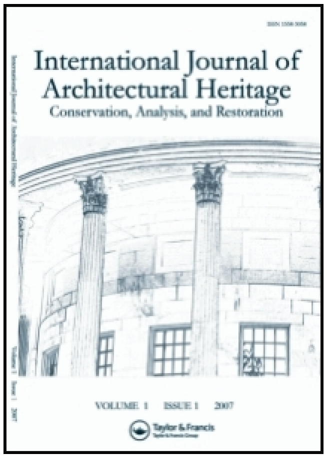

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FROM "OPUS CRATICIUM" TO THE "CHICAGO FRAME": EARTHQUAKE-RESISTANT TRADITIONAL CONSTRUCTION

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Earthquake-resistant traditional construction? One may consider the phrase to be an oxymoron, but there are many examples of traditional construction that have fared well in large earthquakes. This finding is certainly important for historic preservation efforts because 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 point is crucial because in recent earthquakes in diverse parts of the globe it is the modern buildings that often have proved to be most fatal. This finding is also of importance for historic preservation because vernacular buildings that are only admired for their appearance — and not for their traditional construction technology — will never be preserved in a manner that properly protects and reveals their true cultural value. This article will explore examples of timber-laced non-engineered masonry construction that have proven to be comparatively resistant to earthquake damage and discuss the reasons why they have proved more robust than what might be expected.

KEY WORDS: earthquake-resistant, traditional construction, reinforced concrete, masonry, infill-frame, half-timber

1. INTRODUCTION

In earthquakes in different regions around the world, certain historic buildings have fared better than others and even better than modern structures. There are great monuments such as the Hagia Sophia (Istanbul, Turkey) that have successfully resisted many earthquakes over their extended life spans. Even the Hagia Sophia, however, lost part of its great dome twice before a more resistant shape was devised, and its structure has been modified with the addition of many buttresses that were not there originally.

The phrase *traditional construction*, however, does not typically conjure up images of great monuments. Rather, this phrase is more commonly associated with smaller scale vernacular residential construction with comparatively weak materials and economical construction, yet there are many examples of traditional construction that have fared remarkably well in large earthquakes (Figures 1 and 2). This finding is certainly important for historic preservation efforts because the analysis and documentation of this phenomenon can bolster attempts to preserve the fabric of historical

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Figure 1. Characteristic timber-laced masonry traditional houses in Safranbolu, Turkey, 2004. © Randolph Langenbach, 2007.

Figure 2. Upper-story jetties of *hımış* construction in Safranbolu, Turkey, 2000. © Randolph Langenbach, 2007.

structures, but these unassuming buildings also can provide examples of how to improve *new* construction, if people can look through the veil of prejudice against archaic construction technologies to understand how these traditional materials and methods have actually worked. This approach is crucial because in recent earthquakes in diverse parts of the globe it is the modern buildings that often have proved to be most fatal.

2. DESIGN-LEVEL EARTHQUAKES

Unlike other natural threats, earthquakes come without any warning. It is during the event that one must get out of harm's way, which may place the individual at greater risk than simply 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. The practical reason for this is that the forces are expected to be larger than can be economically and practically resisted by all but the most important buildings, such as nuclear power plants, hospitals, and police and fire stations. To conform to code, ordinary buildings must simply avoid collapse.

What about buildings constructed prior to the existence of any earthquake codes? Is it plausible to assume that they must be more vulnerable? As reasonable as this assumption may seem, 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 buildings also have often outperformed nearby new construction. This is where the story in this article begins — first with examples of traditional construction in different parts of the world — and then with a discussion of why they often perform well in large earthquakes.

2.1 Kashmir, 1885

Arriving in the City of Srinagar, India, 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 (Figures 3 and 4). 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 (Figure 4). 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 5) (Langenbach, 1989).

These buildings were observed by Arthur Neve, a British visitor to what is now part of Indian Kashmir, when he witnessed the 1885 Kashmir earthquake, and 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)

Figure 3. Srinagar houses line both sides of the Jelum River where it penetrates through the city, 2005. © Randolph Langenbach, 2007.

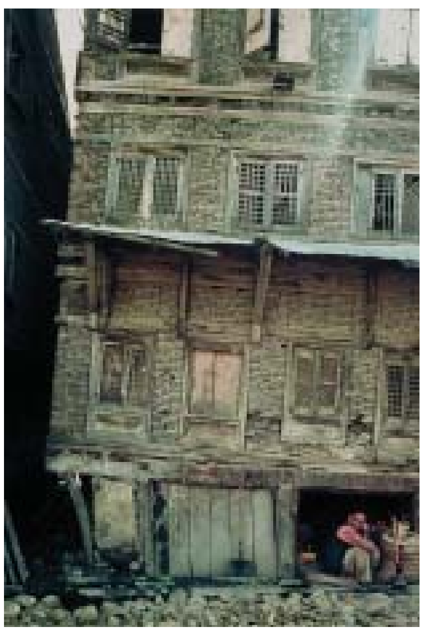


Figure 4. Old canal-side warehouse of *Taq* construction, Srinagar, Kashmir, India. 1981. © Randolph Langenbach, 2007.

Figure 5. *Dhajji-dewari* construction, Srinagar, Kashmir, India, 2005. © Randolph Langenbach, 2007.

2.2 Kashmir, 1967

More recently, two Indian engineers, N. Gosain and 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 & Arya, 1967)

Gosain and Arya note that during the 1967 Kashmir earthquake, buildings of three to five stories survived relatively undamaged. The research of Professor Anand Arya shows that one of the most important reasons for this lack of damage is the damping from the friction induced in the masonry of the *taq* and *dhajji-dewari* walls. Internal damping, as Arya notes:

> 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. (Gosain & Arya, 1967)

His explanation for this finding is that "there are many more planes of cracking in the *dhajji dewari* compared to the modern masonry." (Langenbach, 1989)

The idea that the cracking of masonry may be beneficial may seem counter-intuitive, but when one accepts the fact that even modern buildings are designed to codes that presume that damage will occur in moderate to large earthquakes, a system that is designed to allow the cracking to occur while minimizing displacement of the masonry — and at the same time maximizing frictional energy dissipation — certainly is beneficial. The alternative may be a system that remains rigid until a concentrated failure occurs, which is especially true for traditional materials before the advent of steel and concrete because connections were almost always comparatively weak. The timber in these traditional systems has the added advantage of remaining effective at restraining the masonry even after the masonry begins to crack, which serves to shift the loads onto the uncracked portions of the wall. This shift serves to reduce the danger of both in-plane and out-of-plane collapse of the wall.

2.3 Kashmir, 2005

On October 8, 2005, an earthquake devastated the mountainous area of the Pakistan section of Kashmir, killing more than 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 previously was rarely to be found in the worst affected urban areas on the Pakistan side of the border, where the massive death toll occurred. On the Indian side, however, a number of examples of traditional construction were found in the damage district. The performance of this timber-laced traditional construction confirmed earlier findings (Figure 6). 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

Figure 6. House in Baramula, Kashmir, Pakistan, damaged in 2005 earthquake showing how unreinforced masonry collapsed, leaving the top story of *dhajji-dewari* in place. © Randolph Langenbach, 2007.

performance in this earthquake has once again been shown to be superior with no or very little damage. (Rai & Murty, 2005)

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," and 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).

2.3.1 Timber-laced masonry construction 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 localities 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.

2.3.1.1 Infill-frame construction: In addition to Kashmir's *dhajji-dewari*, regional manifestations are called *colombage* in France, *fachwerk* in Germany, *hımış* in Turkey, and *half-timber* in Britain. Variations that used earthen plaster and sticks or reeds (wattle and daub) include Turkish *Bağdadi* and Peruvian *quincha*. Despite the usually ephemeral nature of the material, 5,000 year old *quincha* construction has been unearthed at the Peruvian archeological site Caral (Barranca, Peru). 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, Italy that had been buried in a hot pyroclastic flow from Mount Vesuvius in 79 AD, they found an entire two story *half-timber* house which they identified as one of the masonry construction typologies described by Vitruvius as *Craticii* or *Opus Craticium* (Figure 7). This example in Herculaneum may provide the only surviving example of the form of construction that had been used in ancient Rome for the *insulae* — the term for the seven- or eight-story tenements that filled that city of 1.5 million 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.

In the centuries that followed 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, during the Byzantine Empire (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.

2.3.1.2 Laced bearing wall construction: Laced bearing wall construction also originated in ancient times. An example has been identified at the Minoan "New Palace" of Knossos, Crete, Greece, dated 1450 BC (Kienzle, 2002). This construction may also be loosely related to the utilization of horizontal bands of wide and flat Roman brick that were sometimes laid at intervals into walls composed of more

Figure 7. House of the *Opus Craticium*, Herculaneum, Italy, 2002. © Randolph Langenbach, 2007.

random mortared masonry. At Pompeii, Italy, 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 the fifth century AD Theodosian city walls of Istanbul, Turkey, where the belts of red brick are an integral part of the architecture that extended through the core of the wall (Figure 8a). Modern restorers, who restored and reconstructed portions of the walls, mistakenly treated this only as an architectural element by applying a brick band as thin layers on the surface, rather than as a structural layers extending through the masonry (Figures 8b and 9). When the 1999 earthquake struck, a newly reconstructed section of the wall collapsed (Figure 8b), while the surviving 1600-year-old heavily deteriorated portions of the wall remained standing (Figure 8a).

2.4 Turkey, 1999

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 *hımış,* pronounced "humush" in Turkish) used for the upper stories. The multi-wythe masonry bearing walls of the first

(a) (b)

Figure 8. (a) Deteriorated original section of the Theodosian City Wall, Istanbul, Turkey, after the 1999 earthquake. The earthquake caused none of this damage. © Randolph Langenbach, 2007. (b) Reconstructed section in 1999 of the Theodosian City Wall Istanbul, Turkey, that collapsed during 1999 earthquake. The bands of brick, which had originally penetrated the wall, were treated as a veneer in the reconstruction. © Randolph Langenbach, 2007.

Figure 9. City wall showing modern "restoration" with stripes of red brick attached as a veneer, demonstrating the artificial look that results when the work is conceived without its original structural rationale. © Randolph Langenbach, 2007.

story are often laced with horizontal timbers. In Turkish, the timbers are called *hatıl* (singular) or *hatıllar* (plural). In contrast to timbers used in Kashmir, these timbers are often very thin 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. In addition to the lower floor of houses, some of the more prestigious monuments were made of dressed stone construction with *hatıllar* throughout, as in the caravansary of Safranbolu, Turkey (Figure 10).

The Turkish Ottoman-style house, with its tiled roof and overhanging timber-and-brick bays above a heavy stone ground floor wall, has become an icon known worldwide (Figures 1, 2, and 11). 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 *hımış* 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 60 cm (25 inches) 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 of Turkey most affected by the 1999 Kocaeli and Düzce earthquakes, most of the settlements were industrial towns developed mainly in the twentieth

Figure 10. Caravansary, Safranbolu, Turkey, showing timber *hatil* in bearing wall masonry, which is the black line visible on right at base of wall, 2000. © Randolph Langenbach, 2007.

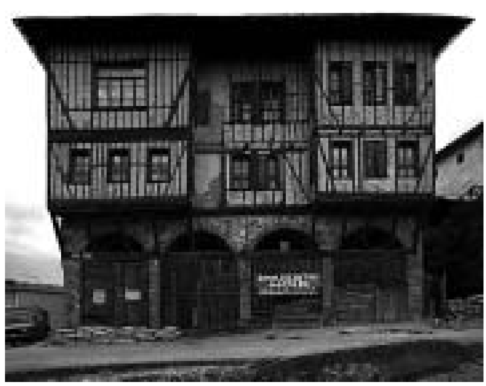


Figure 11. House over shops in Safranbolu Turkey, showing *hımış* construction of upper stories, 2004. © Randolph Langenbach, 2007.

century. The Kocaeli earthquake of August 17, 1999, killed approximately 30,000 people (Kandilli Earthquake Research Institute, 2000). The epicenter was only about 100 kilometers east of Istanbul. In some areas of Gölcük and Adapazari, the earthquake destroyed more than one third of all housing units, almost all of them in reinforced concrete buildings (Figure 12) (Kandilli Earthquake Research Institute, 2000) While the laced bearing wall type was rare, there were clusters of *hımış* buildings in the heart of these districts. The houses were constructed of *hımış* 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 *hımış* houses remained intact, with only a few that were heavily damaged (Figures 13–16).

This finding was confirmed by Turkish researchers Gülhan and Güney who conducted a detailed statistical study in several areas of the damage district Gülhan and Güney, 2000). They found a wide difference in the percentage of modern reinforced concrete buildings that collapsed compared with 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, whereas only four of the 789 two-to-three-story traditional structures collapsed or were heavily damaged. The reinforced-concrete buildings accounted for 287 deaths compared with only with 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, whereas none of the 400 traditional structures collapsed or were heavily damaged and 95 were moderately damaged.

Figure 12. Collapsed reinforced concrete infill-frame in Gölcük, Turkey, after 1999 Kocaeli earthquake. © Randolph Langenbach, 2007.

Figure 13. House, circa 1940 of *hımış* construction in heart of damage district of Gölcük, Turkey, after the 1999 Kocaeli earthquake with no visible damage. © Randolph Langenbach, 2007.

Figure 14. An abandoned early twentieth-century house, Gölcük, Turkey, showing the thin walls and light framing characteristic of *hımış* construction. The damage here was not caused by the earthquake. Instead, the house, even in its partially dismantled state, survived the earthquake with little additional damage. © Randolph Langenbach, 2007.

Figure 15. Detail of exterior wall of early twentieth-century *hımış* construction near Düzce, Turkey. Sometimes the brick infill is deliberately arranged into decorative patterns. © Randolph Langenbach, 2007.

Figure 16. Three-story mid-twentieth-century *hımış* house in heart of the Gölcük, Turkey, damage district less than 0.5km from the fault trace. Whereas the unfinished reinforced concrete building to the left survived, several other occupied buildings in adjacent blocks collapsed. © Randolph Langenbach, 2007.

2.5 Turkey, 2000

A smaller earthquake (M 6.1) that struck the rural town of Orta, Turkey, on June 6, 2000, provided an interesting comparison with the damage caused by the Kocaeli and Düzce earthquakes the previous year. In this smaller earthquake, the damage to the *hımış* structures was similar to those affected in the larger earthquakes, whereas the damage to reinforced concrete (RC) structures was much less. This finding may explain why in Turkey there is a false, but 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. What appeared as small cracks at the beam/column intersections in Orta was evidence of the leading edge of what in the larger earthquake proved to be a rapid degradation to collapse. This observation contrasts with the performance of the traditional *hımış* buildings shaken by the same earthquakes. Even though the onset of damage is at low levels of shaking, 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 (Figures 17a and 17b).

(a)

(b)

Figure 17. (a) Interior of *hımış* house in Orta, Turkey, after 2000 earthquake showing plaster shedding from working of the frame. (b) Interior of *hımış* house in heart of damage district in Adapazari, Turkey, after 1999 earthquake, showing how heavy masonry damage did not jeopardize its stability. This particular house was abandoned and in a more advanced state of decay than the house in Orta, Turkey, and the shaking from the 1999 earthquake in Adapazari was far greater. Most well-maintained *hımış* houses had even less wall damage from the 1999 earthquakes. © Randolph Langenbach, 2007.

The term *capacity* here and elsewhere is used to refer to the overall structural ability to resist destruction from seismic activity. There is an important distinction to be made between the terms *capacity* and *strength* because *capacity* includes all of the attributes in a building's fabric that are brought into action during an earthquake. These attributes include materials and systems that may be weak and even brittle by themselves, but which are often redundant and capable of imparting large amounts of ductility and energy dissipation that can "de-tune" a structure from resonance with an earthquake and thus protect an otherwise vulnerable primary structural system from catastrophic damage.

2.6 India, 2001

After a devastating earthquake struck western Gujarat, India, 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 was divided almost equally between older stone masonry buildings and reinforced concrete structures. Many older masonry buildings were surmounted with upper floors of RC construction, which proved to be an unsafe combination. 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 (Figures 18 and 19).

The earthquake shook most of the rubble stone buildings to the ground (Figure 20). 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 Swaminarayan Temple in Bhuj, dating from the late eighteenth or early nineteenth century. This structure was almost completely unscathed by the earthquake, while the modern reinforced concrete section of the complex partially collapsed (Figure 21).

Figure 18. Bhuj, India, after the 2001 earthquake showing widespread collapse of both reinforced concrete and unreinforced masonry buildings. © Randolph Langenbach, 2007.

Figure 19. Collapsed masonry building, in Bhuj, India, after the 2001 earthquake, showing top-heavy thick walls lacking timber lacing and with shallow joist pockets. © Randolph Langenbach, 2007.

Figure 20. This Bhuj, India, resident, after recovering from his injuries, returned to the site of his masonry and concrete home to dig out the body of his mother shown in the pictures, one of the more than 20,000 deaths in the 2001 earthquake, to cremate her body within the ruins of their home. © Randolph Langenbach, 2007.

Figure 21. Timber-laced masonry Swaminarayan Temple in Bhuj, India, undamaged by the earthquake that collapsed the modern concrete structure in foreground. © Randolph Langenbach, 2007.

The situation in Ahmedabad 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 almost completely intact, despite the fact that many buildings were in extremely poor repair. Of the tens of thousands of buildings in this area, only one was reported to have collapsed, and that had been abandoned before the earthquake. 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 22). The Ahmedabad buildings shared some of the

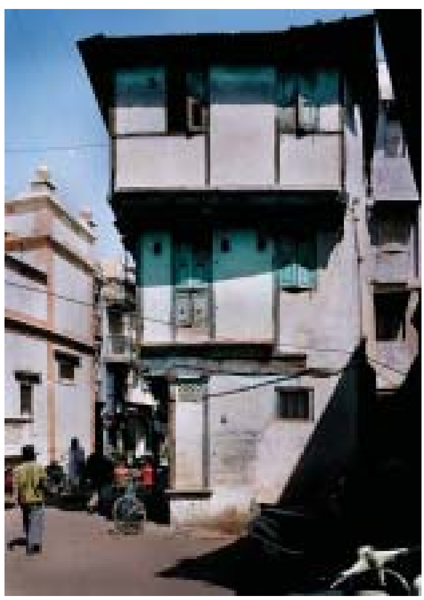


Figure 22. Timber-laced masonry building in Ahmedabad historic walled city area undamaged by earthquake © Randolph Langenbach, 2007.

building tradition found in Turkey and Kashmir, while, except for the Swaminarayan Temple, Bhuj did not.

2.7 Nicaragua, 1931 and 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 local Native American construction methods with timber and masonry infill-frame practices that could be found in parts of Spain and the rest of Europe, 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 5-cm $\times$ 10-cm (2-inch $\times$ 4-inch) studs, approximately 60 cm (25 inches) on center. The heavy timber frame consists of hardwood posts placed at the corners and at the intersection of walls. 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 approximately 85% 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. (Freeman, 1932)

In 1971, however, the results were quite different. In a report by the Earthquake Engineering Research Institute (Oakland, CA), engineers observed "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 (EERI, 1972).

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 that 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" (Freeman, 1932). 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. The evidence, therefore, is 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" (Freeman, 1932) (Figure 23). Likewise, in San

Figure 23. Photograph by American engineer J.R. Freeman of *Taquezal* building in Managua, Nicaragua, after 1931 earthquake used to illustrate his observation that damage to the building was limited the shedding of exterior plaster. © Randolph Langenbach, 2007.

Salvador in 1986 there were many *Bahareque* buildings on which the plaster had fallen off with no evidence of damage to the underlying walls (Figure 24). 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. It draws attention to the fact that 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 microcracking of the substrate that is confined between the studs.

2.8 Portugal, 1755, and Italy, 1783

The largest known earthquake ever to hit Europe struck Lisbon, Portugal in 1755, which also unleashed a destructive tsunami and fire. In planning for the rebuilding of the

Figure 24. *Bahareque* building in San Salvador, El Salvador, after 1986 earthquake showing a similar shedding of plaster from otherwise undamaged walls. © Randolph Langenbach, 2007.

Figure 25. Interior of eighteenth-century building in central Lisbon, Portugal, showing *Pombalino gaiola* construction, 2003. © Randolph Langenbach, 2007.

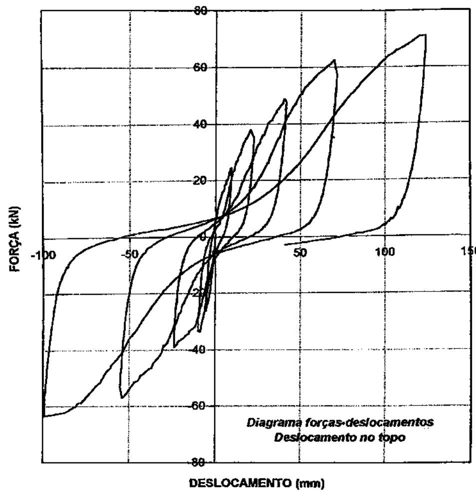
central area, Chief Minister Sabastiao Jose de Carvalho e Melo (who later became the Marquis of Pombal), gathered a group of military engineers led by Manuel da Maia to determine the best manner of earthquake-resistant construction to use for the rebuilding. For this, they developed the *gaiola* ("cage"), 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, 225 years later (Figure 25).

At the time of the earthquake, timber infill-frame construction was common in certain parts of the Iberian Peninsula, including Lisbon and other parts of Portugal, and also the north of Spain, including Madrid. While the system had evolved throughout Europe and the British Isles for reasons other than earthquake resistance, the inspiration to make use this system as a defense against future earthquakes in Lisbon most likely came from the observation of half-timbered structures in Lisbon 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 structures laboratory 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 an 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 26a and 26b).

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

(a)



(b)

Figure 26. (a) Walls sections removed from *gaiola* frame of a late eighteenth- or early nineteenth-century building after having been tested in structures lab to a level of deformation and number of cycles in excess of that expected in a major earthquake, 2003. © Randolph Langenbach, 2007. (b) Hysteresis diagram from one of the wall tests of the walls in Figure 26(a). The wide loops are a measure of a large amount of friction-induced energy dissipation, and the increased height of each successive loop shows that the wall had not exceeded its maximum strength at the conclusion of the test.

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 twentieth century (Barucci, 1990; Tobriner, 2000).

Both the Pombalino and Baraccata systems are significant because they were *deliberately* developed and selected as earthquake-resistant construction. Although it is hard to firmly establish whether the earthquake risk influenced the adoption or proliferation of other more traditional infill-frame examples, the *gaiola* and *baraccata* provide definitive instances in which the infill-frame was adapted from its traditional construction prototypes and then promulgated and even required by law because of its earthquake-resistant qualities.

2.9 San Francisco, 1906

Like the 1755 Lisbon earthquake, the 1906 San Francisco (United States) earthquake triggered fires that destroyed the entire central business district and many of the surrounding residential areas (Figure 27). 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 (United States), 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

Figure 27. Market Street, San Francisco, United States, 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 (Photograph courtesy of Bancroft Library, University of California, Berkeley, Berkeley CA). In 2006, this building remains extant in a remodeled state.

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 the parts of Spain he visited 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 completed to the height of three or four stories, before the masonry has been carried above the foundation. (quoted in Condit 1968: 129, and Look 1972)

Today, the historic center of Madrid (which is not in an earthquake area) is perceived as consisting of solid masonry five-to-seven-story façades, but almost all of these eighteenth- and nineteenth-century buildings are in fact timber infill-frame structures hidden behind a single layer of masonry and stucco (Gonzales Redondo, 2003; Langenbach, 2003a). It is intriguing to think of the possibility that the very issues raised by this article may have influenced American architect William Le Baron Jenney when he designed the building now credited as the first "skyscraper," the Home Insurance Company Building (Chicago, IL), constructed one year later.

Figure 28. 1906 view showing several of the steel skeleton "Chicago frame" buildings in burned-out condition. All of these buildings are still extant in 2007 (Photograph courtesy of Bancroft Library, University of California, Berkeley, Berkeley, CA).

(a) (b)

Figure 29. (a) Lobby of the steel frame St. Francis Hotel after the San Francisco earthquake and fire of 1906 (Photograph, Roebling, 1906). (b) Same view as Figure 29a, 100 years later. © Randolph Langenbach, 2007.

Although 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 infilling and wrapping iron and steel frames with masonry that 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 (United States) 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: 7).

Since even today a "design level" earthquake is expected to cause structural damage, it is remarkable that there was such a low level of earthquake damage found in the San Francisco skeleton frame buildings after the 1906 earthquake. This finding is especially important because that earthquake clearly met or exceeded a design-level event. The lack of serious earthquake damage is demonstrated by the simple fact that a large percentage of these buildings were restored to use not only after the earthquake, but even after the fire which caused far more substantial damage than did the earthquake shaking. Many prominent landmark structures have also survived redevelopment pressures to remain in existence to this day, having recently marked the hundredth anniversary of the 1906 earthquake (Figures 27–29).

3. THE MODERN MOVEMENT

In 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 also 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 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 30a). As described by a contemporary of Le Corbusier, 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: 168–169).

From the Dom-Ino prototype, the RC moment frame spread through Europe, and then the rest of the world including earthquake hazard areas (Figure 30b). However, the "dematerialization" of the walls clashed directly with the enclosure requirements of completed buildings. As a result, masonry did not disappear. Instead of the robust multi-wythe thick infill walls characteristic of the first

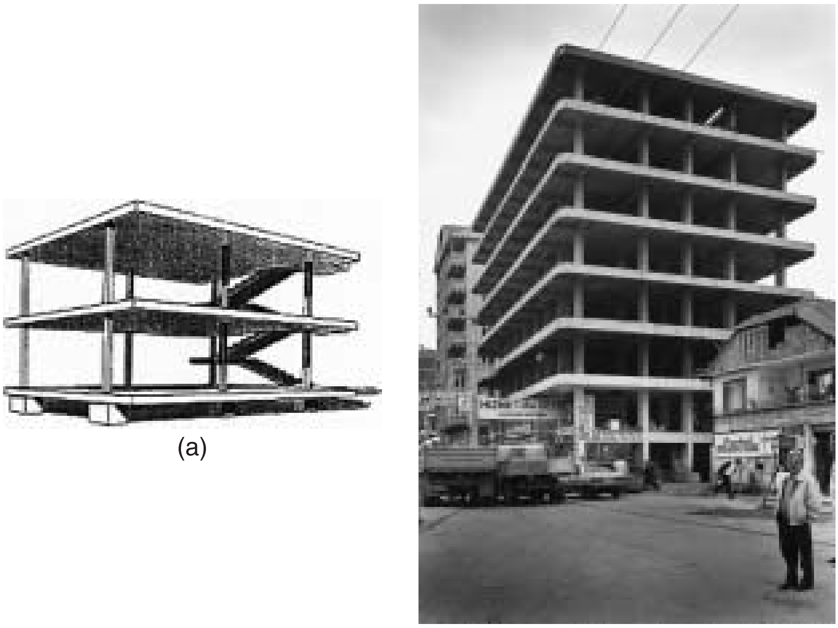


Figure 30. (a) Le Corbusier's conceptual Dom-Ino House, 1915 (Giedion, 1941). (b) Building under construction in Gölcük, Turkey, at the time of the 1999 earthquake. (Reinforced concrete buildings that had not been finished with the infill masonry at the time of the earthquake were much more likely to survive without collapse.) © Randolph Langenbach, 2007.

skyscrapers, the infill masonry walls found in the early modern mid-rise housing blocks had evolved into weak and thin membranes of insufficient strength to provide much supplemental resistance in the event of earthquakes. However, their weight still added significantly to the lateral forces that had to be resisted by the frame. 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. Unfortunately, while ultimately dangerously weak, these infill walls were initially stiff enough to attract higher forces, and capable of remaining intact and strong enough to frequently cause catastrophic damage to the frame before they cracked and fell away (Figure 31). Compounding this problem was the frequent use of open *piloti* or shop fronts on the ground floor, which Le Corbusier had advocated, a risk in earthquakes known as a 'soft' or 'weak story' that has proved to be one of the primary reasons for building collapses.

In the first decades of the twentieth 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 twentieth century until the present (Robison, 1989). The problem is that infill masonry does not fit conveniently into portal frame analysis, and the

Figure 31. Partially collapsed reinforced concrete infill-frame building in Gölcük, Turkey, 1999. The initial stiffness and subsequent rapid degradation and collapse of the infill masonry walls, fragments of which are visible in the photograph, contributed to the collapse of many of the Gölcük concrete frame buildings. © Randolph Langenbach, 2007.

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 flaw has been recognized in codes through the use of ductility factors, 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 31 and 32a).

3.1 Infill-Frames: Strength Versus Capacity

If the masonry infill is a danger to modern reinforced concrete frames, why then 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 the use of low-strength mortar, prevents the formation of large cracks that can extend across the entire surface. It also avoids the initial stiffness that attracts greater earthquake loads, as well as the creation of the "diagonal strut" for which the stiff infill can cause destructive shear stresses on the columns at the critical

(a) (b)

Figure 32. (a) Ruptured frame and collapsed hollow block masonry infill wall in a Gölcük, Turkey concrete building after the 1999 earthquake. © Randolph Langenbach, 2007. (b) Interior of house in Orta, Turkey after the 2000 earthquake, showing the working of the confined masonry panels of *hımış* construction. © Randolph Langenbach, 2007.

column-beam intersections. (For more information on reinforced concrete infill-frame buildings in earthquakes, see Langenbach, 2003b).

In reinforced concrete buildings, if the infill walls are subdivided into panels, as stresses on the individual masonry panels increase, the shifting and cracking begins first along the interface between the panels and the sub-frame members, and then in the panels themselves (Figure 32b). If the mortar is kept weaker, rather than stronger than the masonry units, cracking occurs along the mortar joints. This helps to avoid the concentration of destructive loads onto small sections of the reinforced concrete frame, which can lead to sudden catastrophic failure, especially when the RC frame has hidden faults, which has often proved to be the case. Ensuring that the mortar is weaker than the masonry units avoids the cracking of the bricks or blocks themselves, which is of critical importance in maintaining the stability of the masonry panel (Langenbach, 2003b).

In addition, the hairline cracking along the mortar joints also can dissipate large amounts of the earthquake energy, thus reducing the resonance of the building with the earthquake. This reduction is because the "working" of the materials against each other affects the natural frequency or "period" of the vibration of the structure, damping its excitation from the earthquake. As demonstrated by the behavior of the *hımış* buildings in the epicentral region of the 1999 earthquakes in Turkey when compared with the RC buildings that surrounded them, this working of the composite structure during an earthquake can continue for a long period before the degradation advances to a destructive level. Although these structures do not have much lateral *strength*, what they possess is lateral *capacity*.

This point 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 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 *hatillar* in Turkey with "incorporating ductility [in]to the adobe walls, substantially increasing their earthquake resistant qualities" (Aytun, 1981).

Figure 33. Remnant of a traditional house in Srinagar, Kashmir, India in 2005 after replacement of part of it on the subdivided property, symbolic of the destruction of so many of the historic houses of traditional construction here and in other cities around the world. © Randolph Langenbach, 2007.

It is not engineering "know how," but rather the local economy, labor supply, materials availability, access to engineering expertise, and thoroughness of inspection that determines 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 is not be possible for more than a small minority of all construction projects underway at any given time. By understanding the assets of the simpler but ultimately more robust buildings 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.

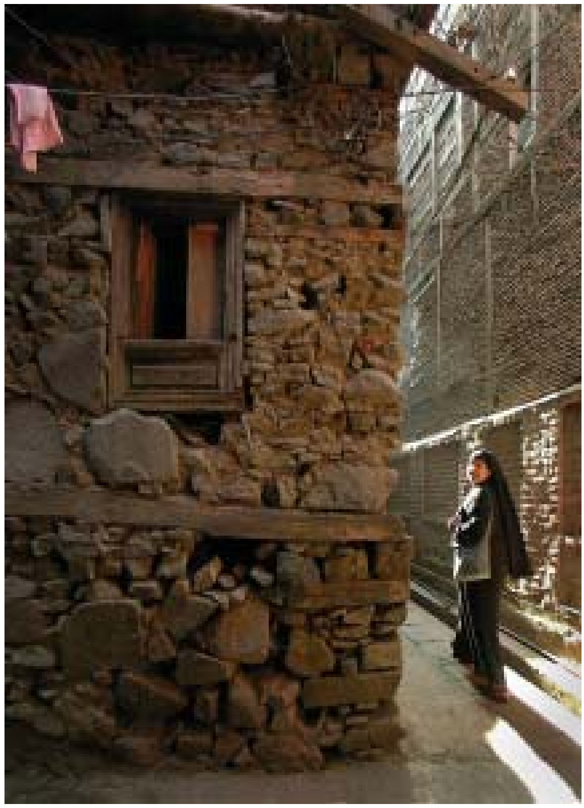


Figure 34. An historic house of *Taq* construction still extant in Srinagar, Kashmir, India in 2005. Rather than serving to as a condemnation, the good performance of traditional timber-laced construction in the damage district of the October 2005 earthquake should serve as an inspiration for the preservation of these often unrecognized, but rich cultural artifacts. © Randolph Langenbach, 2007.

4. CONCLUSION

Having found that infill-frame construction has performed well in earthquakes, the question remains of how to make use of this information. It is, of course, of value in the preservation of the vernacular buildings themselves, particularly in efforts to save them with interventions that augment, rather than replace, their structural systems. In addition, though, this technology of the past may provide a guide for how to improve the modern construction. A description of one such concept, "Armature Crosswalls," proposed and developed by the author, can be found at www.conservationtech.com (Langenbach, 2003b). When people see that traditional pre-industrial materials and methods of construction can be embraced as the source for ideas on how to make new buildings better, people may rediscover parts of their heritage that increasingly have been spurned as backward.

Construction is an unsung area of architectural and cultural history. However, for vernacular buildings it forms a large part of the cultural record. The buildings described here are those seemingly unpretentious, weak, insubstantial, but characteristically common buildings that have been renewed for generations (Figures 33 and 34).

There have been many masonry buildings in history that have collapsed on their occupants, but it is essential to examine those that survived, even when today's conventional wisdom predicts that they would not.

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, such as malaria and polio, with new diseases such as 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 *hımış* 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 them 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.

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