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Preventing Pancake Collapses:
Lessons from Earthquake-Resistant Traditional Construction for Modern Buildings of Reinforced Concrete

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Figure 1: Detail of traditional *hımış* construction in Turkey in mid-20th century house in Gölcük.

ABSTRACT: It seems counter-intuitive to assert that simple, unsophisticated, non-engineered, timber and masonry structures might be safer in large earthquakes than new structures of reinforced concrete, but such has proven to be the case in a number of recent earthquakes, including the İzmit and Düzce earthquakes in Turkey of 1999, the Bhuj earthquake in India of 2001, and the Kashmir earthquake in Pakistan of 2005. The question of what lessons can be derived from this information in present times is even less obvious, as these buildings now seem so archaic as to be more easily associated with the medieval rather than modern world. However, in many different regions of the world, the earthquake record with contemporary structures of reinforced concrete frequently has been abysmal. Such buildings are even responsible for what has come to be called a "*pancake*" collapse – where heavy and unyielding floors collapse one atop the other with people trapped and crushed in between.

In fact, before the advent of the strong materials of reinforced concrete and steel, many societies had developed an approach to seismic resistance that is only slowly being re-learned in the present: that it is wiser to build flexible structures than to attempt to build ones that resist

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earthquakes only by their strength. This paper will explore the specifics of what can be learned from these historical construction practices, 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.

Figure 2: LEFT: Collapsed apartment block, Gölcük.

Figure 3: ABOVE: Aerial view of collapsed apartment blocks, Gölcük. (from UN-ISDR).

Introduction: 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. 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. Quite the contrary, historic preservation has long been viewed more as being in opposition to seismic safety – with efforts aimed at producing a compromise between the preservation of historic building fabric and its replacement with new structural systems of steel and 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."* The pervasive image of floors piled one on top of another with the walls fallen away completely was heart-wrenching when one realized that between those floors lay the bodies of the occupants – thousands and sometimes tens-of-thousands of people. (Figures 2 & 3)

Figure 4: Surviving *hımış* house next to a row of collapsed reinforced concrete buildings, Adapazari, Turkey, 1999.

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."* 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 (Figure 5 & 6), 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 2004 Bam earthquake (Figure 7).

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.

Figure 5: Demolition workers on collapsed RC infill building in Bhuj, 2001 one month after the Gujarat Earthquake. Women work alongside men in heavy construction tasks in India.

Figure 6: Bare frame of incomplete building next to partial collapse in Bhuj, 2001. Bare frames, even if weak and poorly constructed, often do better than expected in earthquakes that happen before the infill is installed because the buildings are lighter than when finished, and frame action can take place.

Figure 7: Collapsed steel frame infill wall building in Bam, Iran, after the 2004 earthquake. Many light frame buildings with infill masonry collapsed in the Bam earthquake largely because of defective welding and poor layout that resulted in torsion.

After the 1999 earthquakes in Turkey, the world's scholars and engineers to 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. (For examples, see Figures 8 & 9) *"Inspection, quality control, better training, that was what was needed. If that was achieved, then all could be set right. The building codes were not at fault. It was all in the execution. If that is improved, then the promise of safety will be kept, and the magic of the new materials and modern engineering will be realized."* 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. They said that these surviving concrete buildings proved that reinforced concrete frame construction itself is not to blame. 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.

Figure 8: LEFT: House being reconstructed to replace one destroyed in Afyon earthquake. Concrete is being mixed on ground with garden hose and without slump test or measurements.

Figure 9: RIGHT: Concrete column in new mosque being constructed on site of building destroyed in Afyon Earthquake showing rock pockets leaving re-bar exposed. Vibrators are not used in most Turkish construction.

The flaw in this reasoning is that,a widespread improvement in the quality of construction will not happen because, realistically, it cannot ever be expected to happen. Given the pressures to produce so many housing units in a developing country, there will always be poorly built buildings, just as there will always be better ones, and the poor ones will more than likely outnumber the better ones. Thus, the problem of earthquake hazard reduction simply cannot be seen as exclusively, or even primarily as an *engineering* problem. It is fundamentally a *socio-economic* problem. As such, we cannot look to the high-quality reinforced concrete survivors to find the key to solving this problem. What the Kocaeli and Düzce earthquakes demonstrated is that we can look to those humble and unassuming survivors – the traditional buildings – because they have proved that the solution is not sophisticated construction, but, rather, *appropriate* construction.

While poor design and bad construction is indeed a good explanation for many of the concrete building collapses, there is something fundamentally wrong with a pervasive reliance on a construction system for conventional building projects that depends on a level of quality control that is so rarely achieved. By contrast, the traditional buildings that survived the earthquake were not engineered and they lacked 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 builder or building designer and few were carefully constructed. On the contrary, they were constructed with a minimum of tools with locally acquired materials, using a minimum of costly resources, and they were 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 thee interstitial spaces were filled with brick or rubble stone in clay or weak lime mortar.

Thus, the traditional buildings possess the same level of deficiencies in construction quality that are identified as reasons why the modern 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 even in small ways from a highly sophisticated level of 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.

Figure 10: 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. [1]

Kashmir

Srinagar has been and continues to be a city obscured to the world by the decades of regional civil strife. When first viewed 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. It was only later that the earthquake resistance of what by all appearances seemed to be fragile and vulnerable buildings was revealed in the historical record. The construction practices used for these

Kashmiri buildings, which stand in contrast to today's codes and commonly-accepted practices, 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 frequent (historical) use of heavy sod roofs. Just such 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* (Neve 1913).

Figure 11: Traditional timber and masonry buildings in Srinagar, Kashmir, 2005.

Figure 12: View of Srinagar from across the river Jelum, 2005.

Even though it was remote from 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. This opportunity has been obscured by the fact that most of the buildings in the most severely affected region did not share the resistive attributes reported on by Arthur Neve above; nevertheless, quoting from 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 recommend that: *"there is an urgent need to revive these traditional masonry practices which have proven their ability to resist earthquake loads."* (Rai & Murty, 2005)

Figure 13: 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.

Figure 14: Example of *Dhajji Dewari* construction in Srinagar, 2005. The timbers form a complete frame, and the masonry is inset into the frame.

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"* (a word derived from the proportional system used to layout the building, rather than the construction but no other more appropriate word seems to exist), and the other, a brick-nogged timber frame construction, known as *"dhajji-dewari"* from the ancient Persian "carpet weaver's" language for "patch-quilt wall." Both use timber within the plane of the masonry wall to serve to hold the buildings together. *Dhajji-Dewari* is characterized by having a complete timber frame, with one wythe of masonry forming panels within the frame.[1]

***Colombage, Fachwerk, Half-timber, Hımış, Bahareque and Quincha*:** In addition to Kashmir's *dhajji dewari*, regional manifestations found in both earthquake and non-earthquake areas alike are called "*colombage*" in France, "*fachwerk*" in Germany, "*half-timber*" in Britain, and "*hımış*" in Turkey. A variation that used loose earthen or stone filling in a bamboo or split-lath "basket" between the studs include *taquezal* and *bahareque* in Central America. Other variations that used earthen plaster and sticks or reeds (wattle and daub) include Turkish *Bağdadi* and Peruvian "*quincha*." Despite the ephemeral nature of the material, 5,000 year old *quincha* construction has been unearthed at the Peruvian archeological site Caral. In the United States, the masonry infill version can be found in New Orleans and other historic French settlements on the Mississippi derived from French colombage, and also in parts of Pennsylvania, derived from the German *fachwerk*. (Langenbach 2006c).

Figure 15: *Bahareque* construction in San Salvador showing effects of 1986 earthquake. The loss of the stucco shows that the wall underwent deformations without loss of its underlying structural integrity.

Figure 16: *Colombage* construction in the French Quarter of New Orleans, 2006.

Opus Craticium: When during the 1930's, archeologists dug up the port town of Herculaneum that had been buried in a hot pyroclastic flow from Mount Vesuvius in 79AD, they found an

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[1] For a lengthy description and illustration of these types, please see Langenbach 1989 & 1992.

entire two story half-timber house which was identified by Italian archeologist Amedeo Maiuri as one of the masonry construction typologies described by Vitruvius as "*Craticii*" or "*Opus Craticium*" (Figure 4a). This example in Herculaneum presents the only surviving example of the form of construction that may have been used in ancient Rome for the seven or eight story tenements (*insulae*) that filled that city of a million and a half people (Figure 19). The reasoning for this hypothesis is that masonry bearing walls would have been too thick at the base to fit on the known footprints of these ancient buildings with space for rooms left over, whereas using the timber frame with infill masonry system found in Herculaneum would have provided a means to build such tall buildings on small footprints. The fact that no evidence of these timber framed structures would have survived for two millennia outside of that found buried by the volcanic fallout is not surprising.

Figure 17: The *Craticii* House at Herculaneum, 2003.

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 (Gülhan and Güney, 2000). The question of whether timber-laced masonry construction evolved in response to the earthquake risk is an interesting one. There are so many more immediate factors that influence building construction typology that it is not easy to segregate out the influence of earthquakes. The use of timber lacing in masonry was more likely often the successful byproduct of a technology developed as much for its economy as for its strength. However, when earthquakes have occurred, it is also clear that the post-earthquake observations on what survived and what did not have had an influence on the continued use of such systems that did well. This can be seen particularly in the adoption and promulgation of the Pombalino "*Gaiola*" system in Portugal after the 1755 Lisbon earthquake, and the *Casa Baraccata* system in Italy after the Calabria earthquake of 1783.

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. Concrete construction requires more than just good craftsmanship, it demands an understanding of the science of the material itself. The problem is that the builders were often inadequately trained so as to know 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.

Figure 18: "Pancake" collapse in Mexico City, 1985.

Figure 19: Partial collapse of RC Building, Gölcük , Turkey, 1999.

In effect, in many countries, reinforced concrete frame construction was introduced into a building delivery process that continued to exist much as in earlier times. The local, casual, rural system of local builders with only a rudimentary knowledge of the science of materials had been sufficient for timber and masonry. However, with the introduction of concrete, it has proved to woefully inadequate. Once reinforced concrete became the default choice for almost all new residential and commercial construction, the problem has expanded exponentially.

Because of the widespread absence of proper professional training in the use of the material and moment-frame system, this requirement has never communicated down to the actual building sites. The severity of this problem may be unique to concrete construction because it is a material that is widely available for use, and can be used with only a modicum of knowledge, but the difference in performance between its correct and incorrect use is profound. In fact, the celebrated robustness of reinforced concrete in earthquakes is lethally compromised even if just one of many different faults are introduced during construction – faults which remain hidden until, years or decades later, the next earthquake strikes. Further compounding the problem, concrete is most often used for high-density multi-story residential projects, where the risk of fatalities at any time, both day and night, is thus greatly amplified.

The use of concrete did not mandate that it be used for moment frames rather than shear wall structures, but with a remarkably small number of exceptions, buildings in earthquake and non-earthquake areas alike have been constructed with moment frames rather than shearwalls. In some locales this may be more economical, but that may not be the reason why it is so common, especially when the track record for shearwall buildings in earthquakes is so much better. It is because of a transformation within the field of structural engineering.

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 (Robison, 1989). 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.

Figure 20: Typical Turkish RC building under construction showing the hollow block infill being installed.

Figure 21: Typical hollow clay block infill as used in reinforced concrete residential construction in Turkey.

As we have seen, the acceptance of the concrete moment frame as a standard form of construction, and of frame analysis as the basic engineering approach, fails to recognize the fact that most buildings end up as solid wall structures once the rooms and exterior enclosures are finished. If the enclosure and partition walls are of stiff and strong materials attached rigidly to the frame, as is the case with the infill masonry used in many countries of the world, the structural system can no longer be correctly defined as a frame. The contraflexure methodology presumes that the column/beam flexure is free to take place throughout the full height of the building, and that the location of the points of contraflexure conforms to that defined in the methodology. The restraint on this motion caused by the insertion of the infill turns this widely accepted analysis method into a fiction. The actual forces no longer bear any relationship to those predicted in the analysis. However, nearly all of the engineering that underlies the design of these buildings is based on their being modeled as frames, with the infill masonry included in the calculations only as dead weight. The collapse of so many residential structures of reinforced concrete has shown that the flaw with this approach: the irrefutable fact is that the infill corrupts the frame behavior under lateral forces on which the portal frame analysis method is based.

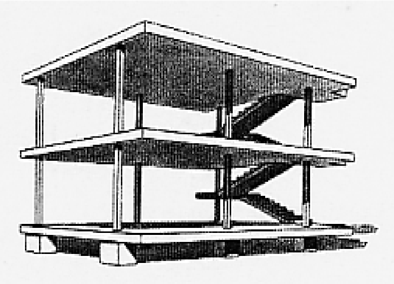

Figure 22: "Domino" frame as ideal structural form by Le Corbusier, 1915. **(Giedion, 1928)**

Figure 23: A massive RC frame in Golcuk, Turkey under construction at time of 1999 earthquake before installation of infill masonry walls. Much greater damage or collapse would have been likely had the infill walls been installed by the time of the earthquake.

The seemingly reasonable explanation for this effect was that by including only its weight, the design would be more conservative than if the infill walls were included as part of the lateral resisting system. Walls then could be moved at will, and the frame (in theory) would be strong enough to carry all of the structural loads as was proposed by Le Corbusier with his publication of his famous "Domino House" in 1915 (Figure 24) which helped to promote the use of this system around the globe. This methodology 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 does not conveniently fit with portal frame analysis. While 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.[2] (More information on the establishment of the European

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[2] More information on the establishment of the European "Modern Movement" and the invention of the "Chicago Frame" and the "skyscraper" on the evolution of the reinforced concrete moment frame can be found in Langenbach, 2006a&b

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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 "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. .

Figure 24: Infill wall RC building in Mexico City damaged in 1985 earthquake. The infill masonry in this structure almost caused the collapse of the building. The damage to the corner column that left the building teetering on the edge of collapse can be seen on the right.

Figure 25: Typical hollow block infill wall partially fallen out of the frame of a building under construction at the time of the İzmit earthquake in Turkey in 1999. The typical infill construction has no mechanical ties other than loosely packed mortar to hold the infill masonry from falling out of the frame. The subdivisions in *himiş* construction help hold the masonry together in the frame because the panels are much smaller.

The masonry infill commonly found in today's modern vulnerable buildings is weak and loosely packed into the frame, yet it is strong enough to interfere with the idealized performance of the frames by throwing stresses onto portions of buildings that are not capable of resisting, mostly because of asymmetrical loading resulting from the progressive loss of the infill masonry (Figure 21 & 27). The contraflexure methodology presumes that the column/beam flexure is free to take place throughout the full height of the building, and that the location of the points of contraflexure conforms to that defined in the methodology. The restraint on this motion caused by the insertion of the infill turns this widely accepted analysis method into a fiction. The actual forces no longer bear any relationship to those predicted in the analysis.

This phenomenon has long been identified as a problem. Research projects in the 1960s and 1970s identified what became known as the "equivalent diagonal strut" model for analyzing the structural effect of the so-called "non-structural" masonry infill walls – a name which draws attention to the profound structural role these walls have, a role that can serve at one and the same time to support an otherwise weak structure, or to precipitate its collapse by tearing apart its beam/column intersections as effectively as if they were a wrecker's ball and chain. The equivalent strut concept was first proposed by Polyakov (1960). Since then, Holmes (1961, 1963), Stafford Smith (1962, 1966, 1968) Stafford Smith and Carter (1969), Mainstone (1971 and 1974), Mainstone and Weeks (1971), and others have proposed methods and relationships to determine equivalent strut properties. Klingner & Bertero (1976) have found the method developed by Mainstone to provide reasonable approximation to observed behavior of infill panels (FEMA 1997: 7-27).

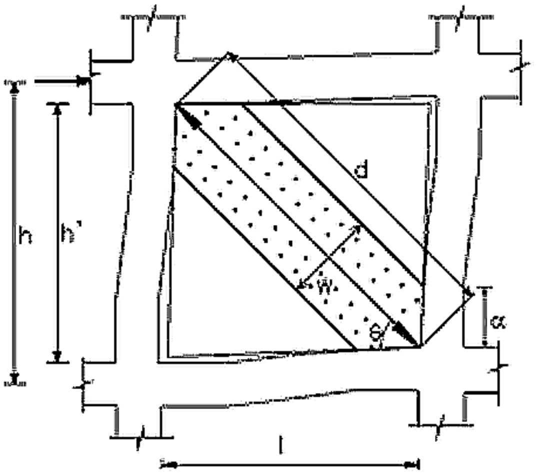

Figure 26: The "Equivalent Diagonal Strut" of a masonry infill wall in an RC frame (Erberik & Elnashai 2003).

This research has continued in various forms over the last forty years but, as remarkable as it seems, the knowledge of the existence of severe problems with this form of construction has had little effect in stemming the massive proliferation of these buildings in earthquake areas worldwide. There have been attempts to find ways to separate the infill from the frame, or find other ways to buffer the frame, but these efforts have foundered on the problems of how to finish the enclosure and ensure the out-of-plane stability of the infill, while leaving a gap between it and the frame.

The research that one sees in university engineering labs around the world most often is focused on the how to strengthen this infill, to enable it to perform more like shear walls, but this aggravates the kind of problems that the equivalent strut model addresses. As many of these experiments have shown, improvements in performance by reinforcing the infill comes at a cost. Because the infill is stiff to begin with, strengthening schemes almost always further increase its stiffness, which in turn increases the forces. In addition, the stronger infill can increase the potentially destructive effects of the diagonal strut on the beam/column intersections of the frame, which can lead to the sudden catastrophic collapse of the building. This, of course, is especially true if the frame suffers from any of the construction flaws so commonly found in reinforced concrete construction.

Figure 27 & 28: Five story building damaged in the 1999 Düzce earthquake in Turkey, being retrofitted with reinforced concrete shearwalls. No.30 shows the existing hollow clay block walls removed and steel being inserted for the construction of a reinforced concrete shearwall. These images illustrate the extent of the work, and disruption needed for earthquake strengthening using shearwalls. The occupants had to move out for the duration of this work as many existing walls were removed.

An alternative to this approach could be to convert the buildings from moment frames to shear wall structures (Figure 29 & 30) 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 the 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 nothing other than demolishing and replacing the buildings has yet been identified as a way to solve this problem, and because the cost of the standard retrofit usually exceeds the value of the buildings.

Lessons from Traditional *hımış* Construction - Armature Crosswalls: Returning to the aftermath of the 1999 Kocaeli earthquake in Golcuk, 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 (Figures 4, 10 & 31). It is their survival that has provided a source for one idea on how to keep reinforced concrete buildings from collapsing – an idea which is based on using this ancient infill-wall masonry technology for modern reinforced concrete construction.

Figure 29: Three story RC building next to a 2½ story *hımış* house near Düzce after the 1999 Düzce earthquake showing the repair of severe damage to the RC building (notice the size of the ground floor columns). The *hımış* structure has lost only stucco on the side. Almost all of the hollow clay block on the RC building has been reconstructed after the earthquake. This shows that even low rise RC buildings sometimes suffered more damage than nearby traditional buildings.

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. The name used for these proposed infill walls is "Armature Crosswalls."[3]

The intention is that these walls would have less initial stiffness and much greater amount of frictional damping than standard infill masonry walls. The reduced initial stiffness has the advantage of reducing the development of the diagonal strut, thus allowing the frame-action on which the portal frame analysis is based to occur. The energy dissipation from the "working" of the materials against each other serves to dampen the excitation of the building by the earthquake. This working of the composite structure during an earthquake can continue for a

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[3] More information on Armature Crosswall technology for reinforced concrete frame buildings can found in Langenbach 2003 & Langenbach *et al* 2006a.

long period before the degradation advances to a destructive level, as demonstrated by the behavior of the *hımış* buildings in the epicentral region of the 1999 earthquakes in Turkey when compared with the surrounding RC buildings.

There are two fundamental questions that 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? In other words, if the infill masonry can damage modern reinforced concrete frames, then why doesn't it crush the much weaker timber frames?

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 (Figure 36). When the mortar is weaker than the masonry units, cracking occurs in the mortar joints, allowing the masonry units to remain intact and stable. Because the bricks are held in place by the armature, the ultimate strength of the wall is determined by the crushing strength of the masonry. 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 (Figure 37).

Figure 30: *Hımış* interior wall in house in Düzce earthquake damage district showing “working” of wall that caused loss of plaster.

Figure 31: Collapse of a brittle interior hollow clay block wall illustrating typical failure pattern for such walls lacking subdivisions.

By comparing the hypothetical strength and deformation curves in Figure 38, it can be seen that the improved performance of the Armature Crosswall is in the extended range between its elastic limit, and the ultimate strength that is established by the crushing of the masonry. It is expected that the computed elastic strength would be slightly lower than that of the standard wall because of the initial slippage between the panels and the armature - which is considered to be a benefit as it allows the overall structure to be more flexible, allowing the frame-action to occur on which the portal frame analysis is based. This kind of initial slippage can be seen in the *hımış* house in figures 39 & 40, where the mud plaster cracks can be seen to be along the frame.

This energy dissipation from the “working” of the materials against each other also serves to dampen the excitation of the building by the earthquake. This working of the composite structure during an earthquake can continue for a long period before the degradation advances to a destructive level, as demonstrated by the behavior of the *hımış* buildings in the epicentral region of the 1999 earthquakes in Turkey when compared with the surrounding RC buildings. While these structures do not have much lateral strength, they possess lateral capacity

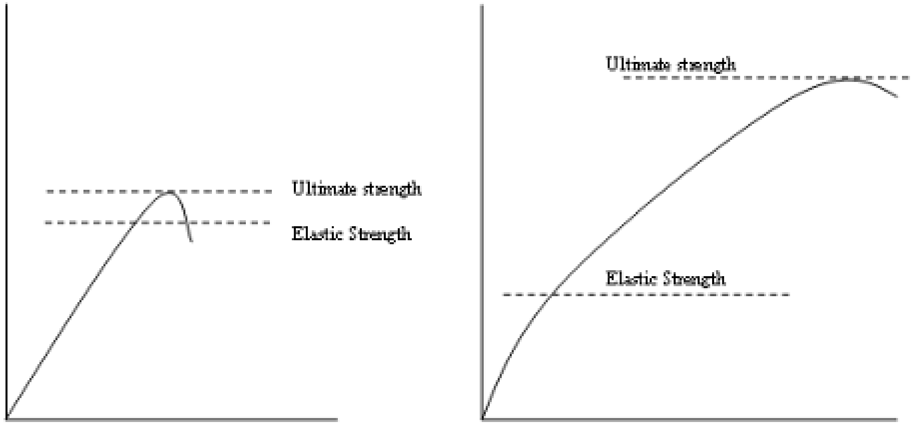

Figure 32: Strength and Deformation Curves for standard infill walls (Left) and Armature Crosswalls (Right).

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.

In other words, 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 1981 published 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."* (Aytun, 1981) While the scale of reinforced concrete buildings may be different, their performance with Armature Crosswalls is predicated on the same phenomenon. The scale issue is reasonably addressed by the fact that the larger residential buildings have more walls in each direction in direct proportion to their size, as the room sizes are very similar. 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.

Figure 33: Exterior of 1955 *hımış* house in Gocuk damage district one month after 1999 earthquake. Do damage is visible.

Figure 34: Same wall as Fig.10 showing earthquake caused cracks in interior mud plaster.

Figure 35: Partially demolished house in Golcuk showing the single brick wythe thickness of typical *hımış* wall. On the LEFT is the exterior and on the RIGHT is the interior face of the same wall.

Figure 36: This house was abandoned and partially demolished at the time of the earthquake. Despite its condition, the earthquake had little affect on it. It was photographed in 2003.

One of the reasons why engineers have failed to recognize the benefits of this inelastic behavior is that for most standard engineering analysis, linear elastic models have been used in the masonry is eliminated from the structural seismic analysis once it reaches its elastic limit at the onset of cracking, which is far short of collapse. 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.

Figure 37: Large 3 story house in *hımış* construction, Safranbolu, Turkey, 2000. Safranbolu is now on the World Heritage List because of its unique collection of intact Turkish vernacular houses.

Figure 38: *Hımış* construction on 3 story house in Safranbolu, Turkey, 2000.

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 - buildings like the ones in figures 43 & 44 in Turkey. 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. Because of the unrecognized lateral resistance provided by archaic structural elements, 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 phenomenon has been and will continue to be a serious problem for the preservation of historic resources that have suffered damage in earthquakes.

Conclusion: Modern construction materials and methods have brought with them extraordinary opportunities for new spaces, forms, and ways of building, and for lower-cost housing of 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. 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 not sufficiently well enough understood or respected to be carried out to an acceptable level of 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.

Recent catastrophes, with their sizeable death tolls, show there is much to learn about how to build in a safe and durable manner. Just as many have begun to rediscover the value of ancient Indian ayurvedic medicine or Chinese acupuncture, earthquakes can serve to reveal the value of forgotten indigenous knowledge as well as shortcomings in the modern methods. Well engineered and constructed modern buildings have fared well in earthquakes, but the effort to improve public policy challenges us to meet the needs of a broader range of rural and urban populations lacking access to well-trained engineers and builders. It is in this realm that the construction methods developed before the introduction of modern materials and modern computational tools have much to teach us, both before and after the inevitable earthquakes. 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. This was true despite the extreme and unpredictable forces experienced in earthquakes - forces that have continued to confound modern-day efforts protect the plethora of buildings that make up the contemporary city.

Figure 39 & 40: After witnessing the destruction of RC buildings in Duzce while his father's *hımış* house survived undamaged, this resident of Düzce decided to stop construction of a new RC house and change it to *hımış* construction.

FOOTNOTES

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[1] The reinforced concrete building visible on the left remained standing consistent with the general observation that those reinforced concrete buildings that were under construction at the time of the earthquake, as this one was, were less likely to collapse than buildings completed with all of the infill masonry in place.

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