layers that fail to work as a single cohesive unit, each part of which is unstable when subject to lateral loads. The philosophical and practical question then is: *What can one do at a site like the Arg-e Bam where both (1) the conservation of surviving ancient fabric, and (2) the restoration of the architectural and symbolic image of the place, is equally compelling from a cultural perspective?*

As the Bam earthquake has proved, these two goals may conflict. The ideal solution for one may be antithetical to the other. The provisions of the 1964 International Charter for the Conservation and Restoration of Monuments and Sites, known as the “Venice Charter,” serve to highlight the technical dilemma. Article 9 stipulates that the “*aim [of restoration] is to preserve and reveal the aesthetic and historic value of the monument and is based on respect for original material... It must stop at the point where conjecture begins, and in this case moreover any extra work which is indispensable must be distinct from the architectural composition and must bear a contemporary stamp*” (emphasis added). The Charter goes on to say in Article 15 that “*all reconstruction work should...be ruled out “a priori.” Only anastylosis...can be permitted. The material used for integration should always be recognizable and its use should be the least that will ensure the conservation of a monument and the reinstatement of its form.*”¹⁴

Thus, while this long accepted international charter establishes the primacy in conservation practice of preserving original material fabric *in situ*, this may be antithetical to the conservation of an earthen monument that also includes its restoration either back into a complete building or into an archeological artifact that can be experienced by the public in a culturally meaningful way. Earthen construction was intended as a constantly renewable, and the conservation ethic appropriate to stone and fired brick construction is antithetical to the nature of a material which historically depended on a cycle of replacement as a standard maintenance procedure. To be stable in earthquakes, the earthen walls cannot be reassembled from damaged and fallen fragments with the same expectation of stability as can be expected from the *anastylosis* of the Parthenon and other great stone ruins. It is even of questionable stability to mix ancient *chineh* construction with modern *Khesht*. It is now most clearly evident that vertical construction joints between earthen materials of different age, density and type of construction not only to put the

new work at risk, but, in the next earthquake, may result in the destruction of the ancient work imbedded in that new work.

The Arg-e Bam is now a World Heritage Site, having been inscribed onto the list after the earthquake. This is a testament to its importance to Iran, and recognition of that importance by the World – but it also places an additional burden of international scrutiny onto the restoration and recovery process, and the Venice Charter provisions are key to this review process.

The Arg-e Bam is not only of archeological importance to academics, but also important as an architectural and historical symbol. This can only be recovered by undertaking strategic reconstruction work to rebuild at least some of the elements that made up that pre-earthquake symbolic image. When this is undertaken, the restorers will have to confront the conflict that exists between the retention and stabilization of the surviving original fabric, and the demand that the restored buildings have an acceptable level of earthquake resistance. Thus, not only are technical solutions needed, but a high degree of political skill is necessary to sort through the alternatives, and then to gain broad acceptance for the implementation of the one that restores the most important part of the symbolic image of the place, while doing the least harm to the archeological remains.

Finally, in order to make the best use of the knowledge that can come from an investigation of the damage sustained by the Arg-e Bam, it is important first to understand, as the Getty researchers did, that the destruction of such monumental earthen architecture from shaking of this magnitude should not be taken as a forgone conclusion, or as a condemnation of the continued use of unfired earth as a building material. What the destruction of the Arg does provide, however, is the cautionary message: *Buildings are not always as they seem to be when looked at from the outside.* This message is particularly profound when it comes to earthen architecture. The transition of the walls of the Arg from their ancient origins as horizontally bedded layers of clay to poorly connected vertical segments resulted from centuries of erosion and renewal. However, through the centuries, the external look of the walls had changed little. It took an earthquake to open the walls up and reveal that the internal composition of the wall was no longer the same as it had been when originally constructed.



Figure 22: The unrestored Khale Dokhtar, a small Arg (or citadel) on the riverbank opposite the Arg-e Bam that survived the earthquake with the collapse of some arches. The high walls of the massive structure otherwise survived intact. (Termites and other insects were also in evidence where the collapses occurred.)

The visual symbol of this earthquake to the world has become the dramatic juxtaposition of the 'before' and 'after' images of the Arg-e Bam (figure 1). However, for the future of both construction with adobe and the conservation of earthen architecture, the symbol should also be the ancient earthen structures around the Arg that did not collapse (figure 3, 11, 20 & 28). Without having been subject to modern-day maintenance or restoration, at the time of the earthquake, these structures were closer to their original centuries-old structural form than were those that had been restored. Having survived the earthquake intact, they stand today as examples of earthen construction that proved to be capable of resisting a major earthquake better even than some of the new steel frame buildings that did collapse. The age of an historic structure thus may be less of a factor in its earthquake resistance than modern-day changes to its fabric, even including modern efforts to strengthen and restore that ancient fabric.

If this is true, we may need to look no further than some of these modern-day construction and conservation practices to begin to find a solution to the problem. It is at this level that the fate of the Arg becomes intertwined with the fate of the modern town that stood along side. The houses in which people died were modern houses. Their walls may have been of *Khesht*, but many also had roof beams of steel, and floors or roofs of fired brick. If both the twentieth century restorations in the Arg and the new houses in the town suffered more than the untouched ancient abandoned earthen ruins in the desert nearby, then the problem had less to do with earthen construction per-se than it had to do with the particular form of earthen construction that was practiced in modern Bam. Therefore, both restoration and new building construction practices need to be changed. Some of the guidance for how they should be changed may be found in the heritage of the nation itself, rather than only between the covers of engineering textbooks.¹⁵ (Figure 23 and 24)



Figure 23: Timbers (LEFT) lying in the debris from the upper citadel and (RIGHT) timber in the ruined wall of the Governor's House provide evidence that there was some timber reinforcement of the earthen walls of the Arg. The timbers seen here are date palm trunks, and show evidence of termite damage.

With so many deaths having occurred in buildings with earthen walls, occurring together with the collapse of such a symbolically important monument, life safety concerns with adobe construction are now tragically highlighted because these two phenomena have been fused in the eyes of many around the world. This has created a severe problem for the conservation of other earthen sites in seismic areas. By coming to understand the collapse mechanisms in the Arg, one can go beyond the level of blaming a construction *material* for the poor performance of construction *systems*. If the unfired clay material itself is all that is considered when determining the causes of failure of the Arg-e Bam, and its use then is banned, all further discussion stops. The fundamental need to determine all of the necessary ingredients that constitute earthquake safety in earthen buildings then will not be achieved.



Figure 24 Views of restoration work undertaken at Shunet el Zabib, (2700 B.C.E.), Abydos, Egypt by Anthony Crosby (USA) utilizing plastic geo-grid material for horizontal reinforcement. By resisting the spreading of the masonry during earthquakes, this serves a similar purpose as timber reinforcement may have served at other sites in the past, but it is more resistant to decay. *Photos by Anthony Crosby.*

Although it would seem that it should be easier to design and construct safe structures out of steel and concrete, in practice, this earthquake, as well as other recent earthquakes in Mexico, Turkey, India, Morocco and many other countries, have tragically proved that safety can be elusive, even with modern materials. In many parts of the world, unfired earth is the most available and economical building material. It is also deeply imbedded as part of the history and culture of Iran and the region. While it may be more challenging to construct safe structures using unfired earth, that does not mean that it cannot or should not continue to be done.

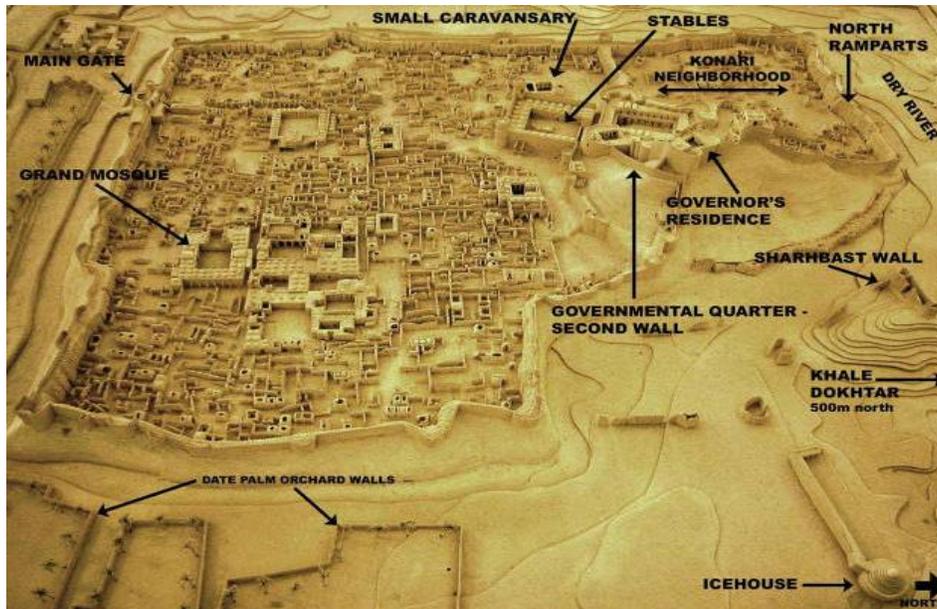


Figure 25 ICHO Model of the Arg-e Bam after recent restorations prior to the earthquake

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- ² Tolles, Leroy; Edna Kimbro; William Ginel, Planning and Engineering Guidelines for the Seismic Retrofitting of Historic Adobe Structures, The Getty Conservation Institute, Los Angeles, 2002.
- ³ The official death toll is 26,000, and unofficial counts have risen as high as 43,000.
- ⁴ Data from IIEES, Iran (http://www.iiees.ac.ir/English/bank/eng_recent.html)
- ⁵ Iran Strong Motion Network (ISMN) <http://www.bhrc.gov.ir>, and Ashtiany, M., *et al*, Preliminary Observations on the Bam, Iran, Earthquake of Dec. 26, 2003, EERI, April 2004.
- ⁶ The inter-atomic forces that give clay its cohesiveness of clay, that allows it to be such a useful building material, are dependent on the presence of moisture.
- ⁷ Photographs by James Blair for the National Geographic Magazine, 1974. Courtesy of the National Geographic Society.
- ⁸ *IBID*.
- ⁹ Aerial photograph in The Bam Citadel, a Comprehensive Report, ICHO, 2004, page 26, dated 1996 (the same image as used on the Workshop poster).
- ¹⁰ As shown in a photograph in the UNESCO-ICHO Joint Mission to Bam and Its Citadel, ICHO 2004, p80.
- ¹¹ Ed Crocker of the USA recommends “*that the fibrous material be soaked with borates. This in fact could have been done historically since borax is common in desert deposits. Borates destroy the digestive enzyme of termites and other invasive critters. It is also inexpensive and marvelously effective for both insects and rot molds.*”
- ¹² For a further discussion of the historical variability of earthquakes at a given site, see: Piero Pierotti, ed, A Manual of Historical Seismography, (published in English and Italian), University of Pisa, Edizioni Plus, 2003.
- ¹³ Although it is not masonry with horizontal bed joints, Iranian *chineh* construction was characteristically constructed with horizontal construction joints through the wall approximately every meter of vertical height. One of the historical reasons for these joints may have been to serve as crack-stoppers. (See Langenbach, (2004).
- ¹⁴ Venice Charter, 2nd International Congress of Architects and Technicians of Historic Monuments, Venice, Italy, 1964. (Available on the web at: http://www.icomos.org/docs/venice_charter.html)
- ¹⁵ A description of various forms of traditional construction, including earthen construction, with seismic resistance are included in Langenbach (2004), as well as other papers available at www.conservationtech.com

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