Performance of the Earthen Arg-e-Bam (Bam Citadel) during the 2003 Bam, Iran, Earthquake

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The Arg-e-Bam (Bam Citadel; in Farsi, *arg* means citadel) is a remarkable example of the earthen architecture and construction that was heavily damaged in the 2003 Bam, Iran, earthquake, which occurred on 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, which resulted 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 loss of cohesion and subsidence of their clay internal cores. Concern is raised about the possibility of similar risks to other earthen monumental structures in future earthquakes. (DOI: 10.1193/1.2113167)

INTRODUCTION

During the four months that followed the 26 December 2003 earthquake, which destroyed much of the Iranian desert city of Bam, much was said in the international press about the damage to the Arg-e-Bam, a majestic, historic, earthen-walled citadel in Iran (Figure 1). Nowhere in this coverage, however, were there any comments about termites. While on a visit to the Arg during the *International Workshop on Bam* sponsored by UNESCO, ICOMOS, and the Iranian Cultural Heritage Organization (ICHO)—now renamed the Iranian Cultural Heritage and Tourism Organization (ICHTO), this author observed 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 that such termites are relatively common in Iran, but few other conservation architects or engineers with whom I spoke were aware of the termites in the Arg. While the 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 2).

This raises the 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

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Figure 1. (a) The Arg-e-Bam before the earthquake (photo courtesy Iran Tourism Organization). (b) Exactly the same view after the earthquake. This and all other "after" photographs were taken by Randolph Langenbach in April 2004.

in this earthquake may have been laid over the many centuries of continuous erosion, decay, and rebuilding that took place on the site. When assessing earthquake damage to an earthen site, it is often easy to look only at the earthquake-shaking itself and to overlook any peculiarities, such as insects, that may have further weakened the earthen walls.

Many engineers and seismologists have cited the intensity of the Bam earthquake itself as sufficient explanation for much of the damage. 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 1 g. With such intense vertical vibration, the earthen walls rapidly cycled from losing their overburden weight to having to sustain double that weight. Because buildings are designed to carry well more than their own weight, the vertical earthquake forces are not generally 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 1 g, the ancient walls were forced to sustain almost double the 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. Almost every structure suffered partial or total collapse into formless piles of rubble, while some parts that did survive had very few cracks.

Figure 2. Evidence of termite damage in a wall of the Arg-e-Bam showing extensive deposits of frass with insect tunnels.

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 is worthy of further investigation—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 3, 10, 12, and 13).

Despite its history as a fortified site, all of the walls and buildings in the Arg were composed of unfired earth, and thus were weak and brittle. Yet even if one recognizes this fact, the extent of the destruction was nevertheless remarkable. 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; 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 that resembled complete buildings. A sea of formless rubble extended out as far as the eye could see (Figure 4). 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 (Figures 1a and 1b).

Figure 3. Shahrbast Wall, an unrestored, ancient earthen structure after the earthquake. The earthquake damage to these high unbuttressed walls was limited to the small amount of debris fall seen on the ground in the photograph.

What occurred to cause this? Is it explained by the intensity of the shaking alone? In a comprehensive ten-year research project by the Getty Conservation Institute on the seismic behavior and protection of historic adobe buildings, 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 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 (Tolles et al. 2000, 2002).

Since it took only a little over ten seconds for the earthquake to level much of the Arg-e-Bam, the Getty project's important findings on adobe structures clearly cannot be applied to this site. Why did 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? In either case, does this mean that the rest of Iran's most celebrated monuments, many of which are largely constructed of unfired earth, eventually may suffer the same fate?

Figure 4. View of the ruins of the Main Mosque within the Arg. The only recognizable structure in this view across what had been the main courtyard is the concrete ceremonial washing basin.

BAM CITADEL AND THE WALLED CITY OF BAM

The Arg-e-Bam, or Bam Citadel, has been recognized as the world's largest earthen complex. Unlike many earthen monuments that are clad with brick or stone, the structures in the Arg were entirely composed of unfired earthen construction. 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* (also frequently transliterated as *chiney*) (Guillaud 2004), (Figure 5 (*chineh*); Figure 18 (*khesht*)).

Even the arches, vaults, and domes were constructed of sun-dried bricks using a construction technique that avoided the need to provide structural centering. Both types of construction could be found in many of the structures, sometimes in layers where the later work, including twentieth-century restoration work, would be in khesht, while the original work would be chineh (Figure 19).

The news accounts that spread around the world gave the impression that tens of thousands of people died in ancient mud buildings. But in fact, almost all of the 30,000 who died in the earthquake were killed in buildings that were less than 30 years old. (The official death toll is 26,000, and unofficial counts have risen as high as 43,000.) For five decades prior to the earthquake, the Arg was an archeological museum. At the time of the earthquake, which occurred at 5:27 a.m., 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.

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; they were maintained as a military base until Reza Shah ordered that they be vacated, following the demise of the Qajar Dynasty in 1925 (Figure 6).

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 sun-dried bricks (*khesht*), rather than in chineh.

Figure 5. *Chineh* wall inside the Arg-e-Bam that was only slightly damaged in the earthquake.

Figure 6. Late Qajar Period (nineteenth-century) view showing soldiers in the inner citadel (photo courtesy of ICHTO).

Figure 7. View from the Shahrbast Wall looking towards the ruins of the inner citadel of the Arg e-Bam. These towering walls, gnarled by time, were largely unaffected by the earthquake.

DAMAGE TO THE ARG-E BAM

The following observations on the damage to the Arg were made over a brief two-day series of visits during the seven-day UNESCO-ICOMOS-ICHO Workshop, which was held in April 2004. These 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 define areas for further research.

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 the few walls and piers that remained standing. 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.

Figure 8. “Before” and “after” views of the tower and enclosure around the Stables Court with the inner citadel in the distance. The pre-earthquake image was taken only a month before the earthquake (“before” image by Mary Hardy, Getty Conservation Institute, 2003).

After an exploration of the site, some patterns in the damage began to emerge. These included the following:

- The circular structures, such as the turrets on the ramparts, fared worse than the long straight walls and rectangular structures (Figures 1, 8, 16, and 23).
- The Governor's House and other structures that were part of the hilltop of the inner citadel were more completely destroyed than were the structures lower down the hill (Figure 1).
- 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 11, 18, and 19).
- Most of the earthen masonry domes and vaults in the complex, many of which had been rebuilt in the late twentieth century, collapsed. The largest dome in the complex was on the icehouse, a structure outside of the walled town and which had been converted into an auditorium. This dome collapsed as if punched in.

With regard to interesting examples of surviving structures, one could not help noticing the following:

- A brick reconstruction of a structure with internal vaults over an ancient water cistern in the center of the stables courtyard (Figures 9a and 9b) 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 (Blair 1974).
- 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 10).
- 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 (Figures 20 and 21).
- Most intriguing and significant, perhaps, is that those structures that had been maintained and repeatedly modified and expanded over time (such as the Governor's House and other structures of the inner citadel) and those structures that had been partially or wholly strengthened and restored during the late twentieth 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 during the twentieth century.

The unmodified and restored structures included most of those in the northwest section of the walled town known as the *Konari* neighborhood (Figure 12), and also those structures just outside of the Arg to the northeast, including the tall *Shahrbast Wall* (Figures 3, 7, and 13), located near the icehouse, and the *Khale Dokhtar,* 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 (Figure 13). Even in a few of these damaged sections, termites were in evidence.

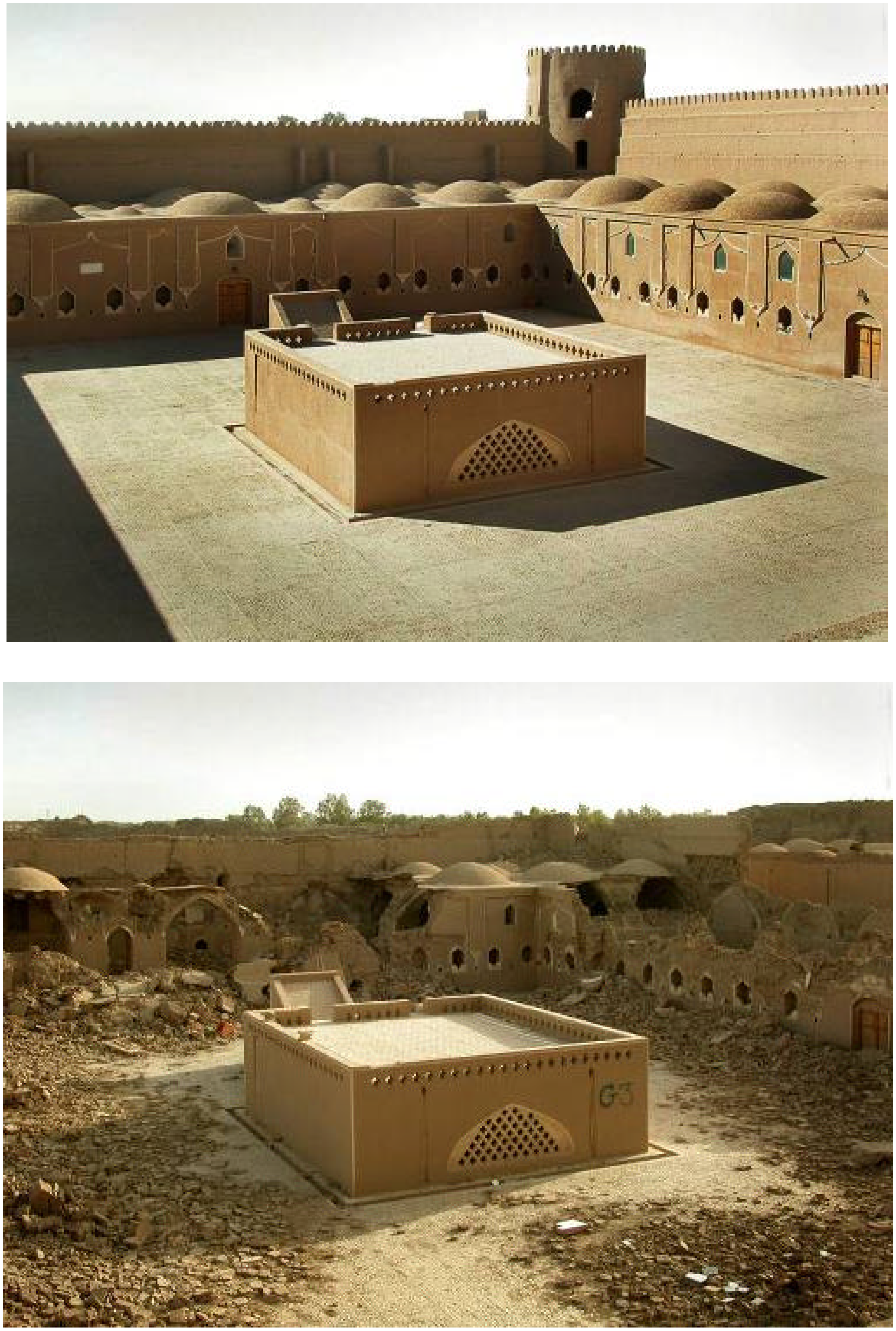

Figure 9. (a) “Before” view (November 2003) of the Stables Courtyard showing the superstructure over the cistern that had been recently reconstructed in fired bricks (photo by James Conlon, Columbia, University). (b) Same view after the earthquake.

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 contributed to assessment of what, in addition to the high frequency vertical earthquake vibrations, may have caused so much damage. One was the discovery of the termite infestations on the first visit to the Arg, 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 Scale (IIEES 2004), rolled through the site at 7:10 a.m. on the 20th of April. Fortunately, on that day, 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 was like standing on a platform above an engine that was just starting up, but not firing on all cylinders. It lasted for only about four or five seconds. A small amount of dust rose from the complex because of isolated debris falls, but no further damage was sustained.

Figure 10. North-facing ramparts were significantly less damaged in the earthquake than the other outer rampart walls surrounding the Arg. Notice that the crenellations are still intact on this one section, the only section where this was observed to be the case.

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 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 in Bam, located near the site of the Arg, recorded strong vertical vibrations of between 15 and 20 hz (cycles per second), a higher frequency than the predominant horizontal vibrations, which were about 10 hz (Iran Strong Motion Network 2004; EERI 2004). 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. This is where the issue of termites enters.

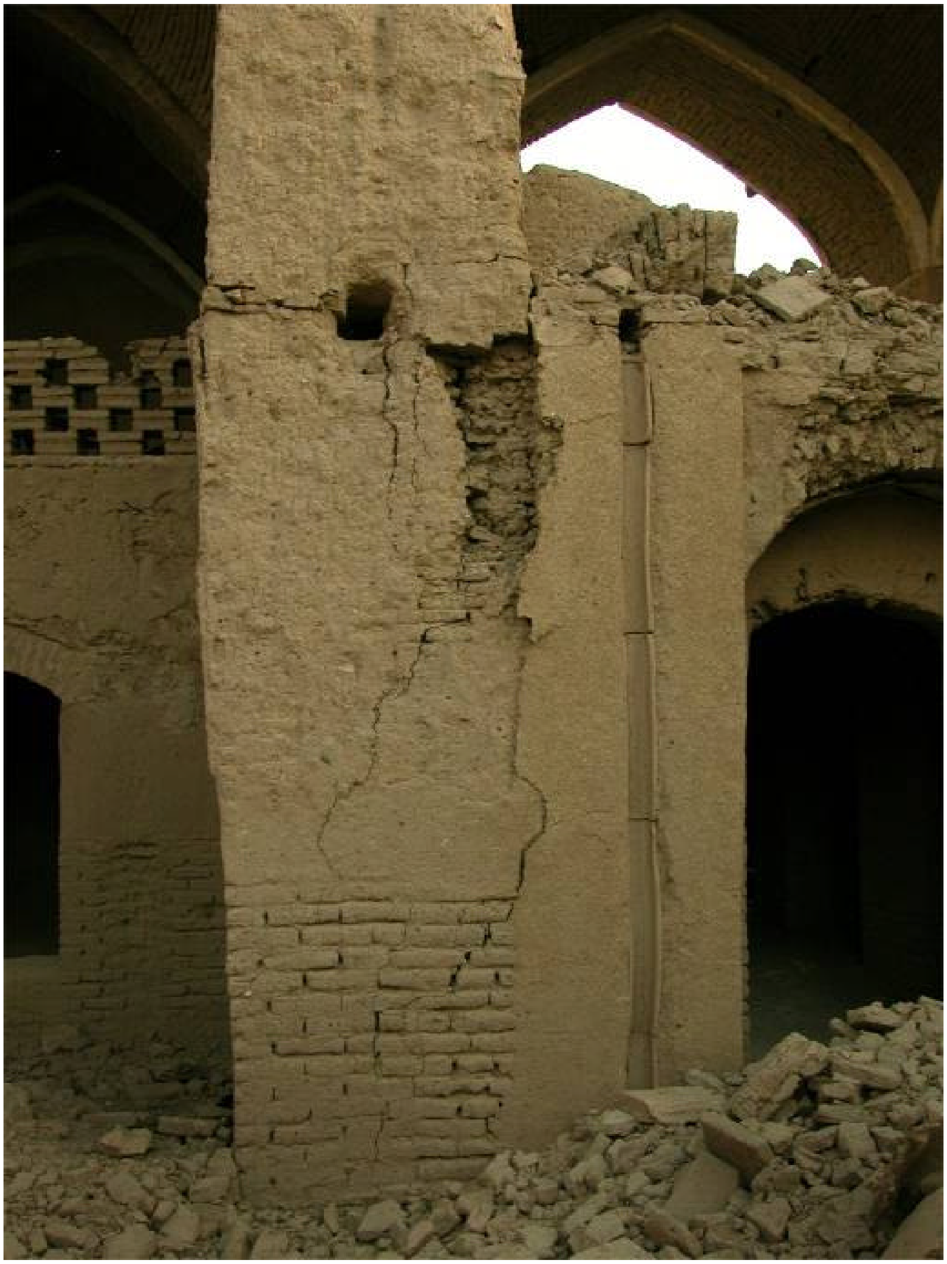

Figure 11. Pier in a partially collapsed section of the Caravansary showing the bursting of the outer layers from internal expansion from the earthquake vibrations.

Figure 12. The unrestored ruins in the Konari neighborhood of the Arg-e-Bam after the earthquake. Although abandoned and untouched for more than 150 years, these structures survived the earthquake with comparatively little damage.

Figure 13. The interior of the Shahrbast Wall showing the onset of damage at the interface of earthen constructions of differing types and periods.

The insect damage was first noticed on the one rampart wall in the center of the complex that survived the earthquake intact, the "second wall of the Governmental Quarter." There was one small area on this wall that had been broken open, exposing the inner core of the wall. Insect tunnels were visible on this newly exposed section, and the entire surface was covered with frass (fecal pellets). Selecting walls at random, similar insect damage could be observed 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 earthen walls in these areas were 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 ran deeper into the (usually) older material that was still standing (Figure 2).

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. This phenomenon has also been identified by preservation architect Anthony Crosby, an American specialist in the conservation of earthen architecture, in conservation projects in Egypt and at Tumacácori National Historical Park in Arizona. In some areas, the perforation was so extensive as to give the appearance of Swiss cheese (Figure 14). In 2005, Crosby reported:

> I have seen two general effects on mass earth walls by insects. One is at interfaces where food sources and moisture exist and where the access, or travel by the insects is easier. This condition often leads to failures at the resulting weak points when the structure is subjected to additional stresses. The second effect is in the reduction of the strength of individual mud bricks as insects eat the organic materials in the individual bricks. The effect compromises the strength of the individual bricks and if extensive can compromise the structural integrity of the entire structure, or a portion of the structure affected (Crosby 2005).

If further research does prove that the termites were concentrated in the Arg e-Bam at the interface between zones of construction of different periods, it may explain why the later construction tended to fall off the older cores of the walls. In addition, once termites perforate the matrix of the earthen wall, the termite tunnels may contribute to the further drying out of the earth itself, with a commensurate loss of cohesion. (The interatomic forces that give clay its cohesiveness and allow it to be such a useful building material are dependent on the presence of a certain limited amount of moisture.)

COLLAPSE FROM INSIDE OUT

The termites are only a part of the larger problem of the internal degradation of the walls, but the pervasive insect tunnels throughout the ruins does point to the possibility that many of the collapses in the Arg may have initiated from failures deep inside the thick walls.

The massive ruins of the earthen complex are still impressive, and it was difficult to come up with a single theory that could explain the nature and extent of the damage. I had expected to find the kind of damage described by the Getty Seismic Adobe Project, with the classic signatures of structural weaknesses inscribed on the ruins: shear "X" cracks, cracks propagating out from the tops of windows and doors, collapsed corners, overturned walls, etc.

Figure 14. Termite damage found in mud bricks dating from 2700 BCE at the Shunet el Zabib at the archeological site of Abydos in Egypt (photo by Anthony Crosby).

However, in the Arg, even the usually common diagonal tension, 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 almost as high as the still-standing remains of the walls. The previously completely restored Grand Mosque, for example, was unrecognizable after the earthquake. In the rubble pile, there was barely enough left intact to discern the outline of what had been its large courtyard (Figure 4). The few ancient vaulted and domed rooms that did survive were often ones that had once been deep within the intertwined fabric of the complex, but now, with everything having fallen away from around them, they stand alone to give an impression of what had once existed (Figure 15).

It was only after taking in all of the evidence that could be 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 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 unconsoli-

Figure 15. This surviving domed room at the base of the inner citadel gives an idea of the simple, but impressive, spaces that had been in the Arg. It is now completely surrounded by rubble from the structures that had surrounded it.

dated earth fill. The study of the situation thus seemed to require a change of discipline—from structural engineering to dynamics of earth mass (such as the seismic behavior of earthen retaining structures).

The more I 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 Courtyard collapsed altogether, carrying away the front half of the rooms constructed on it (Figure 16). 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, while sections of the upper walls slid down the rubble. The upper ornamentations were the only recognizable pieces left (Figures 8 and 17, tower on left).

The aftershock at 7:10 a.m. on 20 April 2004 provided a palpable sense of what had happened during the main shock. As the records showed, the main earthquake on

Figure 16. Buildings above the Stables Courtyard that collapsed from the lateral spreading failure of the retaining wall and fill beneath.

26 December 2003 had a high-frequency vibration, particularly in the vertical direction. The sensation during the aftershock felt like the kind of vibration that could cause soil subsidence—much the same way that a vibrator causes freshly placed, wet concrete to flow. This experience then began to explain each of the seemingly disparate and sometimes counter-intuitive phenomena described above.

After witnessing all of these independent failures, it became increasingly evident that each could be explained in a similar way. For example, 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 to survive is to the right of the second gate (Figure 17). In contrast to the collapsed tower on the left, it has a timber floor diaphragm, with timbers penetrating the walls beneath the upper windows, and 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.

The collapse of the structures at the top of the hill (Figure 1) seems to have been caused in part by 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. The failure of the walls of many buildings and ramparts was also consistent with the lateral spreading of the material in the cores of their walls. The exterior layer of adobe bricks was forced out from internal pressure (Figures 11, 18, and 19).

Figure 17. The turret on the right is one of the few turrets to have survived the earthquake. It is interesting to note that this turret was unique among all of the turrets in that it had a room in its base rather than being solid earth. Although it is counterintuitive to find greater earthquake resistance for a thin-walled structure with a room in it when compared to a solid base, the fact that it did not have the large mass of loosely consolidated fill that collapsed in the others may explain its resilience, in addition to the existence of the timber diaphragm of the second floor that serves to hold it together.

In the case of the collapse of the domes throughout the complex, many simply may have followed their bursting supporting walls to the ground. Others that collapsed inwardly, such as the icehouse, probably suffered from the effect of the intense vertical vibrations on the weak unfired 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 inner part of the dome that collapsed had been reconstructed after 1974 onto the outer part, as these photographs show a hole in the dome with the same basic dimensions as the one caused by the earthquake.

In contrast to the bursting walls, the masonry structure over the cistern in the center of the Stables Courtyard performed much better, despite being of unreinforced masonry.

Figure 18. View of a portion of the wall around the Stables Courtyard showing the vertical fracturing of the wall into segments as it had collapsed from failures at its base.

Most likely in this case, the walls were a uniformly solid and bonded fired-brick masonry construction without a rubble core. The fact that this was constructed of fired brick would have contributed to its strength, but what was probably more important was the fact that the walls were of a fully cohesive, horizontally bedded masonry of uniform density without voids or vertical gaps (Figures 9a and 9b).

As for the better behavior of the north-facing ramparts compared to the other city walls, the subsurface soil conditions along the riverbank where the wall is located may account for some of this difference. The alluvial soils may have served to damp out some of the vibrations rather than causing the increased intensity that is familiar at sites farther from the epicenter. Further research is needed to determine whether this explanation is plausible. Also, like the walls of the nearby Konari neighborhood, these walls had not been altered and restored along their tops as much as the other walls around the Arg. It was the newer, restored, upper-level battlements, walkways, and crenellations that consistently suffered the most damage, possibly because of differences in soil densities and the vibration response of the newer work in contact with the older construction, in addition to the added weight at the top of the wall.

Figure 19. A massive pier composed of different periods and types of *khesht* and *chineh* construction that have separated from each other during the earthquake.

Also of interest is the Caravansary (Figures 20 and 21), where rooms on the second level of the buttressed west side of the complex collapsed, leaving the east side, which lacked buttresses, largely intact. The buttresses themselves were also damaged, with one collapsing from the crushing of its base.

The story of this complex became even more interesting when I learned from the historic photos that the side that collapsed had been largely reconstructed only a few years earlier, whereas the side that remained standing had mostly survived from antiquity. In aerial photographs of the Caravansary taken in 1974, 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 how they were in 1974, except that the small holes in the east side domes had been fully repaired (ICHO 2004a).

At the time of the earthquake, photographs show that the restoration of the west side of the Caravansary had been completed (ICHO 2004b). 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 20. The ruins of the Caravansary show that the domed rooms on the second level behind the buttresses have collapsed, while the ones opposite still remain. There are no buttresses behind the external wall of the opposite side. The fifth buttress has begun to collapse at its base.

All of this evidence taken together seems to point to a phenomenon where earthen walls 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 those of a newly constructed earthen building. These walls no longer consisted of horizontal layers of earth or sundried bricks. 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 19), and the organic material used for reinforcement had rotted or been consumed by insects, leaving cavities and friable earth (Figure 2).

Figure 21. The interior courtyard of the Caravansary. The buttressed side is behind the collapsed rooms to the right.

It seemed apparent that the behavior of vertically disconnected, unconsolidated earth—rather than the uniform, horizontally bedded, earthen construction of the sort analyzed by the Getty project—was a possible explanation for the nature and extent of the earthquake damage. Based on the Getty research, the thick walls of the ramparts and the 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 have 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 resulting from different periods of erosion and reconstruction and from changes from chineh to khesht, quite possibly can cause the earthquake vibrations—particularly vibrations in the high-frequency range like those experienced in Bam—to ricochet off the layers of different densities. This can result in damage or collapse from the local intensification of these vibrations. Evidence of such behavior can be seen in Figure 13, where the wall began to break out at the interface between two vintages of khesht construction, both of which appear to be pre-twentieth century. This subject needs 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 usually composed of uniform layers of unfired brick masonry through the entire wall.

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 segments from each other and reducing the cohesion of the inner core of the walls. In Isfahan, professional restorers of several of the historic monuments in that

Figure 22. 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.

splendid city (Figure 22) have confirmed that termites have been found in the walls of several earthen monuments during recent restoration work. These 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.

In contrast to the strengthening work in Isfahan, some of the twentieth-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 had increased in modern times, simply because of the inadvertent provision of this "banquet" of nonresistant straw-reinforced stucco.

Less than a year after the earthquake, Iranian conservators unearthed the great doors from the main gatehouse of the Arg, visible in Figure 23a, which had been buried since the earthquake in the earthen ruins. They were discovered to have been heavily consumed by termites in the eleven months that had elapsed since they had disappeared into the tumble of rubble of the one majestic gatehouse. This demonstrates that the termites continue to be active on the site (Figures 23 and 24).

In response to the need to use natural fibrous materials for adobe reinforcement, Edward Crocker, an adobe restoration expert in Santa Fe, New Mexico, recommends that the organic material be soaked with borates. He also has observed that this may have been done historically, since borax is common in desert deposits. Borates destroy the digestive enzyme of the termites and other invasive insects. It is also inexpensive and marvelously effective for both insects and rot molds.

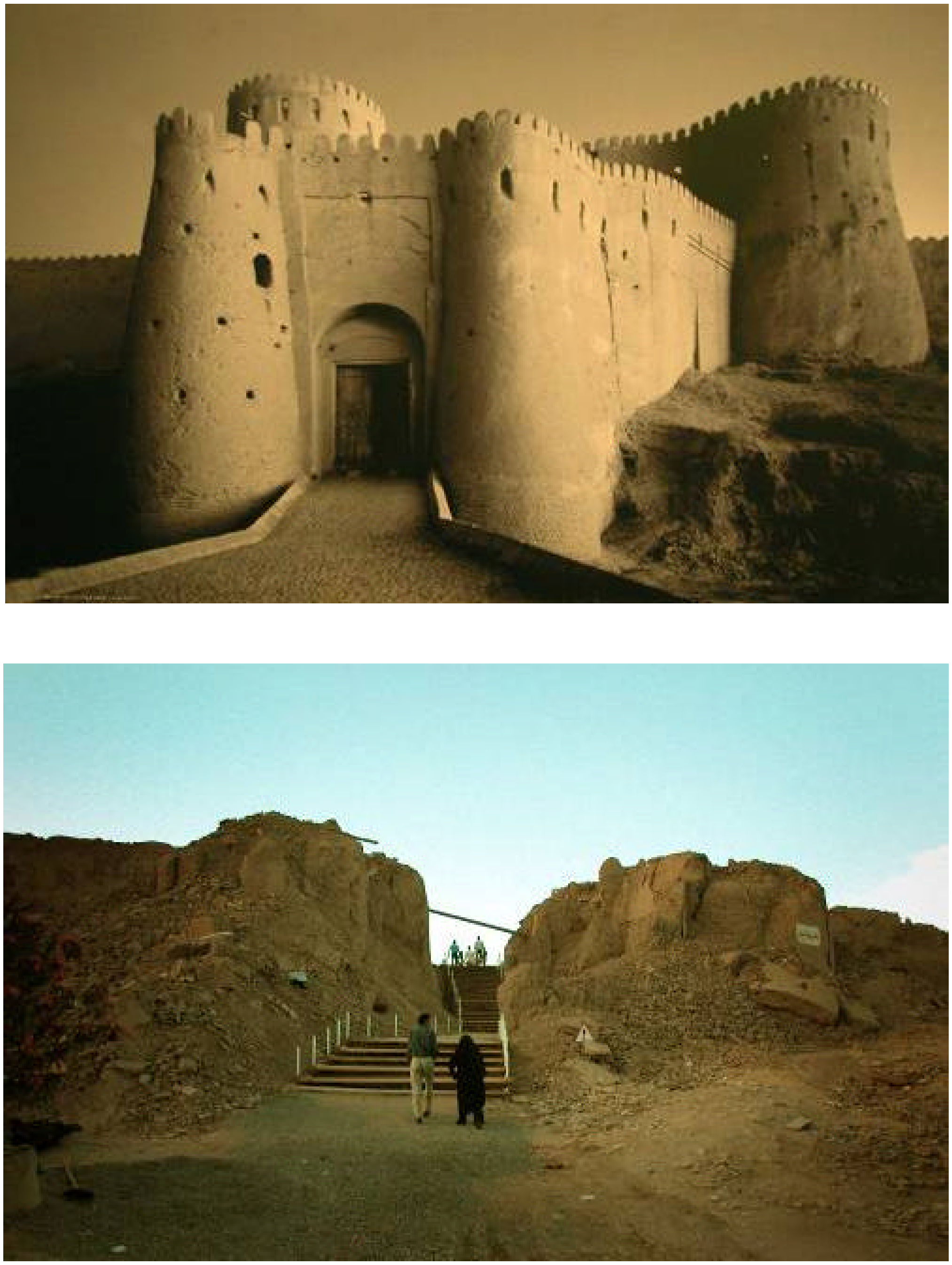

Figure 23. (a) Main Gatehouse to the Arg in 1988 (photo by M.R. Javadi, Iran). (b) Same view after the earthquake.

Figure 24. Iranian professional team of conservators inspecting the doors to the Main Gatehouse of the Arg after they were excavated and found to have been partly consumed by termites after 11 months under the collapsed earth of the gatehouse (photo courtesy of Professor Mehrdad Hejazi).

AN APPROACH TO MITIGATION BASED ON HISTORICAL PRECEDENT

The collapse of the Arg does invite an important question: Since Iran has long been known to be frequently subject to earthquakes, did the original builders of the Arg's buildings take this into account, and if not, why not? In order to recognize pre-modern seismic mitigation practices, one must accept that people would have responded to earthquakes in the past, just as they do today, with consideration of what could be done to reduce the risks. Whether they were successful or not does not change the fact that in centuries past, people did not always simply acquiesce to the risk. In Italy, Turkey, and some other seismically active areas where earthquakes have been frequent enough for there to be living memory from one generation to the next, there has developed what some scholars have defined as a "seismic culture" (Ferrigni 1997; Pierotti 2003).

For example, there are many types of stone construction around the world, but some types have proven to be more resistant than others. Rubble stone construction has proved to be less resistant than dressed and horizontally bedded ashlar; yet in many places rubble stone is all that is available or affordable. In parts of Turkey and Kashmir, a crossweave of horizontal timbers, in the form of a ladder, were laid into stone walls above and below the windows and at the floor levels. These timbers were placed in the wall not to provide a frame, but to resist the propagation of cracks and the lateral spreading of the masonry in the masonry bearing-walls (Langenbach 1989). In Kashmir, the timber-laced masonry was often rubble made up with small stones or bricks set into a thick bed of clay mortar with the timbers holding the walls together. In Srinagar, after an earthquake in 1885, a British visitor observed (Langenbach 1989):

> Part of the Palace and some other massive old buildings collapsed… (but) it was remarkable how few houses fell…. The general construction in the city of Srinagar is suitable for an earthquake country; wood is freely used and well jointed; clay is employed instead of mortar and gives a somewhat elastic bonding to the bricks… the whole house, even if three or four stories high, sways together, whereas more heavy rigid buildings would split and fall

There are few people today who would consider using "clay… instead of (lime) mortar." For years, the accepted wisdom has been that not even lime mortar is strong enough. Currently, many national building codes now require the use of cement. More significantly, this nineteenth-century quote highlights the virtues of flexibility over strength. It also describes a system that has provided an influential model for the present-day development of a similar reinforcement system for rural earthen construction in the rest of India and then later in Nepal, which is now embodied in the Indian and Nepali National Building Codes. (Langenbach 1989, 2004)

Figure 25. *Chineh* garden wall, probably of recent origin, on the opposite side of the river from the Arg. This wall shows the cracks that commonly exist in *chineh* walls, and also how this ordinary earthen garden wall survived the earthquake almost completely intact.

Ensuring stability in earthquakes of earthen structures like those in Bam is clearly more difficult without the timber that is available in Turkey, Kashmir, and other regions. The more lush sections of northern Iran are reported to share the timber-laced building tradition found in Turkey, but in the dry deserts of southern Iran, people do not have the luxury of using extensive amounts of timber; however, date palm logs were sometimes embedded into the walls or used to support floors.

To understand what may have been done in the past with earthen construction in response to earthquakes, it is helpful to begin by looking not only at what fell, but what did not. For this we turn to the chineh garden walls around the date palm orchards throughout the city. The chineh garden walls are generally about 2–2.5 meters high and 50–100 cm thick at the base, with a batter reducing them to only a few cm thick at the top. Most of the date palm groves in Bam and in Baravat are surrounded by walls of this type. The Iranian chineh construction found in Bam is characterized by a series of bands of clay that are about 50 cm high that represent each “lift” in the construction process. These lifts were constructed along the wall from one end to the other and then made smooth and level on the top before proceeding with the next lift (Figures 5, 13, 25, and 26).

Figure 26. The south-facing outside wall of the Stables Courtyard showing how the layering of the *chineh* walls has interrupted the cracking and collapse of sections of the wall, thus helping to maintain the stability of the partly undermined upper part of the wall. This is next to, and at right angles to, the *khesht* wall that is collapsed seen in Figure 18.

This differs from northern European cob construction, which lacks such clearly defined horizontal interfaces between the lifts. There may have been a number of reasons for this construction detail in chineh, such as protection against rising damp and the shedding of water, but one structural reason may have been to avoid vertical cracks through the wall, a problem that is all the more acute in a dry climate. Because these walls are constructed only of uncompressed dried mud, they began their life with many vertical cracks and checks from the initial drying out process. In fact, the Getty Seismic Adobe Project report states: “Substantial cracks nearly always exist in historic adobe buildings as a result of past earthquake activity, wall slumping, or foundation settlement. Cracked walls are a typical feature of these buildings.” Throughout history, Iranian builders would have striven to avoid the negative structural effects of this inevitable cracking as much as possible. This would have been done for stability in general, not just because of earthquake risk, but the earthquake risk may have contributed to the evolution of the system that was used, while the local limitation on resources would have limited the builders to the use of unfired earth. Consequently, the horizontal control joints in the chineh walls may be a result of this effort to control the effects of crack propagation by interrupting the progression of cracks through what would otherwise have been a uniform material.

Many chineh walls, both ancient and modern, did prove to be remarkably durable in the 2003 earthquake. As one passes through areas of gradually increasing damage in the city of Bam, these walls are seen to have remained standing even when nearby houses and multi-story steel frame buildings collapsed. Near the Arg, which is located close to the epicenter, the damage to the garden walls is clearly greater, but large sections have nonetheless remained standing that in both the parallel and perpendicular directions to the earthquake waves. Also, in the Arg, many walls of the unmaintained and unrestored structures mentioned above that survived the earthquake largely intact were of chineh construction (Figures 3 and 13). There are examples where both chineh walls and separate pre-twentieth-century walls of khesht construction survived intact, whereas, in other locations where chineh was later reinforced with khesht, the damage was observed to be the most extensive (Figure 19).

When examining the historic evolution of the chineh walls with the horizontal control joints, it also may be relevant to turn for comparison to the construction practices that evolved in ancient Rome. In Rome, the surviving archeological remains are filled with walls of a form of natural pozzolanic cement. These great lumps of material have shown a remarkable durability, but one feature in many of these walls stands out. Every meter and a half or so, the Romans placed a horizontal band of fired brick masonry that extended through the walls. The Romans used bricks that were essentially flat thin tiles. The original purpose of these bands is not known from any literature source, and archeologists often differ in their interpretations, but it is clear that they did function as “crack stoppers.” By interrupting the uniform matrix of the natural cement with the bedded layer of bricks in mortar, the inevitable cracks that occurred in the cement layer were interrupted, giving added stability to the walls (Figures 26 and 27).

In the Arg-e-Bam, some of the chineh walls had a band of adobe bricks between the lifts at the base of the wall. In one of the eastern rampart walls, there appears to have been a row of adobe bricks between each of the several lifts. These may have served a similar function as the Roman bricks, even though they were not fired bricks and the material being subdivided was clay rather than concrete (Figure 5).

These and other Iranian examples are worth exploring for further information on the effectiveness of such horizontal bands of masonry laid into earthen walls, but the lesson to be learned is that what we sometimes only think of as architectural details originally may have been developed to serve more practical structural needs. This point is reinforced by the following example in Istanbul: during the 1999 Koçaeli earthquake, the only part of the ancient city walls to collapse was a tower that had been completely reconstructed in new masonry only a few years before (Figure 28a).

Figure 27. A wall at Hadrian's Villa near Rome showing the bands of brick that were laid into a wall constructed with natural cement with a tile facing. The crevices are the result of the later chipping out of the bricks for re-use.

The next tower (Figure 28b)—despite its heavily decayed and cracked condition—remained standing. The surviving ancient tower had horizontal brick bands that extended through the rubble stone core of the wall. The restorers of the new tower only placed the brick bands on the surface of the wall as a veneer, constructing the tower with thick walls of rubble set in mortar with a thin cut stone veneer. The lesson that can be learnedfrom this event is that architecture, structural design, and construction practices for ancient buildings are part of an integrated system, not separate or unrelated features. The hidden parts of the ancient walls are every bit as important as what can be seen on the surface. Illustrative of this fact, the pre-modern builders most likely understood the importance of the simple concept of crack-stopping, since it was one of the few measures that they had at their disposal to improve the stability of unfired earthen construction in desert environments.

Figure 28. (a) A modern reconstruction of a tower as part of the ancient Theodesian City Walls in Istanbul, Turkey. This reconstructed tower collapsed during the 1999 earthquake. The bands of red brick on the wall were fake veneers rather than full through-wall layers of brick. (b) A surviving portion of the original Theodesian city walls in Istanbul, which are next to the tower seen in 28a. The large cracks and damage pre-dated the 1999 earthquake, which caused no further damage to this unrestored ancient wall. The bands of brick extend through the rubble core.

CONCLUSIONS

In summary, it appears 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 within its fabric. The initial impression was that the twentieth-century restoration work itself performed far worse than the ancient work; however, it is important to acknowledge that it was not always the newer work that failed per se, but the combination of the new and old. In fact, the newer work often may have 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. Internal wall degradation—dryness and lack of cohesion of the earthen cores, decay and consumption of the reinforcing timbers and fiber reinforcements, the existence of small and large voids between vertical layers in the walls—may have contributed significantly to the collapses. The evidence presented in this paper that thick earthen walls had burst open before they collapsed, lends further credibility to this theory. When all of these elements are put together with the characteristics of this earthquake and its particularly high-frequency vertical vibrations, the collapse of the walls from the inside out appears to be a plausible explanation for most of what happened.

If after further research, these explanations of the causes of the collapses in the Arg described here are substantiated, it is important then to ask: What are the implications of these findings, not only for 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. Behind their exterior surfaces of carved stone and ornate ceramics, many of Iran's most splendid monuments are of earthen construction. 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 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 foregone conclusion or as a condemnation of the use of unfired earth as a building material. What the destruction of the Arg does provide, however, is a 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 horizontally bedded layers to a weak series of vertical segments resulted from centuries of erosion and renewal, but the external look of the walls had changed little over that time. It took an earthquake to open up the walls and reveal that their internal composition was no longer the same as it had been when originally constructed.

More than any other building material, the composition of unfired clay can evolve over time as a result of the cumulative effects of a repeating cycle of erosion and renewal. While this process is repeated over the centuries, there is also gradual, but progressive, deterioration of the hidden core of the walls. This is caused not only by termites, but also by rising damp, water intrusion from the top and sides, 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.

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 1a and b). 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 (Figures 3, 7, 10, 12, and 13). Without having had modern-day maintenance or restoration, at the time of the earthquake these structures were closer to the structural form of their original centuries-old construction. Having survived the earthquake intact, they stand today as examples of earthen construction that resisted this major earthquake better than did many of the new steel frame buildings that did collapse. The age of an historic structure, thus, may be less of a factor in earthquake survival than modern-day changes to its fabric, including, ironically, modern efforts to strengthen and restore that ancient fabric.

If this is true, we may need to look no further than some of these present-day construction and conservation practices to begin finding 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 alongside.

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 abandoned and untouched ancient 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 change, and 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.

The collapse of the Arg, a symbolically important historical monument, and the death of the 30,000 people in houses with walls of unfired earthen construction, have been fused in the eyes of many around the world. Life safety concerns about adobe construction now have been tragically highlighted. This has created a problem for the conservation of other earthen sites in seismic areas, all of which are now known to be at greater risk than they were thought to be before the 2003 Bam earthquake. By understanding 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, instead, the use of unfired earth is made illegal, all discussion stops and the fundamental need to determine all the necessary ingredients that constitute earthquake safety will not be achieved.

Although in practice it would seem easier to design and construct safe structures out of steel and concrete, 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 embedded 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, this does not mean that it cannot or should not continue to be done.

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