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From "opus craticium" to the "Chicago frame"
Earthquake resistant traditional construction

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ABSTRACT: Earthquake-resistant traditional construction? One may consider the phrase to be an oxymoron. There are many examples of traditional construction that have fared well in large earthquakes. This is certainly important for historic preservation efforts, as the analysis and documentation of this phenomenon can bolster attempts to preserve the fabric of historical structures. There is, however, an even more powerful lesson to be learned from these historic structures – a lesson on how to improve *new* construction. This is crucial, as in recent earthquakes in diverse parts of the globe it is the modern buildings that often have proved to be most fatal. This paper will explore examples of timber-laced non-engineered masonry construction that have proven to be comparatively resistant to earthquake damage.

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Figure 1: (a) Safranbolu, Turkey: traditional houses.
(b) Safranbolu, showing upper story jetties of himis construction.

1. INTRODUCTION

Unlike other natural threats, earthquakes come without any warning. Getting out of harms way must take place during the event, and that act may even place the individual at greater risk than standing in place or lying down. This "Hobson's Choice" places a greater burden on designers and stewards of buildings than for other natural hazards. Further complicating matters is the fact that earthquakes are expected to cause structural damage even in code-conforming modern structures. Few non-engineers realize that current national and local building codes in all countries assume that, unlike designing for wind forces, an earthquake of a predictable magnitude will cause structural damage in code-conforming buildings.

What about buildings constructed prior to the existence of any earthquake codes? Is it plausible to assume that they must be hazardous? This is not necessarily so. In earthquake after earthquake, there have been many examples of traditional construction that have survived in good enough condition to have met the intent of current codes. These have often outperformed nearby new construction.

2. EXAMPLES

2.1 Kashmir, India

Arriving in the City of Srinagar in 1981 was like being catapulted back in time – not a century, but half a millennium. When seen in 1981, Srinagar had, for the most part, escaped the rampant modernization that had erased similarly unprotected historic city centers in other parts of the world. Most of the traditional buildings in Srinagar can be divided into two basic systems of construction. The first system, sometimes referred to as *taq*, consists of load-bearing masonry piers and infill walls, with wood "runners" at each floor level used to tie the walls together with the floors, all of which is locked together by the weight of the masonry overburden (Figure 2a). The second system, known as *dhajji-dewari*, consists of a braced timber frame with masonry infill. With its thin, one-wythe thick walls, it provides an efficient and economical use of materials, which helps to account for its use even for new construction until about two decades ago (Figure 2b). (Langenbach, 1989)

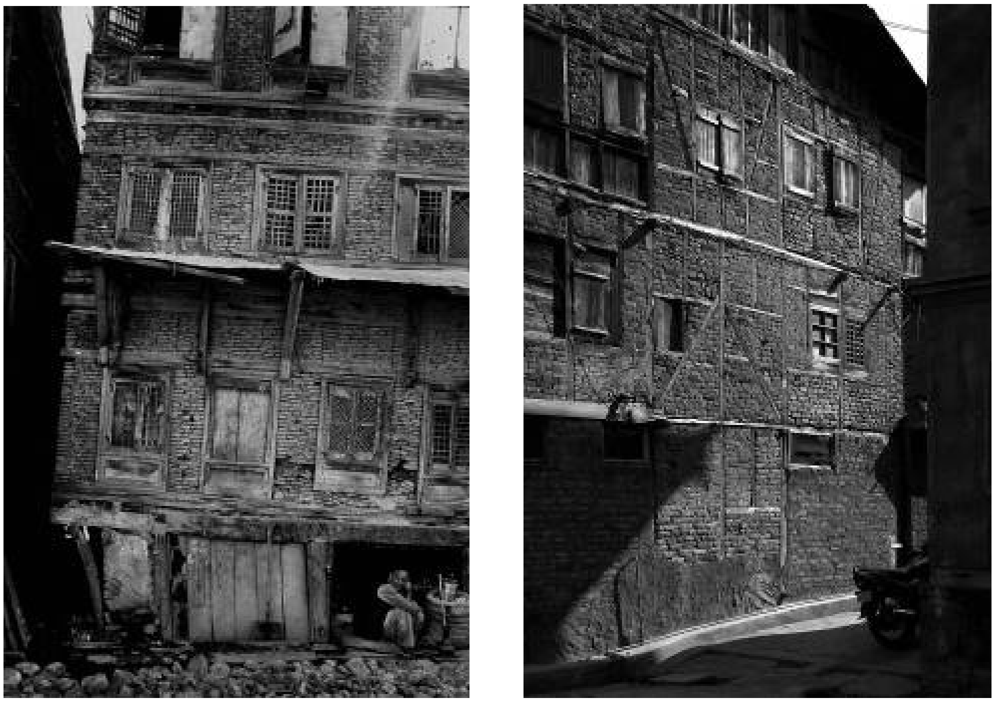

Figure 2: (a) Old canal side warehouse of *Taq* construction, Srinagar, Kashmir, 1981.
(b) *Dhajji Dewari* construction, Srinagar, 2005.

These buildings were observed by Arthur Neve, a British visitor to Kashmir, when he witnessed the 1885 Kashmir earthquake, who reported: *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…the whole house, even if three or four stories high, sways together, whereas more heavy rigid buildings would split and fall.* (Langenbach, 1989)

More recently, two Indian engineers, N.Gosain and A.S.Arya ascribed the level of damage from a 1967 earthquake to the different types of traditional and modern construction in Kashmir: "*Perhaps the greatest advantage gained from [timber] runners is that they impart ductility to an* *otherwise very brittle structure. …This was substantiated by the observation that dhajji-dewaris in which a larger volume of timber was used were comparatively safer*." Gosain and Arya note that during the 1967 Kashmir earthquake, buildings of three to five stories survived relatively undamaged. The research of Prof. Anand Arya shows that one of the most important reasons for this is the damping from the friction induced in the masonry of the *taq* and *dhajji-dewari* walls. Internal damping *"may be in the order of twenty percent, compared to four percent in uncracked modern masonry (brick with Portland cement mortar) and six to seven percent after the [modern] masonry has cracked."* His explanation for this is that *"there are many more planes of cracking in the dhajji-dewari compared to the modem masonry."(*Langenbach, 1989)

On the 8th of October, 2005, an earthquake devastated the mountainous area of the Pakistan section of Kashmir, killing over 80,000 and rendering most of the remaining people homeless. On the Indian side of the border the damage was much less, but another difference was noticeable – the traditional construction as described above was not to be found on the Pakistan side of the border, where the massive death toll occurred. On the Indian side, the performance of the timber-laced traditional construction confirmed earlier findings. Professors Durgesh Rai and C.V.R. Murty reported: *"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 3: House in Baramula, Kashmir damaged in 2005 earthquake showing how unreinforced masonry collapsed, leaving the top story of *Dhajji Dewari* in place.

In general, as the two Kashmiri examples show, timber-laced masonry can be divided into two sub-categories: timber-frame with infill masonry (infill-frame), and horizontal timber-laced bearing wall masonry (laced bearing wall). In some locales these two types were 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 seismically active belt that extends around the globe from Africa and Europe across Asia to Central America.

2.2 Infill-frame construction:

In addition to Kashmir's *dhajji dewari*, regional manifestations are called "*colombage*" in France, "*fachwerk*" in Germany, "*himis*" in Turkey, and "*half-timber*" in Britain. Variations that used earthen plaster and sticks or reeds (wattle and daub) include Turkish *Bagdadi* 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. A type that is best described as halfway between the masonry version and the wattle and daub version can also be found in Central America, where it is known as *bahareque* or *taquezal*. 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*.

When 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 entire two story half-timber house which he identified as one of the masonry construction typologies described by Vitruvius as "*Craticii*" or "*Opus Craticium*" (Figure 4a). This example in Herculaneum may provide us with the only surviving example of the form of construction that had been 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 with space for rooms left over, so it is likely that the Romans constructed many of these tall buildings with timber frames and infill masonry. (http://mars.acnet.wnec.edu).

Figure 4: (a) House of the Opus Craticium, Herculaneum, Italy, 2002.
(b) rear of 18&19thC. timber infill buildings in central Madrid.

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 adoption and continued use of this system until the present time was most likely the successful byproduct of a technology developed as much for its economy as for its strength, rather than specifically because of earthquake risk.

2.3 Laced Bearing Wall Construction

Laced-bearing wall construction may have had its origins in ancient times as well. This kind of construction can be found in the 5th Century AD Theodosian city walls of Istanbul, where the belts of red brick are an integral part of the architecture. Modern restorers, who reconstructed a portion of the walls, mistakenly treated this only as an architectural element by applying a brick band as thin layer on the surface, rather than as a structural layer extending through the masonry (Figure 5b & c). When the 1999 earthquake struck, this newly constructed section collapsed, while the surviving 1600-year-old heavily deteriorated portions of the wall were unaffected by the earthquake. (Figure 5a). This system evolved into the timber-laced systems described below.

Figure 5: (a) Original section of Theodosian City Wall, Istanbul after 1999 earthquake.
(b) Modern reconstruction of a part of the City wall that collapsed during 1999 earthquake.
(c) Modern "restoration" work shows the artificial look that results when the work is conceived without its original structural rationale.

2.4 Turkey

Before the advent of reinforced concrete, houses in Turkey (as well as in Greece and parts of Eastern Europe) were often designed with the laced bearing wall construction on the ground floor level, and the infill-frame (called *himis*, pronounced "humush" in Turkish) used for the upper stories. The multi-wythe masonry bearing walls of the first story are often laced with horizontal timbers. In Turkish, the timbers are called *hatil* (s) *hatillar* (pl). In contrast to those used in Kashmir, these are often very thin timber boards laid into the wall at approximately one-meter intervals, 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.

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 (Figure 6b). The jetties provided more than extra space and light; they 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 upper story is almost always of *himis* construction. This construction utilizes a weak mortar of mud or lime holding a single wythe of masonry into a timber framework of studs and horizontal dividers rarely more than 60cm apart. Because the masonry is only one wythe in thickness, the walls are light enough to be supported on the cantilevered timbers.

In those regions most affected by the 1999 Kocaeli and Düzce earthquakes, most of the settlements were industrial towns developed mainly in the 20th century. The Kocaeli earthquake of August 17, 1999 killed approximately thirty thousand people. (Kandilli, 2000) 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. (Kandilli, 2000) While the laced bearing wall type was rare, there were clusters of *himis* buildings in the heart of these districts. The houses were constructed of *himis* from the ground up. 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 *himis* houses remained intact, with only a few heavily damaged (Figures 7a-c).

Figure 6: (a) Caravansary, Safranbolu, Turkey showing timber hatil in bearing wall masonry visible on right at base of wall, 2000.

(b) House over shops in Safranbolu showing *himis* construction of upper stories, 2004.

This finding was confirmed by researchers who conducted a detailed statistical study in several areas of the damage district. They found a wide difference in the percentage of modern reinforced concrete buildings that collapsed, compared to those of traditional construction (Gülhan and Güney 2000). 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 compared to 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.

Figure 7: (a) *Himis* house in Gölcük damage district after the 1999 earthquake with no visible damage.

(b) An abandoned early 20th C. *himis* house, Gölcük. The house, even in its partially dismantled state, survived the earthquake with little additional damage.

(c) Detail of exterior wall of early 20th C. *himis* construction near Düzce.

A smaller earthquake (6.1 magnitude) that struck the rural town of Orta on June 6, 2000 provided a comparison with the damage caused by the Kocaeli and Düzce earthquakes the previous year. In this smaller earthquake, the damage to the *himis* structures was similar to those affected in the larger earthquakes, whereas the damage to RC structures was much less. This may explain why there is a widespread perception that RC buildings are safer. A comparison of the RC buildings affected by this earthquake with those in the 1999 earthquakes has revealed that the common RC buildings in Turkey have very little reserve capacity. They go very quickly from exhibiting little damage, as seen after the Orta earthquake, to collapse, as shown by the 1999 events. This observation contrasts with the performance of the traditional *himis* buildings shaken by the same earthquakes, where the small difference in the damage caused by the smaller and larger earthquakes demonstrates their ability to absorb the much increased shaking with little increase in damage (Figures8a & b).

Figure 8: (a) Interior of *himis* house in Orta after 2000.
(b) Interior of *himis* house in heart of damage district in Adapazari after 1999.

2.5 India

After a devastating earthquake struck western Gujarat on Republic Day, January 26, 2001, the scene of devastation was as appalling as that after the Turkish earthquakes in 1999. Whole towns were completely leveled. In Bhuj, Anjar, and Bachau, the building stock consisted of an almost equal variety of older stone masonry and reinforced concrete structures, with later additions in RC on top of the earlier unreinforced masonry. The masonry consisted mainly of rubble stone laid in mud or weak lime-mud mortar. The newer construction was of reinforced concrete, with infill masonry walls.

There was no evidence of RC shearwall construction. The earthquake shook most of the rubble stone buildings to the ground (Figure 9a & b). Buildings with horizontally bedded ashlar performed better, but sections of their walls were often missing. Many of the RC structures appeared to have collapsed just as readily. Timber-reinforced construction, either the bearing wall type with horizontal timbers, or the infill-frame type, was extremely rare in Kutch. The one example found in this survey was part of the 19th C. Swaminarayan Temple in Bhuj, dating from the late 18th or early 19th Century. This structure was unscathed by the earthquake, while a modern reinforced concrete section of the complex collapsed (Figure 10a).

Ahmedabad was also affected by the earthquake, but the situation there was very different. Although a number of major reinforced concrete apartment complexes with soft stories and other poor details collapsed, the historic walled city section survived nearly intact. Of the tens of thousands of buildings in this area, only one that was unoccupied was reported to have collapsed. The difference between the masonry buildings in the historic walled city part of Ahmedabad, and the walled city area in Bhuj, is the presence of timber lacing (Figure 10b). The Ahmedabad buildings shared some of the building tradition found in Turkey and Kashmir, while Bhuj did not.

Figure 9: (a) Walled city area of Bhuj after 2001 earthquake.
(b) Top-heavy thick masonry walls with shallow joist pockets collapsed easily.

Figure 10: (a)Undamaged timber-laced masonry Swaminarayan Temple in Bhuj after earthquake.
(b) Timber-laced masonry building in Ahmedabad historic walled city area after earthquake.

2.6 Nicaragua 1931 & 1971; El Salvador, 1986

A different variation on the infilled timber-frame system is common in several countries in Central America. This system, which most likely evolved from a merging of Spanish construction infill-frame practice with local Native American construction traditions, is known in Nicaragua as *Taquezal*, or "pocket" system, and in neighboring El Salvador as *Bahareque*. In these structures, a heavy post-and-beam timber frame is constructed, and the walls set within the frame consist of a row of 5cm x 10 cm studs, approximately 60 cm on center. The heavy timber frame consists of hardwood posts placed at the corners and at points in the walls about every 2 meters. Wood lath or bamboo is then nailed across the studs to form a kind of basket, and the resulting pockets are filled with layers of small stones (*Taquezal con piedra*), or adobe (*Taquezal con barro terra*). The wall is then usually plastered with a final layer of mud or lime plaster.

Buildings of this type at one time filled the Nicaraguan capital, Managua.. In 1932 about 85 percent of the buildings in the city were of this type. American engineer J.R. Freeman reported after the 1931 earthquake that *"In the newer buildings of this type, the only serious damage was* *the shaking off of roof tiles and practically all of the plaster…Tarquezal [sic] construction bears resemblance in its timber frame work and in its safety from collapse and killing people within, to the Baraccata type developed in Southern Italy a hundred years ago (see below).”* In 1971, however, the results were quite different. In a report by the Earthquake Engineering Research Institute, engineers observed that *"approximately 70 percent of the Taquezal buildings in the central area of the city collapsed or were seriously damaged. This mode of construction was the major cause of the high death toll.”* This same report recommends that *Taquezal* should be banned in earthquake-prone areas such as Managua.

Figure 11: (a) J.R. Freeman’s photo of *Taquezal* building in Managua after 1931 earthquake.
(b) San Salvador Bahareque building after 1986 earthquake showing a similar plaster shedding.

The October 10, 1986 earthquake in El Salvador provided the chance to study this discrepancy. Examination of the damage to bahareque buildings revealed that almost every case of structural failure originated where the wood armature was rotted or eaten by insects. Those structures with a greatest level of damage were invariably those which were the most rotten or consumed.

It is interesting to note that Freeman anticipated the problem of wood decay in 1932: *"In the Managua climate this type of structure in course of time may become weakened by decay of the wood posts and by the eating out of the interior of the posts by termites or white ants.”* By 1972, the average age of the existing *Taquezal* buildings in Managua was substantially older than it was in 1931. More significantly, less resistant North American softwoods had replaced the depleted supply of tropical hardwoods. These observations thus support a conclusion that that the primary cause of failures in this class of buildings was not the result of a defect in the structural system itself, but from environmental factors and lack of maintenance preceding the earthquake.

In 1931, Freeman observed that *“the only serious damage was the shaking off of…practically all of the plaster”* (Figure 11a). Likewise, in San Salvador in 1986 there were many *bahareque* buildings where the plaster had fallen off with no evidence of damage to the underlying walls (Figure 11b). The dislodging of the plaster from nearly the entire surface of the walls is evidence of the distribution of the earthquake stress throughout the wall, which is indicative of good behavior because the earthquake stress is dissipated throughout the wall with small movements between the masonry and wood of what is inherently a flexible structure. As a result, there is no single major destructive crack, and the energy of the earthquake is dissipated by the friction from the micro-cracking of the substrate which is confined between the studs.

2.7 Portugal, and Italy

One of the largest earthquakes ever to hit Europe struck Lisbon in 1755, which also unleashed a destructive tsunami and fire. In planning for the rebuilding of the central area, Chief Minister Sabastiao Jose de Carvalho e Melo (who later became the Marquis of Pombal), gathered a group of military engineers led by Manuel da Maia to determine the best manner of earthquake-resistant construction to use for the rebuilding. For this, they developed the gaiola ("cage"), which has become known as Pombalino construction. The gaiola essentially is a well-braced form of half-timber construction. After testing a prototype, they made its incorporation into the reconstructed buildings a requirement (Penn, et al, 1995). Many of the new buildings with the gaiola were five and six stories in height, and most of these remain standing today (Figure 12).

Figure 12: (a) 18th Century building in central Lisbon showing "Pombalino *gaiola*" construction, 2003.
(b) Gaiola wall sections from a late 18th or early 19th C. building after having been tested.
(c) Hysteresis diagram from one of the wall tests of the walls in figure 12b.

At the time of the earthquake, timber infill-frame construction was common throughout the Iberian Peninsula, including Lisbon. The inspiration to use this system most likely came from the observation of half-timbered structures that survived the earthquake. Consistent with this, one eyewitness, Reverend Charles Davy, observed: *"With regard to the buildings, it was observed that the solidest in general fell first."* (Tappan 1914)

The seismic capacity of the Pombalino walls was recently tested in the Portuguese Government's lab, by subjecting actual wall sections removed from a building to cyclical tests. The wide hysteresis loops from these tests show that the walls were able to dissipate energy over many cycles without losing their structural integrity. The sample remained largely intact despite having been pushed cyclically beyond what would be expected from a large earthquake (Cóias e Silva, 2002 & Santos 1997). The loss of plaster shows, just as it did in Nicaragua and El Salvador, that the forces were distributed across the wall section (Figure 11a & b).

The only other known example where a similar anti-seismic system was developed is in Calabria and Sicily, where there had been frequent devastating earthquakes, including one in Calabria in 1783, 28 years after the Lisbon earthquake. This Italian system, known as *"Casa Baraccata,"* was likely influenced by the Portuguese "Gaiola." In Italy, the *Casa Baraccata* became the underlying basis for an extensive series of manuals of practice, and even of patent applications for seismic resistive construction techniques up until the beginning of the 20th Century. (Barucci, 1990).(Tobriner, 2000) Both the Pombalino and Baraccata systems are significant because they were *deliberately* developed and selected as earthquake-resistant construction. While it is hard to firmly establish whether the earthquake risk influenced the adoption or proliferation of other infill-frame examples of traditional construction, the *gaiola* and *baraccata* provide definitive instances where the infill-frame was promulgated and even required by law because of its earthquake-resistant qualities.

2.8 United States

Like the 1755 Lisbon earthquake, the 1906 San Francisco earthquake triggered fires that destroyed the entire central business district and many of the surrounding residential areas (Figure 13 & 14). Ironically, the fire burned the brick, steel, and concrete parts of the city, leaving intact the buildings in many other areas that were built entirely of wood. The early steel skeleton frame skyscrapers that burned were constructed within two decades after the first skeleton frame office buildings in Chicago, to which the term “skyscraper” was first applied. The walls of these first skyscrapers were of brick masonry – masonry that infilled the frame which in turn carried the weight to the ground. It is the masonry infill that places these buildings on a continuum with timber predecessors that date back to include the ‘Opus Craticium’ of ancient Rome.

In 1883, noted Chicago architect, Irving K. Pond, writing for the Inland Architect and Builder wrote an article about his European travels in which he focused on the timber frame and masonry infill construction he observed in Spain where it was still being practiced: “*There is a tendency, from the very first days of Spanish building, to treat the wall, not as a homogeneous mass of masonry or brickwork, but rather as a frame filled in…with…mud, clay, or brick. …In some cities rolled iron beams are used for the frame, though timber frames are more common. …It is not uncommon to see the frame complete to the height of three or four stories, before the masonry has been carried above the foundation.” (quoted in Condit 1968, p. 129 & Look 1972)* Today, the historic center of Madrid is perceived as consisting of solid masonry five to seven story façades, but almost all of these 18th and 19th Century buildings are in fact timber infill-frame structures hidden behind a single layer of masonry and stucco (Figure 4b). (Langenbach, 2003a); Gonzales Redondo, 2003). It is intriguing to think of the possibility that the very issues raised by this article may have influenced William Le Baron Jenney when he designed the building now credited as the first “skyscraper,” the Home Insurance Co. Building, constructed a year later.

Figure 13: (a) Market Street, San Francisco during the post-earthquake fire of 1906, showing how even the new skyscraper of fireproof construction, the Hearst Building, caught fire from the wood windows and interior finishes (Bancroft Library). This building is still extant in 2006 in a remodeled state.

(b) 1906 view showing several of the steel skeleton “Chicago frame” buildings in burned-out condition. All of these are still extant in 2006 (Bancroft Library).

While it may appear to stretch credibility to draw a connection between the traditional way of building that in 1883 was still being practiced in Spain and the design of the first skeleton frame skyscrapers, the connection is not as remote as one may imagine. The Chicago architects and engineers did not invent infill-frame construction. Instead, they adapted it for skyscrapers by wrapping iron and steel frames with masonry which not only enclosed the buildings, but also served to brace the light frame. While the later theorists placed importance on the purity of having the skeleton frame support all loads, the first skyscraper engineers were conscious of the fact that the infill walls required for enclosure and fireproofing also provided the most efficient means to resist wind forces. In 1906, in San Francisco, these same walls were called upon to resist large earthquake forces as well.

An engineer for The Roebling Construction Company of New York City that had patents on some of the pre-fire floor systems, reported in 1906: *"The successful manner in which the tall, steel skeleton frame buildings withstood the effects of the earthquake and the fire is most reassuring, in fact wonderful…These buildings had never before been subjected to violent earthquake shocks, and many architects and engineers doubted their ability to withstand such surface movements without injury."* (Himmelwright 1906, p.7) Since even today a "design level" earthquake is expected to cause structural damage, it is remarkable that the San Francisco skeleton frame buildings had so little damage from an earthquake that met or exceeded what would now be considered a design-level event. The fact that such a large percentage of these buildings were restored after the earthquake and the fire is a testament to their lack of significant structural damage. Many of these structures have also survived redevelopment pressures to remain in existence now for more than a century after the earthquake (Figures 13 & 14).

Figure 14: (a) Lobby of the St. Francis Hotel after the 1906 earthquake & fire (Roebling, 1906). (b) Same view in 2005.

3. THE MODERN MOVEMENT

When one reads about the debate over which building was the first true skeleton steel frame skyscraper, one gets the impression that the introduction of shelf angles supporting the exterior cladding and the eventual elimination of all masonry would lead not only to a new building type, but to a better way of building. The Modern Movement not only brought skeleton frame construction into the realm of mid-rise housing, but established the philosophical basis for the removal of the walls from the structural system. For architects, it would mean the opening up of the interiors and the elimination of the thick membrane that had historically separated the interior from the world outside. In 1915, Swiss Architect Le Corbusier's published a drawing of the prototype bare concrete skeleton for multi-story residences known as the *Dom-Ino* house that became an icon of what he called the "New Architecture" (Figure 15a). As described by Le Corbusier's contemporary, Sigfried Giedion: Corbusier created…a single, indivisible space. The shells fall away between interior and exterior. … There arises…that dematerialization of solid demarcation…that gradually produces the feeling of walking in clouds. (Giedion 1927 p. 168-9)

From the Dom-Ino prototype, the RC moment frame spread through Europe, and then the rest of the world including earthquake hazard areas. However, the "dematerialization" of the walls clashed directly with the enclosure requirements of completed buildings. As a result, masonry did not disappear. Instead, the robust multi-wythe thick infill walls of the first skyscrapers evolved into weak and thin membranes of insufficient strength to provide much supplemental resistance in the event of earthquakes – and yet, their weight still added significantly to the lateral forces that had to be resisted by the frame (Figure 16b). In response to this demand for the open and flexible architecture, engineers eliminated masonry from their engineering calculations except as dead weight, a methodology that was believed at the time to be a safely conservative approach, but the infill attracted increased earthquake forces which it was too weak to resist. Compounding this problem was the frequent use of open "*piloti*" or shop fronts on the ground floor, as Le Corbusier had advocated, a risk in earthquakes known as a 'soft' or 'weak story.'

Figure 15: (a) Le Corbusier's conceptual Dom-Ino House, 1915

(b) Building under construction in Gölcük at time of 1999 earthquake

(c) Partially collapsed reinforced concrete infill-frame building in Gölcük, 1999.

NOTE: Unfinished bare frame reinforced concrete buildings were much more likely to survive the earthquake. The initial stiffness followed by the rapid degradation of the infill masonry walls, contributed to the collapse of many of the Gölcük concrete frame buildings.

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 remain in use for the design of multi-story buildings through the 20th Century until the present (Robison, 1989). The problem is that infill masonry does not fit conveniently into portal frame analysis, and the inelastic behavior of masonry is very difficult to quantify mathematically. As a result, there was a technical as well as a philosophical reason for its elimination from structural design calculations -- even when still used for infill walls.

The fundamental flaw with this approach is that this method of standard analysis is based on linear elastic behavior, which conflicts with the fact that buildings are expected to deflect into the nonlinear range in earthquakes. 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, but such factors are unresponsive to the conditions that exist when stiff and brittle membrane of "non-structural" infill masonry is added to the system, as this masonry is contained and restrained by the frame in a way that changes the behavior of the frame, sometimes with catastrophic results (Figure 15c).

4. INFILL-FRAMES: STRENGTH VS. CAPACITY

If the masonry infill can damage modern reinforced concrete frames, then why is it not more hazardous to the weak timber frames? The explanation is that the subdivision of the walls into many smaller panels with studs and horizontal members, together with low-strength mortar, prevents the formation of large cracks that can extend across the entire surface. As stresses on the individual masonry panels increase, shifting and cracking begins first along the interface between the panels and the sub-frame members, and then in the panels themselves (Figure 16a). When the mortar is weaker than the masonry units, cracking occurs in the mortar joints, allowing the masonry units in the panel to remain intact and stable. The resulting mesh of hairline cracking allows the building to dissipate energy.

This energy dissipation from the "working" of the materials against each other also serves to damp out 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 *himis* buildings in the epicentral region of the 1999 earthquakes in Turkey when compared with the RC buildings that surrounded them. While these structures do not have much lateral *strength*, what they possess is lateral *capacity*.

This explains why traditional infill-frame buildings are capable of surviving repeated major earthquakes that have felled modern reinforced-concrete buildings. The basic principle in this weak but flexible construction 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 other words, although the masonry and mortar is brittle, the *system* behaves as if it were ductile. 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)

Figure 16: (a) Interior of house in Orta, 2000, showing the working of the *himis* wall construction.
(b) Ruptured frame and collapsed masonry infill in Gölcük RC building after 1999 earthquake.

5. CONCLUSION

It is not engineering know how, but rather the local economy, labor supply, materials availability, access to engineering expertise, and thoroughness of inspection which will determine the quality and safety of what is actually built. This is particularly true with reinforced concrete, because of its particular need for quality to avoid collapse from hidden defects.

Between the possible and the practical in most earthquake-affected cities exists a great gap, and the enactment of more stringent engineering regulations is simply not sufficient. In many developing countries, sophisticated engineering and the delivery of materials of uniform quality simply may not be possible. By understanding the assets of the simpler but ultimately more robust buildings that were produced by hand before modern machines and materials existed, one can also recapture a connection with an aspect of cultural heritage in a more durable and sustainable way than if these pre-modern examples are only to be seen as antiquated relics.

For example, this technology of the past may provide a guide for how to improve the modern construction that has been used as a point of comparison in this paper. A description of one concept, *Armature Crosswalls*, proposed and now under development by the author, can be found at *www.conservationtech.com*. (Langenbach, 2003b).

Many alive today have heard the refrain: "*you cannot stop progress*" with the assumption that "progress" represents a relentless movement toward a better life. Lately, with the reemergence of diseases thought to have been eradicated, like Malaria and Polio, and with new diseases like AIDS and Avian Flu; with the destruction caused by the 2004 Sumatra earthquake and tsunami and the 2005 Hurricane Katrina, this view has ceased to be so compelling. The repeated collapse of thousands of reinforced concrete schools, homes and apartment houses in earthquakes around the world is also evidence of the fallacy of eternal progress.

Civilization rests on humble as well as grand contributions. The *himis* and *dhajji-dewari* structures that have been found standing amidst the earthquake ruins of the modern buildings around them do not mock their modern neighbors laid low, but rather, they quietly encourage us to shed some of the arrogance and over-confidence that brought the newer structures into being, forcing us to re-examine the roots of our civilization for ideas of how to build better in the present, even while we explore new and more modern materials and forms for the future.

Figure 17: (a) Remnant of a traditional house in Srinagar, Kashmir in 2005.
(b) An historic house of *Taq* construction still extant in Srinagar in 2005.

NOTE: Rather than serving to as a condemnation, the good performance of traditional timber-laced construction in the damage district of the October, 2005 earthquake should serve as an inspiration for the preservation of these often unrecognized, but rich cultural artifacts.

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