KEYNOTE ADDRESS

ANCIENT CONSTRUCTION TECHNOLOGIES THAT CAN PROTECT MODERN BUILDINGS FROM COLLAPSE IN EARTHQUAKES

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ABSTRACT

This paper explores the specifics of what can be learned from simple, unsophisticated, non-engineered, timber and masonry historical construction that resists earthquakes, by describing the author's concept for "Armature Crosswalls," a concept based on Turkish and Kashmiri traditional construction adapted for reinforced concrete infill-wall construction. The value of this approach for Heritage Conservation is that when people understand historic structures not only as archaic and obsolete building systems, but also as repositories of generations of thought and knowledge of how to live well on local resources, societies can begin to rediscover the value of these traditions once again by seeing them in a new light – one that, at its most fundamental level, can save lives.

RECENT EARTHQUAKES

2003 Bam, Iran Earthquake

Fig. 1. The Arg-e Bam before the earthquake (photo courtesy Iran Tourism Organization)

Fig. 2. The Arg-e-Bam, exactly the same view after the earthquake.

In the morning of 26 December 2003 the world woke up to news of an earthquake in Iran, in which an entire city was reported to have been destroyed and tens of thousands of people killed. This news was illustrated with a pair of pictures of Bam's iconic earthen walled city, the Arg-e Bam. The post-earthquake picture showed a sea of rubble where the majestic undulating earthen walls had once been—like a child's sand castle on the beach after it had been kicked down by rude teenagers. This pair of pictures became the unwitting symbol for the sudden annihilation of approximately 30,000 people estimated to have died in the earthquake. Unfired earthen construction—how can it possibly be safe? Isn't it time that it should be banned outright?

However, the images of the destruction of this historic earthen structure hid the real truth of this earthquake—almost all of the over 30,000 people who died in the earthquake, died in *modern* buildings! Only two people died in the ancient Arg, as it was an open air museum closed at the time of the earthquake. Even within the Arg itself, the worst damage was concentrated in those parts that had been restored and reconstructed over the previous half-century. Ironically, those parts that had remained abandoned and unrestored for as much as 150 years suffered very little damage! [1]

The proof that modern buildings were responsible can be shown with simple arithmetic. At the time of the earthquake, Bam had a population of 100,000, of which approximately a third were killed. However, as recently as in 1968, Bam had only 7,000 residents. While many of the new buildings that housed this expanded population did have adobe walls, their upper floors and roofs frequently were often constructed of steel and fired brick. Lacking ties to secure them to the walls, the roofs collapsed onto the occupants.

Fig. 3. Light steel frame building with jack-arch floors and roof damaged in the 2003 Bam earthquake.

Fig. 4. Ruins from the 2003 Bam earthquake showing the steel and fired brick masonry jack-arch construction used for floors and roofs in Bam that were strong in themselves, but incompatibly rigid for the *Khesht* (unfired adobe) walls.

All of this raises important questions in the fields of disaster mitigation and historic preservation. Does an indisputably weak material (unfired clay) automatically result in construction that is unacceptably vulnerable to earthquakes? Can any form of traditional construction with the historically available materials of earth, timber, stone, and brick ever meet any reasonable modern standards of earthquake safety? Indeed, how does one determine what is an acceptable level of risk?

The 1999 earthquakes in Turkey

In November 2000, one year after two devastating earthquakes struck near the Sea of Marmara in Turkey, a conference was convened by UNESCO, ICOMOS and the Turkish Government in Istanbul called "Earthquake-Safe, Lessons to be Learned from Traditional Construction." [2] The 1999 earthquakes had demonstrated that in spite of all of the knowledge of seismology and earthquake engineering gained over the last century in the science and practice, the death toll in such events has continued to rise. It has become apparent that steel and concrete, even with modern codes and construction practices have not been able to guarantee seismic safety. At the time of the conference, few would have thought that traditional construction would provide any meaningful answers to confront the dilemma of death and destruction in modern buildings of reinforced concrete, but conspicuous among the ruins of the reinforced concrete buildings were many traditional buildings with timber and masonry infill, known in Turkish as *hımış* construction, that had remained standing often with little damage.

Fig. 5. Partially demolished house in Gölcük, Turkey at the time of the earthquake showing the single brick wythe thickness of typical *hımış* wall. The building had been abandoned for many years prior to the earthquake.

Fig. 6. The interior face of the same wall in Fig. 5. Despite its condition, the 1999 Kocaeli earthquake which caused the collapse of hundreds of nearby modern buildings, had little affect on it.

A new term, "pancake collapse," had emerged in recent years to describe the problem with reinforced concrete buildings. At the 13th World Conference on Earthquake Engineering in August 2004, Fouad Bendimerad, Director of the Earthquakes and Megacities Initiative, reported that "*approximately 80% of the people at risk of death or injury in earthquakes in the world today are the occupants of reinforced concrete frame infill-masonry buildings*."

Fig. 7. Steel frame building collapsed by the 2003 Bam, Iran earthquake.

Fig. 8. The Juarez Hospital collapsed by the 1985 Mexico City earthquake.

Thousands have already died in this type of building in earthquakes in different countries around the world, including recently in Turkey and Taiwan in 1999, India in 2001 and Morocco in 2003. In Iran light steel frames, also with masonry infill, are more common than concrete frames, but many of these buildings also collapsed in the 2003 Bam earthquake.

How can a technology of building construction based on the new strong materials of steel and reinforced concrete be linked to such deadly catastrophes? At the beginning of the last century both steel and reinforced concrete held great promise for earthquake-safe buildings, yet in Turkey one hundred years later, the pre-modern buildings of timber and masonry remained standing surrounded by collapsed concrete buildings. Clearly the original promise of these new materials has not been fully realized.

After the 1999 earthquakes in Turkey, the world's scholars and engineers descended on the ruins of the buildings that took the lives of 30,000 people. They made frequent pronouncements that the collapses were caused by bad design and poor construction. Inspection, quality control, better training was what was said to be needed. A number even asserted that nothing new can be learned because the myriad observed faults were well documented—and the well engineered and constructed buildings had survived. From their perspective it may seem that justice had been served, and that bad construction met its rightful fate. Contractors were arrested and developers chased out of town, and so perhaps in the future people could be taught to pay attention to building codes, and graft and corruption would cease. Only then, they say, can we expect that earthquakes will not result in such massive mortality.

The flaw in this reasoning is that, given the pressures to produce so many housing units in most developing countries, there will always be poorly built buildings. Thus the problem of earthquake hazard reduction cannot be seen primarily as an *engineering* problem. It is fundamentally a *socio-economic* problem. What the Kocaeli and Düzce earthquakes demonstrated is that humble and unassuming survivors—traditional buildings—proved that a solution to this problem does not necessarily rely on sophisticated construction. The traditional buildings that survived the earthquakes were not engineered. They were constructed without steel or concrete. No plans for them were ever inspected because none were ever drawn. They were rarely constructed by anyone who could remotely be characterized as a professionally trained designer or builder and no precision tools were used in their construction. On the contrary, they were constructed with a minimum of tools with locally acquired materials, using a minimum of costly resources, and are held together with a minimum of nails and fasteners. In many, the timber was not even milled, being only cut and de-barked. Their frames were sometimes nailed together with only a single nail at the joint before being filled with brick or rubble stone in clay or weak lime mortar.

Thus, the traditional buildings possess the same kinds of construction deficiencies that have been identified as reasons why the concrete buildings fell down, yet they remained standing. It appears that we have one system constructed with strong materials that is subject to catastrophic failure in large seismic events if it deviates from perfection in design and construction, and another considerably less sophisticated system constructed of weak materials by relatively untrained craftsmen that is, with few exceptions, robust enough to withstand major earthquakes.

2.2 Kashmir

Srinagar has been and continues to be a city obscured to the world by decades of regional civil strife. When first viewed by the author in the 1980s, it appeared as a magical world—a city beside a mountain lake with a way of life that seemed unchanged for a thousand years. The construction practices used for the traditional houses in Srinagar, which stand in contrast to today's codes, include (1) the use of mortar of negligible strength, (2) the lack of any bonding between the infill walls and the piers, (3) the weakness of the bond between the wythes of the masonry in the walls and (4) the use of heavy sod roofs (now replaced with corrugated steel sheets).

These buildings were observed almost a century earlier by Arthur Neve, a British visitor to Kashmir, when he witnessed the 1885 Kashmir earthquake: "*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, which are often arranged in thick square pillars, with thinner filling in. If well built in this style the whole house, even if three or four stories high, sways together, whereas more heavy rigid buildings would split and fall*." [3]

There are two basic types of traditional construction with earthquake resistance capabilities found in Kashmir. One, of solid bearing-wall masonry with timber lacing, is known as *taq* and the other, a brick-nogged timber frame construction, is known as *dhajji-dewari* from the Persian words for "patchquilt wall." Both use timber within the masonry wall to serve to hold the buildings together. *Dhajji-dewari* is characterized by having a complete timber frame, with one wythe (layer) of masonry forming panels within the frame.[4]

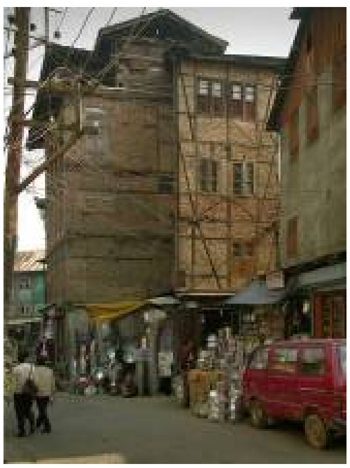

Fig. 9. Buildings in Srinagar, Kashmir. The building on the left is of *taq* construction, and on the right is of *dhajji dewari* construction.

Fig. 10. A partially demolished *dhajji dewari* building showing timber frame with infill masonry construction.

Fig. 11. A partially demolished building showing timber-laced masonry bearing wall typical of *taq* construction.

Even though it was remote from Srinagar and most affected buildings were different from those in Srinagar, the earthquake that centered on the Pakistan portion of Kashmir on October 2005 provides a new source of data on the comparative performance of the traditional buildings in the regions. According to the structural engineering professors Durgesh Rai and Challa Murty of the Indian Institute of Technology-Kanpur: "*In Kashmir traditional timber-brick masonry (dhajji-dewari) construction consists of burnt clay bricks filling in a framework of timber to create a patchwork of masonry, which is confined in small panels by the surrounding timber elements. The resulting masonry is quite different from typical brick masonry and its performance in this earthquake has once again been shown to be superior with no or very little damage."*

They cited the fact that "*the timber studs … resist progressive destruction of the … wall … and prevent propagation of diagonal shear cracks … and out-of-plane failure*." They went on to suggest that: "*there is an urgent need to revive these traditional masonry practices which have proven their ability to resist earthquake loads*." [5]

3. Timber-laced construction in history

The origin of both types of timber-laced masonry systems is known to be at least as far back as the ancient world. The palaces at Knossos have been identified as having possessed timber lacing of both the horizontal and the infill frame variety.[6] This dates what can be reasonably described as timber-laced masonry construction back to as early as 1500 to 2000 B. C. Evidence of infill-frame construction in ancient Rome emerged when archaeologists dug up the port town of Herculaneum that had been buried in a hot pyroclastic flow from Mount Vesuvius in 79 A. D. They found an entire two story half-timber house and interior walls in other houses believed by the archaeologists to be an examples of what Vitruvius has called *Opus Craticium*. After the fall of Rome, infill-frame construction became widespread throughout Europe. Timber-with-brick-infill vernacular construction is documented to have first appeared in Turkey as early as the eighth century.[7]

The question of whether timber-laced masonry construction evolved in response to the earthquake risk is an interesting one, but earthquakes are infrequent, and there were other compelling economic and cultural reasons for the evolution of these systems. For example, many variations of timber frame with masonry infill construction exist in areas well outside of the earthquake regions of the world, including Europe where in Britain it is called "half-timber," in France *colombage*, and in Germany *Fachwerk*. In Madrid, this construction is hidden behind solid masonry facades in most of the 18th and 19th century buildings around the Plaza Major.[8] In non-earthquake areas of the United States, the masonry infill version derived from French *colombage* can be found in New Orleans and other historic French settlements on the Mississippi, and, derived from the German *Fachwerk*, in parts of Pennsylvania.[9] *Colombage*, also found in Haiti, did well during the 2010 earthquake.

Fig. 12. Ancient Roman interior wall of *Opus Craticium* construction excavated in Herculaneum, Italy.

Fig. 13. Backs of 5 to 7 story buildings in central Madrid exposed by demolition of adjacent structures showing the timber frame construction with rubble masonry infill typical of the area in the 17th-19th centuries.

In earthquake-prone areas of Central America, Spanish construction was combined with native methods in what is today called *taquezal* or *bahareque.* In South America, Peru is also seismically active, and a form of traditional construction there known as *quincha* consists of earthen plaster on sticks or reeds (wattle and daub). This system is thought to have predated the

Spanish conquest, after which it was adopted by the Spanish and continued in use almost until the present.

Wattle and daub was also common in Britain, where earthquakes are rare. It also exists in earthquake-prone Turkey, where it is called Bagdadi. Turkey is also important for *hımış*, the masonry infill-frame construction which performed well in comparison to the reinforced concrete buildings in the 1999 earthquakes mentioned above. It may have been the spreading influence of the Ottoman Empire along trade routes into Mogul India (1526-1857) established centuries before during the first and second Persian Empires before and after the conquests by Alexander the Great that carried some of these construction traditions east into the Indian subcontinent, including Kashmir.

Fig. 14. Timber-laced four story masonry building in historic center of Ahmedabad after 2001 earthquake.

Fig. 15. In Bhuj, Gujarat, ruins of unreinforced rubble-stone buildings that collapsed during the 2001 earthquake. Unlike in Ahmedabad, much of the historic center of Bhuj, which lacked timber-laced construction, was destroyed.

This technology transfer along ancient cultural routes could explain why similar construction is found in the historic center of the Mogul city of Ahmedabad, Gujarat, but not in nearby Bhuj. In Ahmedabad, timber-laced vernacular buildings of similar construction to that found in Turkey and Kashmir survived the 2001 Gujarat earthquake when scores of reinforced concrete buildings collapsed. In Bhuj, historically a Rajput princely state, the buildings in the walled city were mostly of unreinforced rubble stone, which were devastated by the earthquake.

In fact, one prominent historic building in Bhuj had almost no damage, while its modern reinforced concrete addition collapsed, is the Swaminarayan Temple. Even that, it turns out, has its roots in Ahmedabad where this Hindu sect became established on land donated by the British in the 19th Century. This first temple in Ahmedabad, as well as the one in Bhuj, utilized the timber-laced building construction technology that had become common in Ahmedabad, but not in Bhuj.

While it may be difficult to identify earthquakes as the most important stimulus for the invention of these construction technologies in the examples above, in earthquake areas there are indeed two historical examples that were invented specifically in response to earthquakes that help to establish the credibility of all of these examples as historically known to be earthquake resistant: Portuguese *Gaiola* and Italian *Casa Baraccata*. The *Gaiola* was developed in Portugal after the 1755 Lisbon earthquake under the direction of the Marquis de Pombal (which is why it is also called *Pombalino* construction). The *Casa Baraccata* was developed in Italy after the Calabria earthquake of 1783, and later was even registered for a patent as an invention.[10]

Fig. 16. 18th century building in central Lisbon showing '*Pombalino gaiola*' construction, 2003.

Fig. 17. *Gaiola* wall sections removed to a government testing lab.

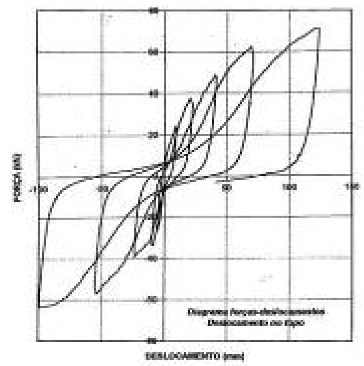

Fig. 18. Hysteresis diagram from one of the wall tests of the walls in figure 17.

Reinforced concrete frame construction with masonry infill walls

With the rapid spread of reinforced concrete construction during the middle of the last century, the traditional vernacular was displaced from all but the most remote rural regions within a single generation. This represented a transformation of the building process from an indigenous one to one more dependent on outside contractors, specialists, and nationally-based materials producers and suppliers of cement and extruded fired brick, and hollow clay tile. Reinforced concrete has been introduced into a building construction process that continues to exist much as it did in the past. The system of local builders with a rudimentary knowledge of materials science was sufficient only as long as they were working with timber and masonry. With concrete moment frames, it has proved woefully inadequate.

Fig. 19. Reinforced concrete building in central Port-au-Prince nearly collapsed by the 2010 Haiti earthquake.

Fig. 20. A formerly four story building in Port-au-Prince showing weak story collapse.

Concrete construction requires more than just good craftsmanship; it demands a basic understanding of the science of the material itself. The problem is that the builders were often inadequately trained to understand the seismic implications of faults in the construction, thus leaving a looming catastrophe hidden beneath the stucco that was troweled over the rock pockets and exposed rebars that characterize construction done without the equipment necessary to do it properly, such as transit mix and vibrators.

From the invention of the Skeleton Frame to the "Modern Movement"

Structural engineering has gone through its own revolution over the past century. The 19th century was an era of enormous ferment, producing engineering giants like Brunel and Eifel, along with Jenny and the other engineers of the first "skyscrapers." In the first decades of the 20th century, buildings went from a height of 10 to 20 stories to over 100 stories. To accomplish this, engineering practice shifted from a largely empirical process working with masonry walled structures to one of rigorous mathematics – almost exclusively of frames. Up until the middle of the last decade of the 19th century, structural calculations for the increasingly taller buildings consisted of the analysis of the frame for each floor separately. In order for the construction to conform to this, each frame had to be very rigidly braced, and constructed with a pin connection at each floor level. A more efficient way to design a multi-story frame came with the invention of portal frame analysis based on the contraflexure methodology of isolating moments in the mid-1990's for the construction of what then became called "skyscrapers" in Chicago, and later New York City and San Francisco. This was both simple and accurate enough for it to have remained in use through the entire 20th century, up until the present for the design of most multi-story structures.[11] This method was able to account for the value of the cantilever effects of beams and columns that run from floor to floor and across the building as continuous members with moment connections at the beam/column intersections.

Fig. 21. Flatiron Building in New York City under construction in 1902 showing the heavy stone masonry façade resting on the steel frame. The upper walls are constructed separately probably to ensure the weight is bearing on the frame rather than the lower masonry walls.

Fig. 22. View of San Francisco after the 1906 earthquake and fire. The three tall buildings visible in this view were burned out by the fire that followed the earthquake, but all three were in good enough condition despite this to be repaired, and they are still extant today.

Contraflecture portal frame analysis thus made a substantial reduction in the sizes of the members of a frame possible. However, the solid masonry exteriors of the first generation of skeleton frame "skyscrapers" did not change. For another generation and a half, the standard form of construction was exactly as it had been in post-1755 earthquake Lisbon, except that the timber frame was now replaced with iron and steel. The walls were of thick masonry. Although no longer load-bearing to the ground, these walls still shared significant loads with the internal steel frame, as well as protecting the frame from exposure to fire.

Many historians of the early skyscraper era view the evolution of skeleton frame building design as one almost like that of a genie waiting to come out of the bottle – true transformation could only come when this traditional masonry envelope was shed, and the open frame itself made the basis for the architectural expression with flexible systems of open spaces and moveable walls. [12] The architectural precursor for the liberation of the skeleton frame 'genie' is often identified as Swiss architect Le Corbusier's 1915 drawing of the prototype bare concrete skeleton for multi-story residences known as the Dom-Ino house. It became the icon of what he called the 'New Architecture'. As described by Le Corbusier's contemporary, Sigfried Giedion: "*Corbusier created…a single, indivisible space. The shells fall away between interior and exterior. … There arises…that dematerialization of solid demarcation…that gradually produces the feeling of walking in clouds.*" [13]

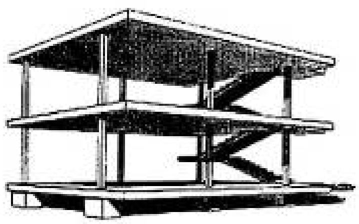

Fig. 23. Dom-Ino House by Le Corbusier, 1915.

Fig. 24. Building under construction in Gölcük, Turkey shown after the 1999 earthquake. Because the masonry infill walls had not yet been installed, frame action was able to occur, and thus the building was not collapsed by the earthquake.

Fig. 25. Building in Gölcük close to the one shown in Fig. 17 collapsed by 1999 earthquake. The heavy masonry infill walls together with open (soft) ground floors were often contributors to such collapses.

From the Dom-Ino prototype, the reinforced concrete moment frame spread through Europe, and then the rest of the world including earthquake hazard areas. However, the 'dematerialisation' of the walls clashed directly with the usual enclosure requirements of completed buildings. As a result, masonry did not disappear. Instead, the thick infill walls of the first skyscrapers evolved into thin, weak, and discontinuous membranes while at the same time engineers eliminated the infill masonry from their engineering calculations, except as dead weight. This was believed at the time to be a conservative approach, however the rigid and brittle infill walls attracted increased earthquake forces which they were too weak to resist, yet, their weight added significantly to the inertial forces that had to be resisted by the frame. To make matters worse, these walls interfered with the flexural movement of the structural frame on which the portal frame analysis was predicated. Compounding this problem was the frequent use of open 'piloti' on the ground floor as advocated by Le Corbusier. In earthquake engineering parlance, this became known as a soft or weak storey, and this has become perhaps the single greatest threat to the safety of these buildings.

The almost universal acceptance of the concrete moment frame as a standard form of construction, and of linear elastic portal frame analysis as the basic engineering approach, over a large part of the earthquake-prone parts of the globe fails to recognize the fact that most buildings are solid wall structures, once the rooms and exterior enclosures are finished when unit masonry placed within the frame is used for the walls. Despite the fact that this condition is known to most engineers, nearly all of the codes and practices that underlie their design are based on the standard infill frame design being modeled as moment frames with the infill masonry walls treated only as dead weight, rather than as an active part of the primary lateral-resisting structural system. The earthquake collapse of so many residential structures of reinforced concrete has shown the flaw with this approach.

This methodology of treating the masonry only as "architectural finishes" is also a product of the well-recognized fact that the infill masonry is very difficult to quantify mathematically and it certainly does not fit with portal frame analysis. Under all but the most severe wind loading, ignoring the effects of the infill rarely causes a failure because the value of the load sharing that occurs in reality between the frame and the infill can offset any unaccounted for behavior of the frame resulting from the infill. In a design level or greater earthquake, however, the situation is very different because, unlike for wind, a building's structural system is expected to deflect into the nonlinear range. In other words, the underlying structural frame is expected to go inelastic in a design-level earthquake. In other words, structural damage is expected to occur. For frames, this has been recognized in codes through the use of ductility factors which are assigned based on the individual elements that make up a structural frame. Such factors, however, are unresponsive to the conditions that exist when non-structural infill masonry is added to the system, as this masonry is usually a stiff and brittle membrane confined and restrained by the frame. The rigid diagonal strut provided by the masonry changes the behavior of the frame, sometimes with catastrophic results. The standard analysis method for code-conforming design, which is based on linear elastic behavior, is thus remote from the actual inelastic behavior of the infilled frame for the structural engineer's calculations to fully account for the effects of the forces on it.

In contrast to moment frames, reinforced concrete shear wall structures have a significantly better earthquake survival record. However, the cost of retrofitting existing buildings with shear walls is prohibitive and involves the added costs of relocating the occupants for the duration of the project. Thus, the financial cost of this and other strengthening procedures is often too high for widespread adoption in the economies where vulnerability is greatest. In Istanbul, for example, mitigation schemes have recently been drawn up and promulgated with World Bank assistance, but a broad retrofit program for the retrofit of reinforced concrete residential structures has been dropped because the number of vulnerable buildings is too vast for any conceivable public budget. This has happened despite the overwhelming need, simply because the costs for each project are so high as to come close to, or exceed that of demolition and replacement for most of the buildings in the database.

Lessons from traditional *hımış* construction—Armature Crosswalls

Returning to the aftermath of the 1999 Kocaeli earthquake in Gölcük, an answer to this problem may lie hidden behind the heaps of rubble from the collapsed concrete apartment houses. As different as they are from their concrete cousins, the *hımış*¸ houses that remained standing amongst the ruins also have masonry infill confined within a frame. It is their survival that has provided a source for one idea on how to keep reinforced concrete buildings from collapsing—a concept, called "Armature Crosswalls." The Armature Crosswall concept is based on using the ancient infill-wall masonry technology for modern reinforced concrete construction. Instead of the existing method of constructing infill walls in reinforced concrete buildings totally out of hollow clay tile or brick, the concept is that they be constructed with a sub-frame of studs and cross-pieces with the masonry infilling this sub-frame. The material chosen for these studs need not be limited to one type. It may be timber, steel, or concrete. The mortar for the masonry, however, is best if it is of LOW strength, rather than of high strength Portland cement. This is best accomplished by using a lime-based mix that is less strong, stiff, and brittle than ordinary cement mortar. In some situations, even unfired clay (mud) mortar could be used, especially if unfired adobe blocks are used for the infill.[14]

The intention behind the assembly of these elements is that the infill walls would have less initial stiffness and more frictional damping than standard infill masonry walls. The reduced initial stiffness can avoid the potentially destructive development of the "equivalent diagonal strut," thus ensuring that the frame-action on which the portal frame analysis relies will occur. In addition, the energy dissipation from the working of the combination of the sub-frame with the bricks and mortar serves to dampen the excitation of the building. As demonstrated by the *hımış* buildings in the epicentral region of the 1999 earthquakes in Turkey, this working of the composite structure during an earthquake can continue for a long period before the degradation advances to a destructive level. This was not the case with the nearby reinforced concrete buildings.

Fig. 26. Interior of a traditional house in Yuva, Turkey of after the 2000 Orta earthquake showing evidence of the working of the *hımış* walls.

Fig. 27. Typical hollow clay tile masonry wall in a reinforced concrete apartment building in Gölcük, Turkey collapsed by the 1999 Kocaeli earthquake.

Two fundamental questions are raised by this proposal: (1) why traditional buildings, with their seemingly weak and fragile construction, survive earthquakes that felled their newer counterparts, and (2) is it reasonable to expect that such a technology could be exported for use in multistory concrete buildings, which are much heavier and larger than their traditional counterparts?

The answer to these questions lies in an understanding of phenomena that already repeatedly have been observed in earthquakes. The subdivision of the walls into many smaller panels with studs and horizontal members and the use of low-strength mortar combine to prevent the formation of large cracks that can lead to the collapse of an entire infill wall. As stresses on the individual masonry panels increase, shifting and cracking first begins along the interface between the panels and the sub-frame members before the degradation of the masonry panels. When the mortar is weaker than the masonry units, cracking occurs in the mortar joints, allowing the masonry, which is held in place by the studs and cross-pieces, to remain in place and stable. The resulting mesh of hairline cracking produces many working interfaces, all of which allow the building to dissipate energy without experiencing a sudden drop-off in lateral resistance. By comparison, standard brittle masonry infill walls without the "armature" lose their strength soon after the initial development of diagonal tension X cracks and the separation of the infill wall panels from its surrounding frames. This can rapidly lead to their collapse, which can then precipitate a progressive collapse of the building.

This difference in configuration, material strength and system ductility (including the counter-intuitive fact that weaker mortar is likely to be better) explains why traditional infill-frame buildings are capable of surviving repeated major earthquakes that have felled modern reinforced concrete buildings. The basic structural principle behind why this weak but flexible construction survives is that there are no strong and rigid elements to attract the full lateral force of the earthquake. The buildings thus survive the earthquake by not fully engaging with it in much the same way that a palm tree can survive a hurricane. Although the masonry and mortar is brittle, the *system* displays ductile behavior. Ductility is not a quality normally used to describe the structural behavior of unfired brick masonry, however, what is being described here is ductile behaviour of a system, not of a single material. For example, Prof. Alkut Aytun credited the timber bond beams in unfired clay masonry walls in Turkey with "*incorporating ductility [in]to the adobe walls, substantially increasing their earthquake resistant qualities*." [15]

Fig.28. Apartment block in San Salvador that suffered a soft-story collapse in the 1986 San Salvador earthquake. The progressive collapse of the upper floors was stopped by the resistance of the infill masonry.

Fig. 29. Typical infill masonry wall found inside the upper stories of the building in Fig. 28 showing that the infill wall was subdivided with a concrete beam and column similar to that advocated for Armature Crosswalls.

Even though reinforced concrete buildings are often much larger and taller, their performance with Armature Crosswalls is predicated on the same phenomenon observed by Prof. Aytun because larger residential buildings have more walls in each direction in direct proportion to their size. Since the Armature Crosswall system is based on flexibility and on a reduction in initial stiffness compared to standard infill walls, the building's deflection in an earthquake is likely to engage all of the crosswalls parallel to its deflection in rapid succession. Because the initial cracking of each wall does not represent any loss of the ultimate strength of any given wall, the load shedding is interactive, with loads passed along from one wall to another and back again as the overall deflection increases until all of the walls have been engaged relatively uniformly.

While this behavior in traditional construction during earthquakes may seem relatively easy to comprehend, few disaster recovery engineers and other personnel have understood its significance when evaluating the performance of damaged timber and masonry vernacular buildings—with sad consequences in terms of the loss of cultural heritage. This failure has also seriously harmed relief efforts to provide safe and liveable housing after earthquake disasters by leading sometimes to the replacement or relocation of whole villages after earthquakes, which in turn brings about destruction of the social fabric of the communities as well represent an extraordinary waste of resources. Many such new villages in Turkey and other countries have eventually been abandoned. [16]

All too often, the post-earthquake inspection process is where cultural heritage takes an unnecessary hit, especially with cultural properties that are not officially recognized, a category into which vernacular buildings commonly fall. The inspectors who are sent into areas after a disaster often have no training and even less sympathy for vernacular buildings and archaic construction simply because they have no reference point in their training to understand how such buildings can competently resist earthquakes. Earthquake damage has often been looked at with little understanding of what it represents in terms of loss of structural capacity. The standards applicable to reinforced concrete, where a small crack can indicate a significant weakness, are often wrongly applied to archaic systems where even large cracks may not represent the same degree of degradation, or even any loss of strength.

7. Conclusion

One of the problems that plagues the assessment of existing buildings and the archaic structural systems used for non-engineered buildings is the basic difficulty of establishing a norm for earthquake safety and performance when no damage is not a viable objective. Earthquakes are unique among natural disasters because they come with very little or no warning. When the shaking begins, people can only take cover in the spot where they find themselves. Thus in areas where the tectonic plates shift, earthquakes engender a level of consternation that is out of proportion to their frequency and the relative risk to any one individual. With wind, for example, one uses real expected maximum wind speeds with an added safety factor. With earthquakes, however, it has been determined that to require all buildings to remain within their elastic range for design-level earthquakes is economically infeasible for such a large but infrequent event, so the codes have been drafted with reduced forces to be used for linear elastic analyses with ductility factors to account for the expected non-linear response. Thus, in this context, it is difficult to properly recognize the post-elastic performance of archaic non-engineered structural systems constructed of materials that do not appear in the codes, and for which there are little or no codified test results.

This problem is not just academic; it is integrally connected to the longer-term issues of post-disaster recovery and regional development. Old ways of building that are based on an empirical wisdom passed down through the ages will probably defy most attempts to be rationalized into systems that can be fully calculated, but the evidence remains that some of these systems nevertheless have worked well even in large earthquakes—in fact so well that it is important to learn why. Because of this lack of set rules and methodologies for quantification, the evaluation of older structures after earthquakes can lead to broadly divergent views on the significance of particular damage and on the reparability of the structures. This inevitably has led to the unnecessary destruction of traditional houses and even whole city districts and rural villages. Many such drastic measures have ultimately failed at tremendous social costs.

Modern construction materials and methods have brought with them extraordinary opportunities for new architectural forms and ways of building. However, in many parts of the world they have also been disruptive of local culture, resulting in building forms and ways of building that are alien to the local society, but which have been promoted to the local populations as safe and modern. The earthquake risk is just one way in which we can observe what this disruption represents in terms of a loss of cultural and technical knowledge and memory. Earthquakes have proven to be particularly unforgiving when the new ways of building are locally not sufficiently well enough understood or respected to be carried out at an acceptable level of quality and safety. By opening up to learning from indigenous pre-modern examples of earthquake resistant technologies, we can also learn to preserve the surviving examples of these now seemingly ancient ways of building in a way that respects what these buildings are, not just how they look.

Returning to the collapse of the Arg-e Bam in Iran, finding one and two-story high earthen remains of buildings that have been roofless and abandoned for over 150 years still standing atop the epicenter of an earthquake that turned nearby modern steel buildings into twisted pretzels and destroyed concrete buildings even farther from the epicenter has to make one reexamine some of our present day preconceptions. American journalist Henry Louis Mencken (1880 –1956) once wrote: "*There is always an easy solution to every human problem – neat, plausible, and wrong*." There has to be a reason why the earthquake did not collapse these walls when it pulverized walls that had been repaired and rebuilt back into complete buildings, but teasing the message to be learned out of the ruins of what had been such a grand monument requires more than training in a single discipline. It also requires a certain amount of humility and willingness to learn to listen with our eyes to the message our ancestors are telling us through the cultural artifacts they have left behind.

Fig.30. 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.

Fig. 31. 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.

As the world moves from an era of profligate energy use to one where fossil fuels are gradually depleted, sustainability and green have become the catchwords in building design and construction. Wood is nature's most versatile renewable building material. Stone and unfired earth, together with wood, represent the most energy efficient materials that can be used. To this can be added fired brick and lime mortar, which require far less energy to manufacture than Portland cement. Thus finding traditional vernacular construction practices that have performed well against one of the strongest forces that nature can throw at structures also can serve to provide a lens through which to see that the preservation of vernacular buildings represents far more than the saving of frozen artifacts. It is an opportunity for cultural regeneration—a reconnection with a way of building by people who traditionally had learned how to build successfully for themselves with materials readily at hand.

Fig. 32. An engraving by Giambattista Piranesi of the Terme Grande (Large Baths) at Hadrian's Villa dating from the middle of the 18th Century overlaid on the author's photographs which were assembled into a single image matching the view drawn by Piranesi. The ruin of this structure stands as a monument to the remarkable durability of Roman concrete. The structure is 2,000 years old and has been a ruin for most of that period. ***Artwork by © Randolph Langenbach***

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Acknowledgements

The Author thanks UNESCO, ICOMOS, The American Academy in Rome, the Earthquake Engineering Research Institute (EERI), IIEES, World Monuments Fund and various governments and organizations in the different countries discussed for assistance and support for the research used for this paper.