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Understanding What Works: Learning from Earthquake Resistant Traditional Construction

Introduction

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—illustrated with a pair of pictures of the ancient Bam Citadel, known as the »Arg-e Bam,« a site that was claimed to be the largest earthen structure in the world. The »after« picture (fig. 2) showed a sea of rubble where layer upon layer of undulating earthen walls had once been—like a child's sand castle on the beach after it had been kicked down by rude kids. Soon 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—namely that almost all of the over 30,000 people who died in the earthquake, died in collapsed *modern* buildings! Even within the Arg itself, those parts that had remained abandoned and unrestored for as long as 150 years suffered very little damage. The worst damage was concentrated in those parts that had been restored and reconstructed over the previous half-century.

Bam had only 7,000 residents in 1968, but it had grown to 100,000 by the time of the earthquake. It was the new buildings housing this expanded population that killed almost all of the 30,000. Many of the new buildings did have adobe walls, as unfired earthen construction remains a common way of building here as it does in many desert areas of the globe, but their roofs frequently were constructed of steel and fired brick. Lacking any fasteners to secure them to the walls, the roofs collapsed onto the occupants. The earthquake also collapsed modern multistory steel frame structures, which were more common here than reinforced concrete buildings.

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 acceptable risk?

Earthquakes

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 risk to

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 (photograph © Randolph Langenbach)

Fig. 3 Aerial view of collapsed apartment blocks, Gölcük (photo courtesy UN-ISDR)

any one individual.[1] The fact that people do not have the opportunity to evacuate structures prior to an earthquake thus continues to raise particular concerns about historic preservation. Any conservation plan for a structure has to deal with the responsibility for the safety of the occupants during a *design level* earthquake, which is one that has a reasonable chance of happening at the site anytime over a period of several hundred years.

Thus, the collapse of large parts of the Arg-e Bam in the 2003 earthquake has served to shine the spotlight onto other historic structures with thick earthen walls, raising concerns that they too could fall down suddenly. While this may spur people to upgrade other monuments at risk, the negative effect is that earthen construction will be so discredited that productive efforts to research how to improve its resistance—both for new construction and for the upgrading of existing construction—will be discouraged in favor of concrete and steel. That is why it is so important to look more carefully at the actual performance of archaic construction systems after earthquakes. Hidden by the mounds of rubble was a clue that points to a different way to interpret the results of this earthquake on the Arg-e Bam. The clue was the counterintuitive fact that the unrestored parts of the complex had suffered dramatically less damage than had those parts that had been restored and reconstructed. On further examination, it was discovered that the restored sections were infested with termites, and that modern mud stucco obscured the substantial deterioration that existed underneath. As a result what at first appeared to provide a case study for determining the threshold for the collapse of earthen structures in general shifted to one of determining why the restored sections proved to be so vulnerable.[2]

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.*[3] The 1999 earthquakes proved that in spite of all of the knowledge gained over the last century in the science and practice of seismology and earthquake engineering, the death toll in such events had continued to rise. It has gradually become apparent that modern construction has *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.

The 1999 earthquakes, however, provided an opportunity to re-visit this issue from a different perspective, as it was the *newest* buildings in the damage district that suffered the most damage. A new term had emerged in recent years to describe the problem—not with old buildings, but with new reinforced concrete buildings: *pancake collapse*. 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.«

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[1] The effect of this phenomenon was reinforced the very morning the author began writing this chapter when a rattling tremor awakened the San Francisco area household at exactly 4:42 a. m., 20 July 2007, from a quake that emanated from only 3 miles below and 6 miles away from the home. Before the tremor ended, the first thing through everyone's mind was, »Is this going to be the ›big one‹?«

[2] For detailed explanation of the findings on reasons for the earthquake collapse of the Arg-e Bam see: Langenbach 2004 and 2005, www.conservationtech.com

[3] For the program details and published papers from this 2000 conference in Istanbul see: http://www.icomos.org/iiwc/istanbul2000.htm

Fig. 4 Surviving *hımış* house next to a row of collapsed reinforced concrete buildings, Adapazari, Turkey, 1999 (photograph © Randolph Langenbach)

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, pouring over the wreckage and making frequent pronouncements that the collapses were caused by bad design and poor construction. Inspection, quality control and 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. Then—and only then—could 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

Fig. 5 This three story house in Gölcük located less than one km from the fault was undamaged by the 1999 earthquake, while a number of reinforced concrete buildings on the adjacent blocks collapsed (photograph © Randolph Langenbach)

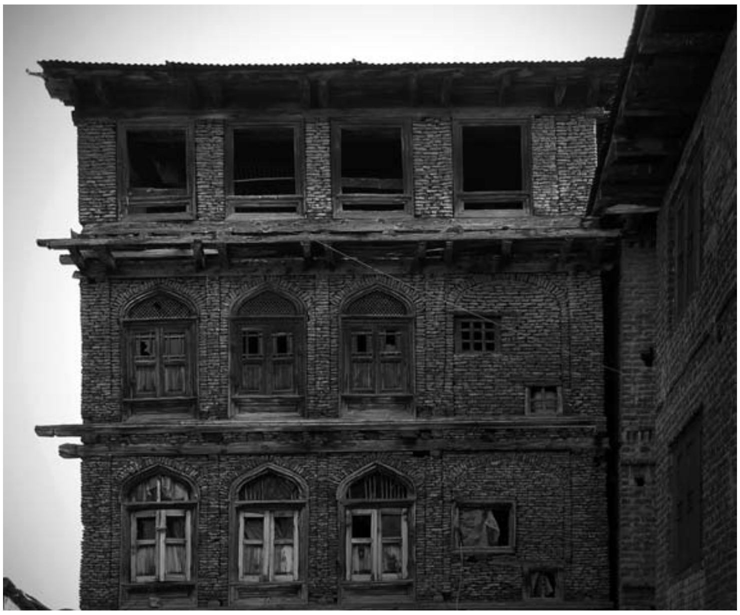

Fig. 6 Example of *taq* construction in Srinagar, Kashmir, 2005. The timbers in the masonry walls only run horizontally parallel to the wall and through the wall (photograph © Randolph Langenbach)

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 the solution need not be sophisticated construction, but, rather, *appropriate* 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.

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.«[4]

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*. Both use timber within the plane of the masonry wall to serve to hold the buildings together. *Dhajji-Dewari* is characterized

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[4] Arthur Neve: Thirty Years in Kashmir, London 1913.

Fig. 7 Example of *dhajji dewari* construction in Srinagar, 2005. The timbers form a complete frame, and the masonry is inset into the frame (photograph © Randolph Langenbach)

Fig. 8 The Craticii House at Herculaneum, 2003 (photograph © Randolph Langenbach)

by having a complete timber frame, with one wythe of masonry forming panels within the frame.[5]

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.«[6]

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.[7] 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 archeologists 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 which is believed by the archeologists to be an example of what Vitruvius has called *Opus Craticium*. This may present the only surviving example of the form of construction used in ancient Rome for the seven or eight-story tenements (insulae) that filled that city of a million and a half people. Masonry bearing walls would have been too thick at the base to fit on the known footprints of these ancient buildings and still leave any space for rooms, so it is likely that the Romans constructed many of these tall buildings with timber frames with infill masonry.

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.[8] The

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[5] For more information on Kashmiri traditional construction, see Langenbach (1989) at www.conservationtech.com and www.traditional-is-modern.net

[6] Durgesh C. Rai/C. V. R. Murty: Preliminary Report on the 2005 North Kashmir Earthquake of October 8, 2005, Indian Institute of Technology, Kanpur 2005, www.EERI.org

[7] Peter Kienzle, Architect, Archaeological Park Xanten, Germany, oral interview, October 12, 2002.

[8] Demet Gülhan and İnci Özyörük Güney (2000): The Behaviour of Traditional Building Systems against Earthquake and Its Comparison to Reinforced Concrete Frame Systems; Experiences of Marmara Earthquake Damage Assessment Studies in Kocaeli and Sakarya, Conference

Fig. 9 and 10 Views of ruins of a house in the walled city of Ahmedabad, showing a form of timber lacing similar to that found in *taq* construction in Kashmir. In the partially dismantled building, the construction with runner beams tied together with cross-timbers pegged to the beams is visible (photographs © Randolph Langenbach)

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.[9] 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.[10]

In earthquake-prone areas of Central America, Spanish construction was combined with native methods in what is today called *taquezal* or *bahareque*, in which a bamboo or split-lath enclosed »basket« between timber studs is filled with loose earth and stone. In South America, Peru is also seismically active, and the traditional construction with earthen plaster and sticks or reeds (wattle and daub), known as *quincha*, that can be found there is thought to have predated the Spanish conquest, after which it was adopted by the Spanish and continued in use almost until the present. Despite the ephemeral nature of the material, 5,000 year old *quincha* construction has been unearthed at the Peruvian archeological site Caral.

Wattle and daub was also common in Britain, where earthquakes are rare, and in earthquake-prone Turkey, where it is called *Bağdadi*. Turkey is also important for *hımış*, mentioned above, the masonry infill-frame construction which performed well in comparison to the reinforced concrete buildings in the 1999 earthquakes. It may have been the spreading influence of the Ottoman Empire into Moghul India that carried some of these construction types east into Kashmir and also into Ahmedabad, where similar timber-laced vernacular buildings survived the 2001 Gujarat earthquake when scores of reinforced concrete buildings collapsed.

While it may be difficult to identify earthquakes as the stimulus for the above examples, 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 earthquake-resistant construction: Portuguese *Gaiola* and Italian *Casa Baraccata*. The *Gaiola* was developed in Portugal after the 1755 Lisbon earthquake under the direction of the Marquis

Proceedings for Earthquake-Safe: Lessons to Be Learned from Traditional Construction, an International Conference on the Seismic Performance of Traditional Buildings. Istanbul 2000, also: http://www.icomos.org/iiwc/seismic/Gulhan.pdf

[9] E. Gonzales Redondo/R. Aroca Hernándes-Ros (2003): Wooden Framed Structures in Madrid Domestic Architecture of the 17th to 19th Centuries, Proceedings of the First International Congress on Construction History, Madrid, Instituto Juan de Herra, Escuela Técnica Superior de Arquitectura, vol. 2 (2003).

[10] Randolph Langenbach (2006b): From »Opus Craticium« to the »Chicago Frame«: Earthquake Resistant Traditional Construction, Proceedings, Structural Analysis of Historical Constructions (SAHC) Conference, P. B. Lorenço/P. Roca/C. Modena/S. Agrawal (ed.), New Delhi 2006, also: www.conservationtech.com

Fig. 11 Typical Turkish reinforced concrete building under construction showing installation of the hollow block infill (photograph © Randolph Langenbach)

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.[11]

Reinforced concrete infill-wall construction

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.

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.

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 Eiffel, 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 to one of rigorous mathematics.

Portal frame analysis based on the contraflexure methodology of isolating moments was invented and became the standard methodology for code conforming building design. This calculation method 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 skyscrapers.[12] For short and tall buildings alike, the isolation of the structural frame from the rest of the building fabric has made the structural design a relatively straightforward process. The enclosure systems could then be treated simply as dead weight in the calculations, eliminating the need to deal with the complexity introduced by solid walls into the calculation of the linear elements of the frame. This also meant that the frame could be standardized into a simple system of rebar sizes and overall beam and column dimension, which in turn has served to allow for the construction of multi-story buildings that are not individually engineered.

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[11] Franco Laner/Umberto Barbisan (2000): Historical Antiseismic Building Techniques: Wooden Contribution, Convegno Internazionale Seismic Behaviour of Timber Buildings, www.tecnologos.it, Venezia. 2000

[12] Elwin C. Robison: Windbracing: Portal Arch Frames and the Portal Analysis Method, unpublished manuscript, Kent State University, Kent, Ohio, July 1989.

Fig. 12 *Hımış* interior wall in a house in the Düzce earthquake damage district showing »working« of wall that caused loss of plaster (photograph © Randolph Langenbach)

Fig. 13 Collapse of a brittle interior hollow clay block wall illustrating typical failure pattern for such walls lacking subdivision of the masonry (photograph © Randolph Langenbach)

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, fails to recognize the fact that most buildings are solid wall structures once the rooms and exterior enclosures are finished. However, nearly all of the engineering and codes that underlie the design of these buildings are based on their being modeled as moment frames with the infill masonry walls treated as dead weight, rather than as structural elements. The collapse of so many residential structures of reinforced concrete has shown the flaw with this approach. The irrefutable fact is that the infill corrupts the frame behavior when subjected to the lateral forces on which the portal frame analysis method is based.

This methodology of treating the masonry only as dead weight was also a product of the well-recognized fact that the infill masonry is very difficult to quantify mathematically and it does not conveniently 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 load sharing that occurs in reality between the frame and the infill can off-set any diminished performance of the frame resulting from the infill. In a »design level« or greater earthquake, however, the situation is very different because a building's structural system is expected to deflect into the nonlinear range. In other words, the structure will go inelastic in a design-level earthquake, which means that 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 contained 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 too remote from the actual inelastic behavior of the infilled frame for the calculations to recognize the effects of the forces on it.

An alternative to moment frames could be to convert the buildings to shear wall structures, which have a significantly better record of survival in earthquakes, but 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 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 retrofit of the vast numbers of reinforced concrete residential structures has been dropped from consideration, despite the overwhelming need, simply because the costs are so high as to come close to that of demolition and replacement.

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*, that is based on using this ancient infill-wall masonry technology for modern reinforced concrete construction.

Figs. 14 and 15 Partially demolished house in Gölcük at the time of the earthquake showing the single brick wythe thickness of typical *hımış* wall. Fig. 14 shows the exterior and fig. 15 the interior face of the same wall. Despite its condition, the earthquake had little affect on it. 2003 (photographs © Randolph Langenbach)

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 timber, steel, or concrete sub-frame of studs and cross-pieces with the masonry infilling this sub-frame. The mortar to be used for this construction is intended to be a high-lime mix that is less strong, stiff, and brittle than ordinary cement mortar. When finished, the wall would be plastered as it would normally.[13]

The intention is that these walls would have less initial stiffness and a much greater amount of frictional damping than standard infill masonry walls. The reduced initial stiffness lessens the development of the diagonal strut effect, thus allowing the frame-action on which the portal frame analysis is based to occur. The energy dissipation from the »working« of the combination of timber, bricks and mortar against each other serves to dampen the excitation of the building by the earthquake. As demonstrated by the behavior of the *hımış* buildings in the epicentral region of the 1999 earthquakes in Turkey when compared with the surrounding reinforced concrete buildings, this working of the composite structure during an earthquake can continue for a long period before the degradation advances to a destructive level.

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 multi-story concrete buildings, which are much heavier and larger than their traditional counterparts?

The answer to these questions lies in the fact that 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 degradation of the masonry panels themselves. When the mortar is weaker than the masonry units, cracking occurs in the mortar joints, allowing the masonry units, held in place by the studs and cross-pieces, to remain intact 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 an »armature« lose their strength leading to their collapse soon after the initial development of the diagonal tension »X« cracks.

This 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 stiff 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 behaves as if it were ductile. Ductility is not a quality normally used to describe the structural behavior of unfired brick masonry, but in the paper *Earthen Buildings in Seismic Areas of Turkey* Alkut Aytun credited the bond beams in Turkey with »incorporating ductility [in]to the adobe walls, substantially increasing their earthquake resistant qualities.«[14]

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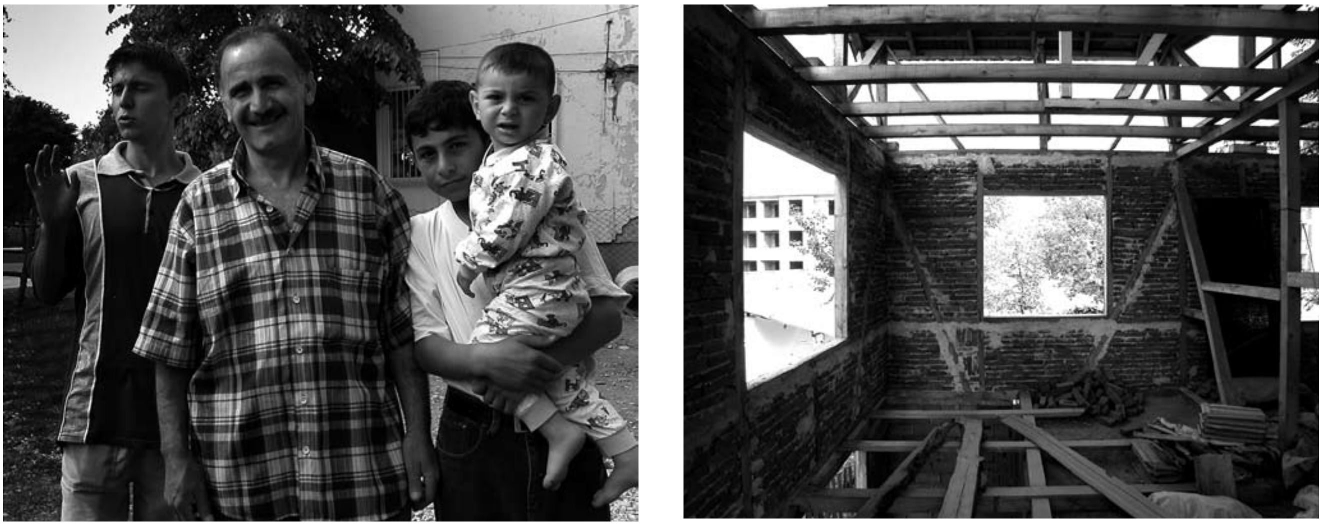
[13] More information on Armature Crosswall technology for reinforced concrete frame buildings can be found in Langenbach (2003) and Langenbach et al (2006a).

[14] Alkut Aytun: Earthen Buildings in Seismic Areas of Turkey, Pro-



Figs. 16 and 17 After witnessing the destruction of reinforced concrete buildings in Düzce while his father's *hımış* house survived undamaged, this resident of Düzce (left) decided to stop construction of a new reinforced house and change it to *hımış* construction (right) (photographs © Randolph Langenbach)

Even though reinforced concrete buildings are often much larger and taller, their performance with Armature Crosswalls is predicated on the same phenomenon 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 when 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 of traditional construction in earthquakes may seem relatively easy to comprehend, few disaster recovery engineers and other personnel have understood its significance when evaluating the performance of damaged 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 livable 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 as an extraordinary waste of resources as many such new villages in Turkey and other countries have eventually been abandoned.[15]

All too often, the post-earthquake inspection process is where cultural heritage takes an unnecessary hit, especially with unlisted and unofficially recognized cultural properties, a category which most likely includes almost all the vernacular buildings. 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.

Another problem is that when linear elastic analysis methods are used to analyze confined masonry buildings, often the resistance provided by the masonry is treated as falling to zero once its elastic limit is exceeded with the onset of cracking. In such an analysis methodology, the post-elastic strength and energy dissipation of the system will remain unrecognized and unaccounted for, thus showing an unrealistically high loss of capacity from the earthquake damage when cracks are observed. Because of this unrecognized lateral resistance, historical buildings are thus often forced to meet a level of lateral resistance that is, in effect, higher than that required of fully code-conforming newly constructed buildings. This can result in the unnecessary condemnation of buildings. This phenomenon has been and will continue to be a serious problem for the preservation of historic resources that have suffered damage in earthquakes.

ceedings of the International Workshop on Earthen Buildings, vol. 2 (1981), p. 352.

[15] For a description of the relocation and destruction of whole villages after the Orta earthquake of 2000 in Turkey see Langenbach (2006c) and after the Molise earthquake of 2002 in Italy see Langenbach and Dusi (2006).

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. 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. Thus, how does one 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 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—so much so 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 entire 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 spaces, forms, and ways of building, and for lower-cost housing for great numbers of residents. But 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, yet 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 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, 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. As has been attributed to Mark Twain: »For every problem there is always a solution that is simple, obvious, 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 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.

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 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 one can 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.

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