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SURVIVORS AMONGST THE RUBBLE:
Traditional Timber-laced Masonry Buildings that Survived the Great 1999 Earthquakes in Turkey and the 2001 Earthquake in India, While Modern Buildings Fell

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Summary

The Kocaeli and the Bhuj Earthquakes in Turkey and India were devastating disasters, with vast destruction of buildings and countless deaths and injuries in both urban and rural areas. One particular problem unique to urban areas was dramatically illustrated in the recent Bhuj Earthquake when, in the town of Anjar, several hundred school children participating in a Republic Day parade were killed while standing *outside* the buildings. This tragedy occurred because the walls of the surrounding buildings collapsed outward into the narrow street where they were standing, from which there was no escape.

Figure 1: View of Anjar City Center after the Bhuj Earthquake of January 26, 2001.

The Bhuj Earthquake devastated older masonry buildings and newer reinforced concrete buildings alike. In Bachau, the entire city was effectively wiped out, with nothing left undamaged and little even left standing. However, in the nearby city of Ahmedabad, and also in 1999 earthquake damage districts of Turkey, the profiles were very different. In Ahmedabad, where the older masonry houses were constructed with timbers in the walls, all survived the Bhuj Earthquake with little damage and no collapses, while a significant number of new apartment blocks collapsed with a high death toll. In the Marmara Region of Turkey after the devastating 1999 earthquakes, hidden among the many heavily damaged or collapsed modern buildings were many older timber and masonry buildings that, with few exceptions, survived with very little damage.

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Did historical earthquake threats influence the invention and evolution of the timber-laced construction types, and if so, why is there such a wide discrepancy between the construction and performance of the buildings around Bhuj and those in the Walled City area of Ahmedabad? In addition, why did these seemingly weak and vulnerable older buildings prove to be safer than many of their more recent reinforced concrete neighbors? What the recent earthquakes in Turkey and India have shown is that the development of modern strong materials and the greater sophistication in engineering design have not always resulted in safer structures, as it was the *modern* buildings in both India and in Turkey that often proved to be more vulnerable than traditional forms of construction practiced for thousands of years.

Timber-laced construction can also be found in both Spain and Portugal. In Madrid, many of the buildings in the historic central area around the Plaza Major which appear today as solid masonry buildings underneath a layer of stucco are, in fact, composed of walls of timber with brick or rubble stone masonry infill (Figure 2). Many of the buildings in Lisbon that were rebuilt after the great Lisbon earthquake of 1755 were constructed with heavy timber frames imbedded in the masonry, in this case a deliberate response to the earthquake risk. In fact, the Lisbon example may have been based on observations of earlier timber-laced buildings that may have done comparatively well in the earthquake, thus encouraging its more elaborate use for earthquake hazard mitigation during the reconstruction.

Figure 2 a&b: Timber and masonry infill-frame construction near the Plaza Major in Madrid – hidden in the facades, but revealed by demolition behind.

Historical Background

Timber-laced masonry can be divided into two sub-categories: timber-frame with infill masonry (infill-frame[1]), and bearing wall masonry with horizontal timber-lacing (laced bearing wall). These two types were often used in the same building, with the laced bearing wall system used for the ground floor and the infill-frame for the upper floors. Variations on these types of construction can be found across the broad, seismically active belt that extends around the globe from Africa and Europe across Asia to Central America. Rather than earthquakes per se, the circumstances that led to the survival of these buildings are likely to be the successful byproduct of technologies developed as much for their economy as for their strength. However, the recent earthquakes in Turkey and India provide an opportunity to compare the performance of the two types of timber-laced masonry construction with that of masonry buildings without timber-lacing, as well as with the performance of modern buildings constructed of reinforced concrete. [2]

Infill-Frame Construction

Because it is rare for the wooden armature of these sorts of buildings to survive as archeological ruins, the chance of finding ancient examples of the infill-frame construction type is low, but the unique burial under volcanic mudflows, and the modern-day archeological uncovering of the Roman town of Herculaneum in Italy has provided the unique opportunity to peer back through 2000 years and find early examples of this type of construction. (Figure 3)[3]

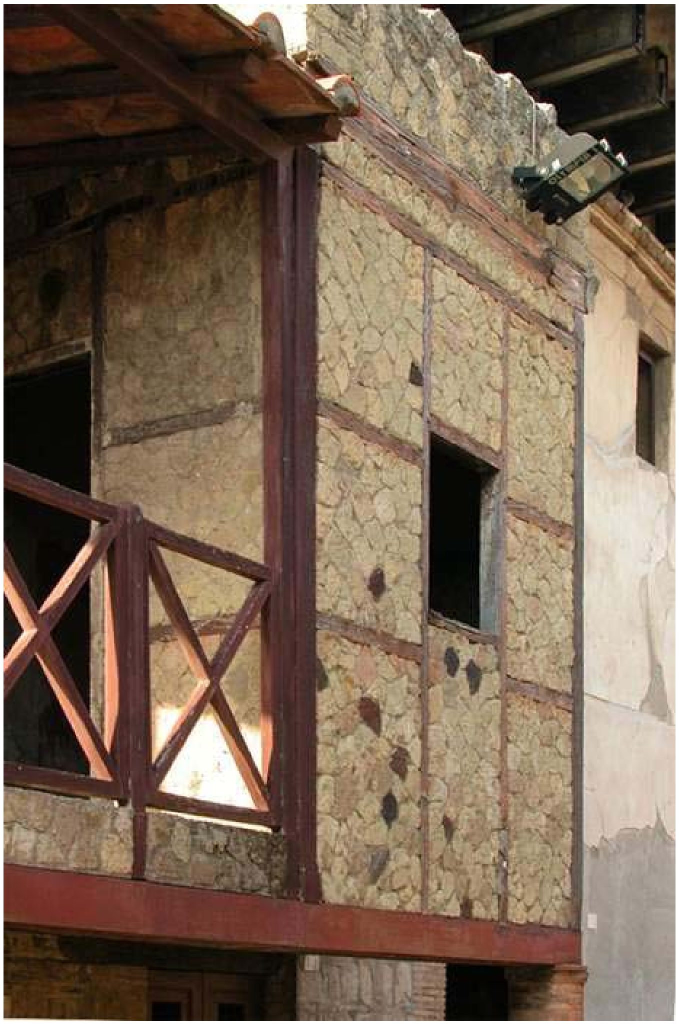

Figure 3: Pre-79AD Infill-frame construction found and restored at Herculaneum.

Because of its economy and ease of construction, it is probably safe to assume that infill-frame construction became widespread throughout Europe from an early period. Timber-with-brick-infill vernacular construction is documented to have first appeared in Turkey as early as the eighth century (Gülhan and Güney, 2000). One hypothesis is that the building tradition traveled from Europe into Asia as a result of the reach and influence of the Ottoman Empire, which at one time extended almost from Vienna to the Caspian Sea.

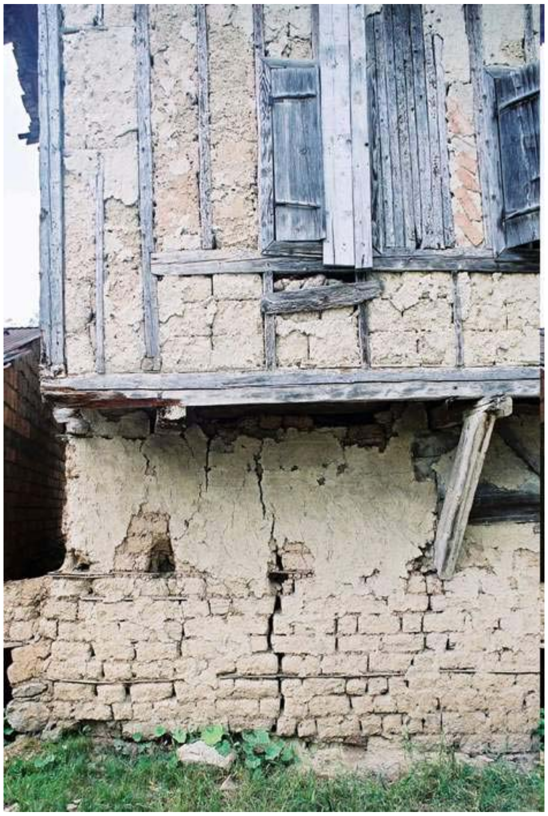

Figure 4: View of Infill-frame construction in the historic Ottoman town of Safranbolu, Turkey

Today, variations on this type can be found in almost every part of Europe, including England and Spain, as well as Asia. It also can be found in Central America, and can even be found in the United States in New Orleans, a city of French origins, in some other historic French settlements on the Mississippi, and in parts of Pennsylvania, where it has been derived from the German *fachwork*.

Laced Bearing Wall Construction

Laced Bearing Wall construction may have had its origins in ancient times as well, although it is not so identified in Vitruvius' work. An even earlier example has been identified at the Minoan "New Palace" of Knossos, dated 1450BC (Kienzle, 2002). It may also be loosely related to the utilization of horizontal bands of wide and flat Roman brick that was sometimes laid at intervals into walls composed of more random mortared masonry. At Pompeii, a number of the piers between storefronts were reconstructed with brick bands, and this construction may have been part of repairs of damage from an earthquake that occurred 17 years prior to the volcanic eruption that buried the city. This same type of construction can be found in Istanbul most notably in the medieval city walls, where the belts of red brick are an integral part of the architecture – so much so that when modern restorers reconstructed a section of the walls, they applied the brick band as a thin layer on the surface, rather than as a structural layer extending through the masonry. Interestingly, it was only this newly constructed section that collapsed when the tremors which radiated out from the distant August 17, 1999 Marmara earthquake reached Istanbul. The far more deteriorated portions of the wall where the brick bands remained in their original form remained standing.

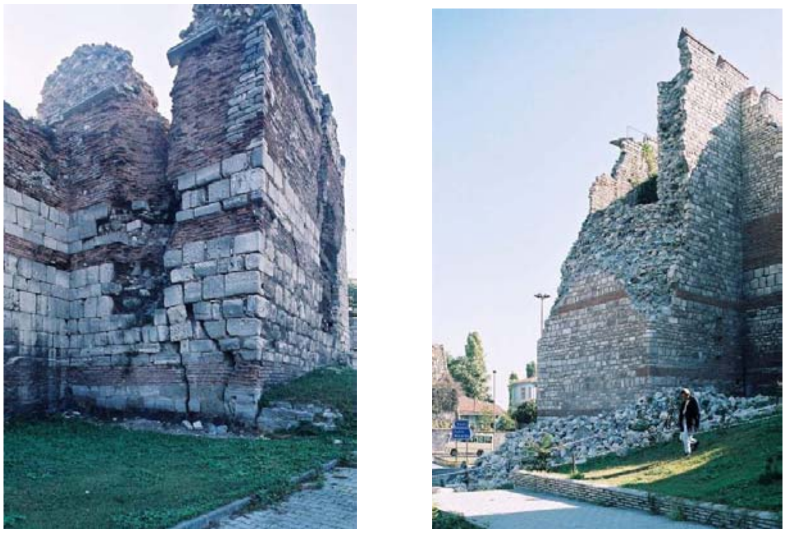

Figure 5 & 6: Istanbul City walls showing brick banding in surviving historic section and collapsed reconstructed section with fake banding.

Some of the most elaborate examples of laced bearing wall construction can be found in Srinagar, Kashmir, where this type of construction, referred to as *Taq,* is the predominant historical vernacular type. Here the type evolved to allow building of structures onto soft waterlogged banks of the alpine lakebed in the Vale of Kashmir, where the heavy masonry structures were subjected to differential settlement. Here the heavy timber beams are laid in only horizontally, with the masonry carrying all of the vertical loads. The timber bands, which resemble ladders laid into the walls, run both above and below the window frames and at each floor level, where the joists extend through the wall and are secured to the wall by the timbers laid below and above them, which are themselves surmounted by the weight of the overburden of masonry of the floor above or the parapet under the roof.[4]

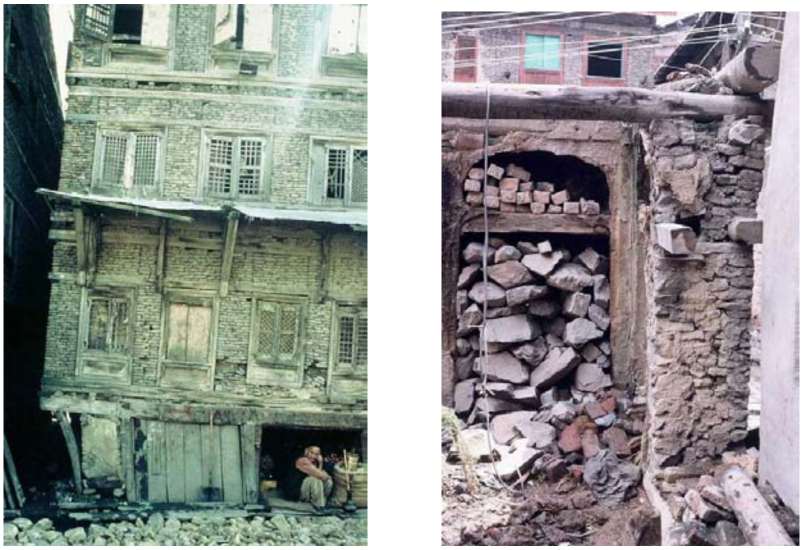

Figure 7 & 8: *Taq* construction in Srinagar, Kashmir and demolished section of wall showing timber lacing in wall section.

The Ottoman Method of Construction in Turkey

In Turkey, and also in Greece, houses were often designed with the laced bearing wall construction on the ground floor level, and the infill-frame used for the upper stories. The thicker, often windowless, bearing walls served to enclose the storage or barn area of the structures, with the lighter more open infill walls above enclosing the living quarters. The Turkish Ottoman-style house, with its tiled roof and overhanging timber-and-brick bays above a heavy stone first floor wall, has become an icon known worldwide. Where they survive, the overhanging upper stories, or jetties, contribute to the visual vitality and delight of historic Turkish towns. The jetties strengthen the buildings because the joists that cantilever over the walls below hold those lower-story walls firmly in place with the help of the weight of the infill masonry overhanging upper story. This compressive force gives the heavy walls below added strength against lateral forces.

Figure 9: Traditional Ottoman style Turkish architecture in Safranbolu, Turkey.

The upper story is almost always constructed with the infill-frame type of construction, with the frame infilled with a single-withe of fired brick or stone masonry. This type of construction is referred to in Turkish as "*hımış"* (pronounced "humush"). This construction utilizes a weak mortar of mud or lime holding a single wythe of masonry into a timber framework of studs rarely more than two feet (60cm) apart. The studs are themselves tied at mid-story height by other timbers. Because the masonry is only one withe in thickness, the walls are light enough to be supported on the cantilevered timbers.

For those houses where the *hımış* style rests on the heavy load bearing masonry base, the multi-wythe masonry bearing walls of the first story, are often laced with horizontal timbers, (in Turkish, the timbers are "*hatıl* (s) *hatıllar* (pl)*"*). In contrast to those used in Kashmir, these are often very thin timber boards laid into the wall at vertical intervals of about 3 feet (1m). They are placed so that they overlap at the corners. They thus serve to bind the stone layers together without interrupting the continuity of the masonry construction. In those regions most affected by the 1999 earthquakes, however, the bearing wall type was rare. There, the houses were of *hımış* construction from the ground up, thus the discussions of earthquake performance of the timber-laced construction as witnessed following the recent earthquakes in Turkey and in India will be focused primarily on this type.

Figure 10: Laced bearing wall in Safranbolu, Turkey

The Marmara and Düzce Earthquakes

The Marmara earthquake (also called the Kocaeli earthquake) of August 17, 1999 killed approximately thirty thousand people.[5] The epicenter was just 200 kilometers east of Istanbul. In some areas of Gölcük and Adapazari, the earthquake destroyed more than a third of all housing units, almost all of them in reinforced concrete buildings.[6] There were clusters of *hımış* buildings in the heart of these districts. These houses, mostly dating from the early part of the twentieth century, pre-dated the ruined reinforced-concrete apartment blocks nearby. Many of the older *hımış* houses remained intact, but a few were heavily damaged. This finding was confirmed by two Turkish professors who conducted a detailed statistical study in several areas of the damage district who found a wide difference in the percentage of modern reinforced concrete buildings that collapsed, compared to those of traditional construction (Gülhan and Güney 2000).[7]

In one area surveyed in Adapazzari a single *hımış* house collapsed, killing an occupant – a rare occurrence of a death caused by the collapse of *hımış* construction. Decayed timbers could be seen in the ruins. It was the partially damaged traditional buildings here and in Gölcük provided evidence of how this type of construction responded to earthquake forces. Once each building was inspected, and the damaged area in each building identified, a pattern began to emerge. Of those inspected where structural damage was found, most of the damage was concentrated at areas around rotted timbers. Interviews with residents often revealed that the buildings with the most timber decay had been unoccupied for years. It appeared that decayed timber significantly degraded a buildings' performance in earthquakes. In occupied houses, the most severe damage resulted mainly from alterations and modernization work that had corrupted the integrity of the original frames and walls.

Figure 11: *Hımış* house in Gölcük after earthquake constructed in 1955.
There was only slight damage to the interior of this house.

Inspecting the interiors of some of the houses provided a more complete understanding of the behavior of *hımış* as a structural system. It was evident that the infill masonry walls responded to the stress of the earthquake by "working" along the joints between the infilling and the timber frame; that is, the straining and sliding of the masonry and timbers dissipated a significant amount of the energy of the earthquake. The only visible manifestation of this internal movement was the presence of cracks in the interior plaster along the walls and at the corners of the rooms, revealing the pattern of the timbers imbedded in the masonry underneath. This level of damage was evident in every house. On the exterior, unless the house was stuccoed, damage was impossible to see. The bricks themselves were only infrequently displaced sufficiently for a crack to be visible. The movement was primarily along the interface between the timbers and the brick panels rather than forming a crack within the panels themselves.

Figure 12: *Hımış* interior wall in Düzce after earthquake.

The typical *hımış* construction does not have mechanical ties between the timber and masonry to hold the infill masonry in place. As a result, in some cases, small sections of the infill were shaken out from between the studs near the top of the upper-story walls. Because of the existence of the timber studs, which subdivided the infill walls into small panels, the loss of portions or all of several panels did not appear to lead progressively to the destruction of the rest of the wall. Many walls were missing some of their infill, but evidence of 'X' shear cracks, so common in the infill in the modern reinforced concrete buildings, was non-existent in the *hımış* structures. The closely spaced studs reduced the likelihood of the propagation of 'X' cracks within any single panel. In addition, the subdivision of each structural bay with a tight network of vertical, horizontal, and diagonal timbers, rather than vertical studs alone, appeared to have been successful in reducing the possibility of the masonry falling out of the frames.

An important additional factor in the performance of the walls was the use of weak, rather than strong mortar together with bricks that are stronger than the mortar. The mud or weak lime mortar tended to encourage sliding along the masonry bedding planes instead of cracking through the masonry units when the masonry panels deformed, reducing the contrast between rigid masonry panels and the flexible surrounding frames.

Strength versus Capacity

This pattern of damage helped explain why these buildings were capable of surviving a major earthquake that had felled modern reinforced-concrete buildings. The basic principle in this weak, flexible-frame-with-masonry-infill construction is that there are no strong and stiff elements to attract the full lateral force of the earthquake. The buildings thus survive the earthquake by not fully engaging with it. This "working" during an earthquake can continue for a long period before the degradation advances to a destructive level.

While these structures do not have much lateral *strength*, what they possess is lateral *capacity*. These buildings respond to seismic forces by swaying with them, rather than by attempting to resist them with rigid materials and connections. This is not an elastic response, but a plastic one. The swaying and deformation of these structures is different from that of a tree, the suppleness of which allows it to bend elastically. When these structures lean in an earthquake, they do so with incremental low-level cracking which is distributed throughout the wall by the interaction of the timber structural elements with its confined masonry infill.

This controlled damage is what the "working" of the structure means. It is how a building made with a disparate assembly of brittle materials is able to survive seismic forces that are far larger than could be resisted by it in a fully elastic undamaged state. In other words, although the masonry and mortar is brittle, the *system* — rather than the materials that make up that system — behaves as if it were "ductile."[8]

In addition, by dissipating energy, the "working" also affects the natural frequency or "period" of the vibration of the structure. Resonance with earthquake vibrations is a principal factor in the cause of earthquake damage to buildings in general. The controlled sliding and cracking of the infill masonry reduces the infill-frame structure's ability to resonate with the earthquake by providing damping, just as a shock absorber does for a car. In contrast to this, there are many examples of modern structures that were strong enough to resonate elastically at ever increasing amplitude until the catastrophic failure of a critical structural member caused their sudden collapse. Simply stated, all of this is the difference between *strength* and *capacity*.

The Orta Earthquake of June 6, 2000

Ironically, it was a much smaller earthquake that followed the 1999 earthquakes in Turkey that has provided one of the best sources of data from which to evaluate the capacity for earthquake resistance of the construction, compared to that of the standard low-quality concrete construction. This smaller earthquake occurred six months later, in June, 2000, and was centered on the village of Orta, north of Ankara. It measured only 5.9[9] on the Richter Scale and thus was small enough to escape international attention.

Figure 13: Interior of *hımış* house in Orta after earthquake showing damage to mud and lime plaster over infill walls.

In this earthquake, many *hımış* houses did suffer widespread cracking and shedding of plaster and stucco, and a few had damage to the infill masonry. This level of damage was hard to explain when compared to that found in the infill-frame houses subjected to the full brunt of the Marmara earthquake, where the shaking was stronger and continued for a longer period. The *hımış* houses in Gölcük and Adapazari had about the same level of damage as the Orta houses. This stands in sharp contrast to the performance of the reinforced concrete buildings. While in Orta the reinforced concrete buildings were only lightly damaged, in the Marmara and Düzce earthquake area vast numbers of them suffered heavy damage or collapse.

What can explain this discrepancy between the performance of the infill-frame buildings and that of reinforced concrete in the two earthquakes? To look for an explanation for this phenomenon, it is valuable to compare the Marmara and the Orta earthquakes with each other. The modern reinforced-concrete buildings went from performing well in the moderate seismic event in Orta to being lethally dangerous in the larger event, while the traditional houses did not. Thus the minor cracks seen in the reinforced concrete buildings in Orta may in fact be the onset of damage that, in a larger event, might have led rapidly to the collapse of the buildings.

This observation is underscored by the fact that many of those buildings in Düzce that were *damaged* in the August 17, 1999 Marmara earthquake, *collapsed* in the November 11 Düzce earthquake. This observation is significant in that it indicates that, only at one's peril, could one draw conclusions about a building's performance from observations of a single earthquake taken in isolation – particularly a moderate one like that in Orta in a seismic zone capable of producing a large one.

By comparison with the ordinary and often poorly constructed modern Turkish reinforced-concrete housing blocks, the traditional infill-frame structures demonstrated a greater ability to sustain a long duration of severe shaking without progressing much beyond the level of damage sustained in the more moderate Orta earthquake. Thus, the fact that the traditional buildings suffered a level of damage that was similar in both the larger and the smaller earthquakes serves to illustrate their ability to survive massive earthquake shaking, despite the fact that damage begins to occur at lower levels of shaking than it does in reinforced concrete structures.

Lessons from the Past for Modern Reinforced Concrete Construction

The shift from traditional low strength materials to reinforced concrete is a radical transformation of the entire building construction process that has affected many regions of the world. Reinforced concrete is an industrialized high-tech material that is safe and strong *only* when it is used in a way that shows knowledge and respect for its properties. And indeed, therein lies the problem. In many countries where this method of construction now predominates, it is subjected to a low-tech building process not unlike that used for the vernacular masonry buildings it has now displaced. When misused, it is dangerous – as the recent earthquakes have so tragically shown.

The most common form of reinforced concrete structural system now used in most places is the moment frame with masonry infill walls. In contrast to shearwall buildings, the moment frame relies on the strength of the beam/column intersections to resist deformation and collapse in earthquakes. The most significant problem with this form of construction is that a failure to provide for sufficient strength or ductility in the frame joints can lead rapidly to collapse in an earthquake.

The infill walls in modern reinforced concrete construction generally have strong mortar binding weak masonry units, and these masonry walls fill each structural bay without intervening studs. In Turkey, the most common infill for the interior partitions and exterior walls is a lightweight hollow clay block that has barely more strength than a dinner plate. In India, commonly it is a low temperature fired brick that performs better than the Turkish material, but none-the-less it can crumble easily.

Rarely is the infill considered in the engineering design process as part of the lateral resisting system, and it is often ignored in calculations. In spite of this, the masonry infill does play a significant role that sometimes can help to save a building that has weakened joints. More often, however, it can contribute to the collapse of a building because its rapid degradation in specific areas can transfer concentrated loads onto localized parts of the frame, which are then overwhelmed. As can be seen in Figure 14, these infill walls can readily collapse completely when an earthquake distorts the building's frame. Sometimes, to avoid damage to the surrounding reinforced concrete frame from the "diagonal strut" effect, where the stiff infill causes a corner column to break, leading to collapse, the infill material is sometimes deliberately separated from the frame.

Figure 14: Collapsed interior infill wall in reinforced concrete building in Gölcük

While the infill in modern construction has often performed badly, the infill in traditional construction has performed well. What accounts for this apparent discrepancy? Two things may account for this: (1) the subdivision of the infill masonry into smaller panels with horizontal and vertical studs within a single bay of the building's structural frame, and (2) the use of weak mortar with strong masonry units in the traditional infill compared with what are often weak masonry units and cement-based strong mortar used in the modern infill walls.

The principal lesson embodied in comparing the performance of the timber-laced vernacular construction with that of the modern buildings that collapsed in the earthquakes is thus: strength and rigidity are less effective in than flexibility, ductile behavior, and cumulative nondestructive damping. To improve the performance of reinforced concrete infill-wall construction, the lesson from the traditional construction is to make the infill walls act not as shear walls, which they cannot be, but as "cross walls," which they are eminently capable of being. (A "shear wall" is designed to be strong enough to carry to the foundation all of the imparted lateral loads of the building. A "cross wall," which may be only a floor-to-floor partition, is only designed to take loads and distribute them to other horizontal or vertical elements in the overall structural system). They can also serve to dissipate large amounts of energy by cracking in a controlled manner. With the introduction of studs like those found in traditional construction, collapse from shear failure of the entire panel can be avoided because the infill can deflect nondestructively and be restrained from falling out of the frame.

Conclusion

Further research is required to determine whether earthquakes in the past have shaped the form of traditional construction methods. . People surely must have responded to known earthquake risks in the past, but how they did so is very difficult to ascertain. It is logical to believe that earthquakes must have been a factor in the evolution of building design and construction in affected regions. However, at the same time, they may not have been a defining one. The economy and availability of building materials and craftsmanship is likely to have had a stronger influence than the infrequent risk from earthquakes. The infill-frame form of timber-laced masonry was economical in its use of materials and labor. In the case of the timber-laced bearing walls, the use of the timbers was a cost-effective way of giving a rubble stone wall a great deal of added stability when the dressing of the stones was impractical.

Regardless of their historical sources, recent earthquakes have shown that, intentional or not, timber-laced buildings have demonstrated a level of life-safety in earthquakes that was conspicuously absent from many of the more recent reinforced concrete residential buildings. It is not enough to simply explain collapses of modern buildings and their consequential carnage as the result of inadequate design and/or poor construction. As long as reinforced concrete is used ubiquitously in many areas as the default material for ordinary construction, then a large number of the buildings constructed with it should be assumed to be less than well built.

Moreover, earthquake safety is thus not achieved by pointing fingers at builders after earthquakes; it can only be achieved by recognizing that a certain amount of bad construction is inevitable, and looking for ways to mitigate its most dangerous consequences by changing construction practice so that the safety does not depend solely on the quality of the concrete frames. That is where some of the characteristics of traditional construction can provide lessons for contemporary building practice. They have proved that they can survive earthquakes of great magnitude based on structural behavior that is dependent neither on formal engineering nor on sophisticated knowledge of construction through flexibility, energy dissipation, and redundancy.

As we look for solutions to the problems that have been so profoundly thrust on so many by the tragic earthquakes of the last several years, it is important to be open to receiving what the wisdom of the ages may have infused into traditional structures. It is important to realize that the cultural value of indigenous architecture lies in their structural characteristics as well as in their visual image. There is more to traditional buildings than their architectural veneer. Too often what passes for conservation is the reconstruction of buildings in reinforced concrete, with false timbers simply attached to the surface. When it is understood that there are many historical systems from which we can learn valuable lessons for construction today, then these historical structures take on a meaning that brings them to life in ways that transcend their contribution to style. People have coped with the larger than life forces of earthquakes and other natural disasters long before the invention of strong construction methods in reinforced concrete and steel – and as seen from some of these examples here – they sometimes have been remarkably effective.

Figure 15: Collapsed Reinforced concrete building in Gölcük.

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Notes

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[1] In England, this is referred to as "half-timbered," but to avoid confusion with the specific English version still visible in many surviving Elizabethan buildings, the less regionally specific term of "infill-frame" will be used here. The Elizabethan half-timbered buildings are usually characterized by the use of heavy timbers for the frame, rather than the lighter, more frequently spaced, timbers seen in the Roman, Ottoman and other Southern Europe and Middle Eastern versions.

[2] To avoid confusion, the reference to "modern reinforced concrete" construction here and throughout this paper is focused primarily on the common, largely unregulated, concrete construction of housing and office blocks that fill the earthquake damaged cities and towns. In reporting on the poor performance of these structures, the author does not mean to imply that all structures of reinforced concrete construction performed poorly. As the engineering surveys have established, there were many reinforced concrete buildings that had

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been engineered and constructed to a high standard, and for the most part, these buildings did perform well in both India and Turkey.

[3] Vitruvius, in his description of different wall types refers to "cracticii" as a particular type of light-weight wall construction. Different translators have interpreted the term "cracticii" differently. While Ingrid Roland (1999) translated it to "half-timbered" based on the Herculaneum examples, in 1914, Morris Hicky Morgan translated it to "wattle and daub." Ingrid Roland's translation is based on the findings by archaeologist Amadeo Maiuri, who excavated examples of timber and masonry infill walls in Herculaneum. He had identified this find as the "craticii" described by Vitruvius. However, Vitruvius' description for plastering of craticii walls tends to reinforce a conclusion that what he is discussing is more likely a wattle and daub-like form of construction. Vitruvius was critical of the craticii as a construction practice because of the risk of fire and its tendency to swell and shrink, neither of which is a major problem with the type of construction unearthed at Herculaneum, so the Herculaneum examples may only be distantly related to what Vitruvius was describing. What Vitruvius' passages do illustrate, and however, is that the Romans were quite experimental in developing lightweight forms of construction out of less permanent materials than stone and natural cement concrete, but, except for the example at Herculaneum, examples of these have not survived the intervening 2000 years.

[4] For a more detailed description of the architecture and construction found in Srinagar, Kashmir, see Randolph Langenbach, "Bricks Mortar and Earthquakes," APT Bulletin 31: 3-4 (1989).

[5] Kandilli Earthquake Research Institute (2000). Web Site, Boğaziçi Üniversitesi, Istanbul, Turkey.

[6] *IBID*

[7] Gülhan and Güney documented that in one district in the hills above Gölcük of the 814 reinforced-concrete, four-to-seven-story structures, 60 collapsed or were heavily damaged, while only 4 of the 789 two-to-three-story traditional structures collapsed or were heavily damaged. The reinforced-concrete buildings accounted for 287 deaths against only 3 in the traditional structures. In the heart of the damage district in Adapazari, where the soil was poorer, this research shows that of the 930 reinforced concrete structures, 257 collapsed or were heavily damaged and 558 were moderately damaged, while none of the 400 traditional structures collapsed or were heavily damaged and 95 were moderately damaged.

[8] *Ductility* refers to a material's capacity for being bent beyond its elastic range without breaking. In the case of this traditional construction, where most of its lateral resistance is provided by the brittle masonry, the term applies to the behavior of the system, not the materials which make up that system. In the 1981 published paper "*Earthen Buildings in Seismic Areas of Turkey*," Alkut Aytun credits the bond beams in Turkey with *"incorporating ductility to the adobe walls, substantially increasing their earthquake resistant qualities."* From Proceedings of the International Workshop on Earthen Buildings, Vol. 2 (Albuquerque, 1981), p. 352.1.

[9] As reported in the Turkish daily papers the day after the earthquake. The USGS web site reported 6.1.