Rescuing the Baby from the Bathwater: Traditional Masonry as Earthquake-Resistant Construction

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ABSTRACT:

It seems counter-intuitive to assert that unsophisticated, non-engineered timber and masonry structures might be safer in large earthquakes than structures of reinforced concrete, but such has been the case in a number of recent earthquakes. The question of what lessons can be derived from this insight is even less obvious. However, in many different regions of the world, the earthquake record with structures of reinforced concrete frequently has been abysmal. This paper explores the specifics of what can be learned from historical construction practices, and describes the author's concept for "Armature Crosswalls". When historic structures are understood not only as obsolete building systems but as repositories of generations of thought and knowledge of how to thrive using local resources, societies can rediscover the value of these traditions once again by seeing them in a new light – one that, at its most fundamental level, can save lives.

Keywords: *Earthquake, Traditional construction, Reinforced Concrete, Crosswall*

1 INTRODUCTION

Reflecting back on the trajectory of my work, it began in the industrial towns of New England, Great Britain and India, and then from California to the remote city of Srinagar, Kashmir to Turkey, Pakistan, Afghanistan, Iran, and from there to Portugal and Italy. Now it also has come to include the Island of Hispaniola – first the Dominican Republic, and now, earlier this year, Haiti. And, it is masonry that links the cities of the industrial revolution with the seismically vulnerable ancient cities of the Raj in India, the rural villages of Pakistan and Turkey, 18th Century Lisbon, and the archaeological sites of Iran and ancient Rome.

The industrial cities have an important role in this trajectory because the masonry buildings involved were very large and subjected to strong lateral vibrations imparted by the machinery. In studying the evolution of masonry construction with iron and brick floors in Britain compared with the United States, where wood was abundant and used instead of iron, one sees that in the American mills of six to as much as nine stories the looms were placed high up in the mill buildings. The picker sticks of as many as a thousand looms in a single mill building batted their heavy shuttles back and forth with such force that the entire building would shake from the vibrations almost like an earthquake. Indeed, it was a deliberate strategy to buffer the looms from the ricochet forces that would otherwise have broken their cast iron frames. The masonry and iron construction of the British mills would have been shaken to destruction had the looms not been placed in separate one-storey weave sheds.

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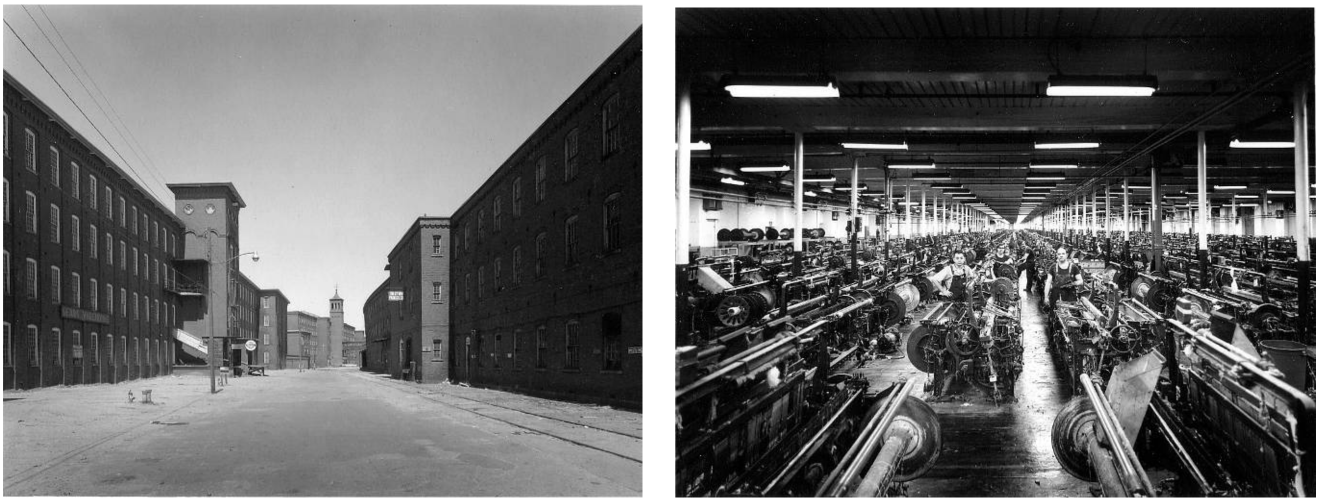

Figure 1. **left**: The Amoskeag Millyard, Manchester, New Hampshire, USA with buildings dating from the 1830's. **right**: Weave room containing 1000 looms dating from 1920's. Photograph was taken after the mill had ceased operation in the 1980's. *All photographs in paper except as marked © Randolph Langenbach.*

It was this history of building technology that led me to question the conventional wisdom I encountered when I moved to California. At just that same time in California, a number of the more creative engineers with an interest in preserving historical masonry buildings were working on ways to retrofit masonry buildings against earthquakes – and the most fundamental element of the new code provisions they came up with is exactly what was developed in the first decades of the 19th century in New England to prevent the multi-story timber and masonry textile factories from falling down from the vibrations from the looms. Now it is an accepted part of the State of California building code which has come to be called "bolts plus" because the main element is to bolt the load-bearing masonry walls to the timber floor diaphragms, together with other upgrade strategies that are building-specific. [1]

2 SRINAGAR, KASHMIR

While documenting the Indian textile industry in 1981, I became fascinated by the different types of traditional masonry construction found in Srinagar, Kashmir. The vernacular masonry buildings were constructed with a lacing of timbers laid into the walls that has become referred to as *taq* construction with local variations on what in English is called "half-timbered" construction. In Kashmir, this was given a textile term *dhajji dewari* to describe it, which means "patch quilt wall" in old Persian.(Fig. 2)

In California three years later, I had to confront the collision between earthquake risks and my chosen field of historic preservation. I was drawn to research the history of these vernacular buildings in Kashmir more closely, and I discovered anecdotal evidence in literature of their resistance against earthquakes.

The architecture and construction of the buildings in Srinagar enabled me to examine the potential that heritage buildings constructed with weak materials could nevertheless exhibit robust behaviour in earthquakes that was largely unrecognized in the field of earthquake hazard mitigation. Those very caveats that are embraced by conservators – the value of flexibility and deformability, the use of lime or even mud mortar and the avoidance of the use of Portland cement – have long been anathema to many seismic engineers. Whether these discrepancies between the fields could be reconciled thus emerged as the primary focus of my research.[16]

Figure 2. Buildings in Srinagar, Kashmir. **left**: The building on the left is of *taq* timber laced bearing wall construction, and on the right is of *dhajji dewari* construction. **middle**: A partially demolished *dhajji dewari* building showing timber frame with infill masonry construction. **right**: A partially demolished building showing timber-laced masonry bearing wall typical of *taq* construction.

3 EARTHQUAKES IN TURKEY IN 1999 AND 2000 AND GUJARAT, INDIA IN 2001

The Kocaeli Earthquake in Turkey in 1999 was soon followed by the Düzce earthquake. Turkey was home to historic construction systems similar to those found in Kashmir, and these earthquakes affected buildings similar to the *dhajji dewari*, which in Turkish are called *hımış.* In the epicentral area cities of Gölcük and Düzce, surviving *hımış* construction buildings could frequently be found standing next to collapsed modern engineered buildings of reinforced concrete.(Fig. 3)

Perhaps as important as the major earthquakes of 1999 is a lesser-known one in 2000 that affected a rural area around the central Anatolian village of Orta. The shaking in this one was significantly less than in the 1999 earthquakes. Thus, unlike those in Gölcük and Düzce, the reinforced concrete buildings suffered little damage. The *hımış* houses, however exhibited damage in the form of fallen plaster and stucco and some disruption of the infill masonry. Following the earthquake, government inspectors condemned many of the traditional houses, and advocated the resettlement of their owners in new houses of concrete and brick construction – in effect disregarding the poor record that such construction had exhibited in earthquakes that had occurred 250 km to the west only 6 and 9 months earlier.

Figure 3. **left**: Undamaged three story *hımış* house in Gocuk, Turkey after the 1999 earthquake. **right**: View of a collapsed row of reinforced concrete apartment buildings with *hımış* house standing behind.

None of the traditional houses that had been maintained and occupied fell down, but the early onset of damage – which is fundamental to how weak materials react to such overwhelming forces – was interpreted by the inspectors as indicative of future risk that could not be easily mitigated when they would be repaired. In other words, they applied assumptions that would have been correct when inspecting concrete buildings with heavy damage to the timber and masonry structures – but these assumptions are incorrect. When the damage to the traditional houses was compared to that seen in Gölcük and Düzce in similar houses, there was little difference – meaning that both large and small earthquakes cause the buildings to manifest damage, but that their flexibility and the energy dissipation from the working of their masonry within the timber frames effectively prevented the damage from progressing to collapse, even in the largest of earthquakes.[1]

Soon after the earthquakes in Turkey, came the 2001 Bhuj earthquake in Gujarat, India. Historic masonry buildings along with modern concrete buildings in the city of Bhuj were devastated. These were often made of rubble stone construction without any timber lacing in the walls. By contrast, the historic walled city of Ahmedabad, where the masonry buildings had timber lacing or timber frames, remained almost completely intact, while many modern buildings collapsed. One masonry structure in Bhuj did, however, stand out – the three-storey residential building that was part of the Swaminarayan Temple. (Fig. 4) It survived with only minor cracks, while the concrete pavilion structure in front of it collapsed. It was unique in Bhuj because it had been constructed with timber lacing, a traditional form of construction that was common in Ahmedabad, rather than in Bhuj, were it was not. This had been done because the Bhuj temple was a branch of the sect that was based in Ahmedabad, so its building followed the Ahmedabad construction technology.

Figure 4. **left**: Total destruction of rubble stone and concrete buildings the city of Bhuj after the 2001 earthquake. **right**: Swaminarayan Temple complex in Bhuj after the earthquake.

The lack of damage to the Swaminarayan building in comparison to most of the rest of the city of Bhuj provided further evidence that such details can make a critical difference. However, it leaves unanswered the question of how to quantify that difference, and does not offer an objective measure of such buildings against a threshold for acceptable seismic performance in the modern world.[2]

Each new earthquake raises the question of whether these forms of traditional construction would be suitable for *new buildings*. Engineers reasonably assert that there is not enough scientific data to establish building standards under which to approve such construction for new buildings. However, already from well before the Bhuj earthquake some incomplete elements of the timber-laced bearing wall masonry construction and timber frame and masonry infill construction had been included in the Indian National building code for rural non-engineered masonry construction. These code provisions were essentially rules of thumb rather than calculation-based proscriptive requirements, but as Professor Anand Arya, one of the principal authors of the code, explained, they were influenced by his knowledge of the construction methods found in Kashmir. However, including these provisions in the Indian code did not mean that such construction would be embraced by government officials and international non-governmental organizations for post-earthquake disaster new construction. That only begin to happen in the next earthquake, a short four years later, in Kashmir itself. (See Fig.13)

4 TIMBER-LACED CONSTRUCTION IN HISTORY

The origin of both types of timber-laced masonry systems is considered to be ancient times. The palaces at Knossos possessed timber lacing of both the horizontal and the infill frame variety.[3] dating timber-laced masonry construction back to as early as 1500 to 2000 B. C. Evidence of infill-frame construction in ancient Rome emerged when archaeologists dug up the port town of Herculaneum that had been buried in a hot pyroclastic flow from Mount Vesuvius in 79 A. D., uncovering an entire two story half-timber house and interior walls in other houses considered to be examples of what Vitruvius has called *Opus Craticium*. After the fall of Rome, infill-frame construction became widespread throughout Europe, and timber-with-brick-infill vernacular construction first appeared in Turkey as early as the eighth century.[4]

The question of whether timber-laced masonry construction evolved in response to the earthquake risk is an interesting one, but earthquakes are infrequent and there were other compelling economic and cultural reasons for the evolution of these systems. For example, many variations of timber frame with masonry infill construction exist in areas outside of the earthquake regions of the world, including Europe - where in Britain it is called “half-timber,” in France *colombage*, and in Germany *Fachwerk*. In Madrid this construction is hidden behind solid masonry facades in most of the 18th and 19th century buildings around the Plaza Major.[5] In non-earthquake areas of the United States, the masonry infill version derived from French *colombage* can be found in New Orleans and other historic French settlements on the Mississippi, and, derived from the German *Fachwerk*, in parts of Pennsylvania.[6] The recent earthquake revealed that *colombage* is also common in Haiti.

In earthquake-prone areas of Central America, Spanish construction was combined with native methods in what is today called *taquezal* or *bahareque*. In South America, a form of traditional construction in seismically active Peru is known as quincha, consisting of earthen plaster on sticks or reeds (wattle and daub). This system is thought to have predated the Spanish conquest, after which it was adopted by the Spanish and remaining in use almost until the present.

Wattle and daub was also common in Britain, where earthquakes are rare, and it also exists in earthquake-prone Turkey, where it is called *Bagdadi*. Turkey is also important for *hımış*, a masonry infill-frame construction which performed well in comparison to the reinforced concrete buildings in the 1999 earthquakes, as described below. It may have been the spreading influence of the Ottoman Empire along trade routes into Mogul India (1526-1857) established centuries before during the first and second Persian Empires before and after the conquests by Alexander the Great, that carried some of these construction traditions east into the Indian subcontinent, including Kashmir and in the historic center of the Mogul city of Ahmedabad, but not in nearby Bhuj, which historically was a Rajput princely state.

5 HAITI

The earthquake of January 12, 2010 in Haiti shocked the world. It is believed to have killed as many as 300,000 people, which if true would make it one of three earthquakes causing the largest loss of life since 1556, when 830,000 people are reported to have been killed in Shaanxi, China. At the very least, it is in the same order of magnitude with the largest earthquake-caused loss of life in the 20th Century – the 1976 Tangshan earthquake in China which resulted in 240,000 deaths.

The Haiti earthquake is a watershed event, with a death toll from collapsing buildings ten times higher than in most prior earthquakes. The photographs on the news showed vast devastation and heart-wrenching scenes of piles of dead bodies in the streets, with both modern and historic buildings reportedly destroyed. The 1920 National Palace with its three collapsed domes became the iconic image of the disaster.

Several engineering surveys have documented the usual suspects – a lack of building codes, no enforcement, poor design, and bad construction. Almost all have focused on the reinforced concrete and concrete block construction, which is now the predominant form of construction for new buildings. Very little information on the performance of masonry other than concrete block masonry has been disseminated, yet until the advent of concrete frame and infill construction, this was a predominant form of construction in Haiti for urban and inner suburban buildings.

5.1. *Pan-de-bois* in the Haiti earthquake

An interesting and somewhat surprising feature in Haiti is that in the Gingerbread District, and also in Jacmel, there are buildings with *colombage* construction, which locally is called by its other French term, *pan-de-bois*. This was reportedly a 19th century French stylistic import of a medieval architectural form found most often in Normandy.

Figure 5. The three photos on the left show *pan-de-bois* houses in Haiti. The left view shows brick infilling, the middle, with stucco over rubble stone, and the right shows a house that was heavily eaten by termites, yet which survived. The interior timber cladding is visible where the infill stone has fallen. The right hand view shows medieval *pan-de-bois* houses in Paris with their steeply gabled roofs.

The masonry infilling used in the *pan-de-bois* was either fired brick or hollow clay tile, or the same kind of rubble stonework with clay mortar used in the bearing wall masonry buildings described below. The question of whether the Haitian version would exhibit the resistance characteristics of its Kashmiri or Turkish cousin is complex. Clearly, the *pan-de-bois* buildings survived the earthquake much better than did the buildings with the rubble stone masonry. Those with the *pan-de-bois* on the 2nd floor with bearing wall masonry on the ground floor were often left with the pan-de-bois floor almost perfectly intact atop the heavily damaged brick and rubble masonry walls of the floor below.

The Haitian *pan-de-bois* is different from the Kashmiri and Turkish examples in a crucial way – the interior walls are clad with sawn wood boards in all but a very few instances. These boards make the building almost into an all-wood structure, with the brick or stone infilling simply an architectural feature. There is, however, clear evidence that the masonry infilling did have a beneficial effect by helping to damp out the earthquake excitations, and thus help prevent the collapse of those timber structures – and there were many – that had been so heavily eaten by termites that much of the wood structure had been compromised.

5.2. Unreinforced masonry in the Haiti earthquake

The traditional bearing-wall masonry in Haiti can be divided into two categories – brick masonry and rubble stone masonry. Both are laid in a lime-rich mud mortar. It appears that generally the lime was not generated from hydrated quicklime, but directly from quarried beds of unconsolidated lime. Thus it did not have setting properties when used as an ingredient in the masonry mortar. Further study is needed to determine if hydrated lime was used in some of the buildings.

The most significant problem for many of the masonry buildings was that the two types – brick and rubble stone – were used together in almost all the masonry buildings. As a variant on the European practice of placing rubble in between two wythes of brick to form a wall, in Haiti the rubble stone was empanelled between brick piers that surrounded the windows, doors and corners of the buildings. The extensive damage and collapse of a significant number of the historic masonry buildings can be attributed to the extremely low strength and rapid degradation of these rubble stone panels.

Visual and initial acid testing suggests that the stone used for the rubble masonry in the Gingerbread Houses is made from calcareous deposits. What has turned out to be both interesting and problematic in the Port-au-Prince houses is that this stone is uniformly extremely weak. Indeed, it is difficult to even characterize it as stone because it has less strength than a good clay mortar. This supports a hypothesis, yet to be proven by scientific testing, that the stone when quarried was originally much harder and stronger, but that after it was removed from its natural bedding in the hillside and used in the construction it lost its strength from exposure to the atmosphere and loss of the overburden weight. This may be because it was geologically too young to have yet completely consolidated into natural rock before it was quarried, which would account for the almost uniform weakness of the stones used in this rubble masonry work regardless of their exposure or distance from the ground. By comparison, the stones in the rubble work in Léogane and Jacmel are much harder because those locations had access to igneous rocks, not just weak limestone.

Figure 6. **left**: masonry wall in Port-au-Prince after the earthquake showing the typical Haitian construction with brick surrounding panels of rubble stone. **middle**: The Villa Castel Fleuri, a mansion in the Gingerbread District of Port-au-Prince after the earthquake. **right**: Interior of Villa Castel Fleuri showing partial collapse of a rubble masonry panel between the brick piers.

These infill panels were often crossed at one-meter levels with two courses of brick on the inside and outside faces of the wall. These brick courses crossing the rubble masonry panel may have been intended to serve as crack-stoppers, to help with stabilizing and confining the rubble stonework. This use of brick courses in rubble stone walls continues a building tradition that can be found in many other places, in ancient Rome and Medieval and Renaissance construction,, and in Haiti is probably a carryover from French medieval and early Renaissance masonry construction practices. Unfortunately, several examples showed that the brick courses were not bonded through the wall, but were extended only across the inside and outside surfaces.(Fig. 6)

5.3. The brick masonry Hotel Oloffson

An important point of comparison is the Hotel Oloffson (Fig. 7), which had been constructed as a private home at the end of the 19th century. This building is unique among the masonry Gingerbread houses because it was constructed of unreinforced load bearing masonry, but without the rubble stone panels. The masonry was laid in a Flemish bond. The walls appear to have been laid up in brick all the way through, and of similar thickness (about 20 inches or 50cm) as in other buildings, and the building is constructed on an upslope site with two stories plus a full height basement in front. Thus, the loads were by comparison higher than for the many smaller Gingerbread houses with only one story masonry walls overtopped with timber framed second stories.

Figure 7. **left**:: First story front wall of the Hotel Oloffson after the earthquake showing the undamaged masonry wall penetrated by many doors. **right**: A section of the exterior wall of the Hotel Oloffson. Most of the walls are hidden behind wide porches, but this section shows the brick construction.

This building stands as an icon in Port-au-Prince because it suffered almost no damage during the earthquake, and the hotel has remained open since the earthquake. The hairline cracks seen on the second floor are too small to show in any but high resolution close-up photographs, despite the fact that two of the total of seven piers between the windows, including the corners of the building on the rear of the building, had been removed to form large floor to ceiling openings to expand the public room into the rear yard of the building. To allay any suspicion that the site was uniquely quiet during the earthquake, behind the Oloffson was a multi-story concrete hotel building that collapsed completely, providing evidence of considerable shaking at the site. Its survival in an almost undamaged state provides a good data point showing that the much greater damage to many of the other masonry buildings was largely a result of the unique weakness and vulnerability of the rubble masonry panels. It also conspicuously shows that the vast numbers of newer reinforced concrete infill wall buildings that collapsed were way below the onset of damage to unreinforced brick masonry.

This is consistent with the findings of a number of the scientists and engineers who have surveyed Haiti, who, despite the lack of local instrumentation, have concluded that the earthquake shaking was not as violent as first thought. Instead, the earthquake is characterized by the fact that an unusually large number of buildings proved to be particularly vulnerable – more vulnerable than a 110 year old masonry building, and also more vulnerable than many of the most rudimentary occupant-built confined masonry block squatter housing that is ubiquitous in Haiti.

5.4. Brick with rubble stone Gingerbread houses

While the damage to some of the bearing wall masonry buildings was severe, few of the masonry houses actually collapsed. By rough estimate approximately 5% to 10% of the brick and rubble stone masonry houses suffered substantial or total collapse. A survey of the Pictometry oblique aerial imagery revealed about 50 collapsed houses out of a total of approximately 800 Gingerbread houses, and about 35 to 40 of the collapses show evidence of being of masonry construction. Approximately half of the 800 were of masonry.

The reason that the severely damaged buildings did not collapse was a rare phenomenon. Unlike the more usual behavior of masonry construction in earthquakes which more often tends to fall apart from the top of a building where there is no overburden weight, the low shear strength of the walls with the rubble stone caused buildings to degrade across the bottom first where the overburden weight was greatest. This then isolated the upper stories from further damage. Because of the combination of rubble stone with brick as a series of panels surrounded by brick piers, the working of the structure caused by the earthquake vibrations resulted in rubble collapsing from between the piers, leaving some buildings standing on the piers as a series of legs. It is clear that some of the buildings may have swayed considerably while the earthquake was ongoing after the infill panels degraded. The breaking of the rubble undoubtedly served to dissipate a lot of energy, and thus may have ultimately saved the structures from collapse, even though the weakness of this material made for an extremely low threshold for the onset of significant damage.

5.5. Iron chains:

One very important asset found in many of the masonry buildings in the Gingerbread district is that walls were tied together with iron or steel rods at the floor and roof levels. These rods were hooked together to form chains and laid into the masonry walls, with ornamental plates at either end in the form of a star or something resembling a double ended fleur-de-lis. They were installed as rings around the buildings, and sometimes across the interior masonry walls at the floor levels. There is considerable evidence that these proved very effective at preventing the collapse of many of the masonry walls. This observation is supported by examples where the plates were missing, having failed from rust, or not installed when the building was built. In comparison to those buildings where they were present, their absence was associated with a greater amount of damage and disruption of the masonry.(Fig. 8)

Figure 8. 2nd storey wall of a masonry house showing the iron brackets that connect the through wall steel ties that form a continuous ring around the house. The left view shows the wall deflected outward because the plate was missing on the wall around the corner, whereas the view of right hand end of the same wall shows no visible damage because the plate was still attached and thus effective in preventing the spreading.

5.6. The lessons from the Haiti earthquake

The damage to historic masonry buildings in Haiti suggests insights on the larger question of what led to the profoundly high casualties in the newer buildings. Except for the Hotel Oloffson, it was apparent that the historic masonry construction with the rubble stone in the walls in Port-au-Prince was profoundly weak and vulnerable to earthquake damage. Thus, by conventional wisdom, these buildings should have done worse than those of reinforced concrete. However, they proved more resilient than many, but not all, of the concrete buildings. Even more interesting is that on average, if one does not include houses destroyed from landslides, a larger percentage of the larger multi-story buildings that were professionally designed and contractor built in Port-au-Prince collapsed than did those built of concrete in the squatter settlements.

As to why the death toll in Haiti was so profoundly higher than in an earthquake with a much higher energy output a few weeks later in Chile, Florida International University Department of Foreign Relations Professor Richard S. Olson is quoted on the Forbes Video Network as saying: “*This fundamental difference [between 1st and 3rd] "Worlds" goes a long way toward explaining why Haiti would have at least 200,000 people killed in a magnitude 7.0 earthquake, while Chile appears to have* *lost fewer than 500 killed in a magnitude 8.8."* [7] At the same time, the engineers and scientists who made a post-earthquake reconnaissance for the United States Geological Survey (USGS) and Earthquake Engineering Research Institute (EERI) stated: "*The severe damage to numerous buildings could have been avoided with greater attention to seismic performance."*

While it would seem that the second observation could be best explained by the first, neither of the observations address the fundamental problem with modern construction in Haiti – or for that matter, the many similar parts of the world where earthquake hazards underlie rapidly urbanizing poor communities. The problem is the almost exclusive reliance on reinforced concrete moment frame with masonry infill construction – a building type that is unusually dependent not only on seismic detailing but also highly competent construction for it to reach the most basic levels of life safety in earthquakes.

Figure 9. **left**: An example of vulnerable construction: earthquake collapsed reinforced concrete building, Port-au-Prince. **right**: An example of good construction: view of large open air gazebo at the Hotel Oloffson of reinforced concrete construction that survived the earthquake with nothing more than a few cracks in the pantry wing behind the photographer.

In downtown Port-au-Prince fully 36% of the commercial and industrial buildings were totally or partially collapsed, and an additional 15% were heavily damaged, but the number drops to 11% collapsed in the high density residential areas, which presumably includes the squatter settlements. This means that the remaining 64% in the downtown area and 89% in the high density residential areas were still standing.[8] While shocking, this level of damage is not even close to what has occurred in some other recent earthquakes – including the city of Bachau, in Gujarat in 2001 where almost 100% of the buildings had collapsed, or the city center of Bam, Iran, in 2003 where there were areas where one could look around a full 360 degrees and not see a single building still standing in its entirety, or the Pakistan Kashmir hilltop town of Balakot in 2005 which looked more like a Tsunami hit it rather than an earthquake.

Had this kind of construction been adopted in California for one hundred percent of all new urban construction - as it has been in Haiti - then an earthquake of similar magnitude there would probably cause a similar level of damage. The carnage would have been less only because the buildings in the USA are less crowded with people. Instead of concrete, 90% to 95% of all buildings in the US, (including California) are constructed of timber, which is both easier to build correctly and far more forgiving of mistakes in design and construction than concrete frames with masonry infill. With such a small percentage of the total of ongoing new construction being done in reinforced concrete, it is considerably easier to give the "greater attention to seismic performance" to that smaller more premium category of buildings, than would be true if this system encompassed 100% of all construction. This would even be more so if the cities were expanding as fast there as they have been in Haiti - and continue to be in much of the developing world.

Thus, it was mostly extreme variations in quality of reinforced concrete frame design and construction rather than particular construction typologies, that made a difference. The fact that 36% of these downtown commercial buildings collapsed compared to about 10% of masonry buildings with the weakest form of rubble stone should lead to a more fundamental change in approach to mitigation in rapidly developing cities in earthquake areas than simply saying that what is needed is a “greater attention to seismic performance” in building design. It is time to curtail the current near-total reliance on the current form of reinforced concrete frame with infill construction. In addressing this problem, it is masonry rather than concrete that may be the key.

6 REINFORCED CONCRETE AND STEEL FRAME CONSTRUCTION WITH MASONRY INFILL WALLS

With the rapid spread of reinforced concrete construction during the middle of the last century, the traditional vernacular has been displaced from all but the most remote rural regions in many parts of the world, within a single generation. This represented a transformation of the building process from an indigenous one to one more dependent on outside contractors, specialists, and nationally-based materials producers and suppliers of cement and cement block. Reinforced concrete has been introduced into a building construction process that continues to exist much as it did in the past. The system of local builders with a rudimentary knowledge of materials science was sufficient only as long as they were working with timber and masonry. With concrete moment frames, as demonstrated not only by the recent earthquake in Haiti, but also the ones in Pakistan, India, the Philippines, and China, it has proved woefully inadequate.

Concrete construction requires more than just good craftsmanship; it demands a basic understanding of the science of the material itself. However, builders were often inadequately trained to understand the seismic implications of faults in the construction, thus leaving a looming catastrophe hidden beneath the stucco that is troweled over the rock pockets and exposed rebars that are so common in construction done without the necessary equipment to do it properly, such as transit mix and vibrators. Bridging this knowledge gap in places like Haiti (which has a 55% illiteracy rate) is not something that can happen soon enough to avoid further tragedies.[9]

6.1. From the invention of the Skeleton Frame to the “Modern Movement”

Structural engineering has gone through its own revolution over the past century. The 19th century was an era of enormous ferment, producing engineering giants like Brunel and Eifel, along with Jenny and the other engineers of the first “skyscrapers.” In the first decades of the 20th century, buildings went from a height of 10 to 20 stories to over 100 stories. To accomplish this, engineering practice shifted from a largely empirical process working with masonry walled structures to one of rigorous mathematics, applicable almost exclusively to frames. Up until the middle of the last decade of the 19th century, structural calculations for the increasingly taller buildings consisted of the analysis of the frame for each floor separately. In order for the construction to conform to this approach, each frame had to be very rigidly braced, and constructed with a pin connection at each floor level. A more efficient way to design a multi-story frame came with the invention of a portal frame analysis method based on the contraflexure methodology of isolating moments in the mid-1990’s for the construction of what then became called “skyscrapers” in Chicago, and later New York City and San Francisco. This method was able to account for the value of the cantilever effects of beams and columns that run continuously from floor to floor and across the building as continuous members. This was both simple and accurate enough for it to have remained in use through the entire 20th century, up until the present for the design of most multi-story structures.[10]

Contraflecture portal frame analysis thus made a substantial reduction in the sizes of the members of a frame possible. However, the solid masonry exteriors of the first generation of skeleton frame “skyscrapers” did not change. The walls continued to be thick masonry, and although no longer load-bearing to the ground, these walls still shared significant loads with the internal steel frame, as well as protecting the frame from exposure to fire. Many historians of the early skyscraper era view the evolution of skeleton frame building design as one almost like that of a genie waiting to come out of the bottle – true transformation could only come when this traditional masonry envelope was shed, and the open frame itself made the basis for the architectural expression with flexible systems of open spaces and moveable walls. [11]

Figure 10. **left**: Flatiron Building in New York City under construction in 1902 showing the heavy stone masonry façade resting on the steel frame. The upper walls are constructed separately probably to ensure the weight is bearing on the frame rather than the lower masonry walls. *Credit: vazyvite.com*. **right**: View of San Francisco after the 1906 earthquake and fire. The three tall buildings visible in this view were burned out by the fire that followed the earthquake, but all three were in good enough condition despite this to be repaired, and they are still extant today. *Credit: Bancroft Library*.

The architectural precursor for the liberation of the skeleton frame ‘genie’ is often identified as Swiss architect Le Corbusier’s 1915 drawing of the prototype bare concrete skeleton for multi-story residences known as the Dom-Ino house. (Fig. 11) It became the icon of what he called the ‘New Architecture’. 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.”* [12]

From the Dom-Ino prototype, the reinforced concrete moment frame spread through Europe, and then the rest of the world, including earthquake hazard areas. However, the ‘dematerialisation’ of the walls clashed directly with the usual enclosure requirements of completed buildings. As a result, masonry did not disappear. Instead, the thick infill walls of the first skyscrapers evolved into thin, weak, and discontinuous membranes – after engineers had eliminated the infill masonry from their engineering calculations except as dead weight. This was believed at the time to be a conservative approach, however the rigid and brittle infill walls attracted increased earthquake forces which they were too weak to resist, yet, their weight added significantly to the lateral forces that had to be resisted by the frame. To make matters worse, they were still capable of interfering with the flexural movement of the structural frame on which the portal frame analysis was predicated. Compounding this problem was the frequent use of open ‘piloti’ on the ground floor as advocated by Le Corbusier, and later to satisfy city planners interested in providing off-street parking under the buildings, as in the case of Ahmedabad. In earthquake engineering parlance, this became known as a soft or weak storey, and this has become perhaps the single greatest threat to the safety of these buildings.

The almost universal acceptance of the concrete moment frame as a standard form of construction and of linear elastic portal frame analysis as the basic engineering approach, over a large part of the earthquake-prone parts of the globe fails to recognize the fact that most buildings are solid wall structures when the masonry walls are constructed within the frame. Nearly all of the codes and practices that underlie their design are based on their being modeled as moment frames with the infill masonry walls treated only as dead weight, rather than as an active part of the primary lateral-resisting structural system. The earthquake collapse of so many residential structures of reinforced concrete has shown the fundamental flaw with this approach.

Figure 11. **left**: Dom-Ino House by Le Corbusier, 1915. **middle**: Building under construction in Gölcük, Turkey shown after the 1999 earthquake. Because the masonry infill walls had not yet been installed, frame action was able to occur, and thus the building was not collapsed by the earthquake. **right**: Building in Gölcük close to the one shown in Fig. 17 collapsed by 1999 earthquake. The heavy masonry infill walls together with open (soft) ground floors were often contributors to such collapses.

This methodology of treating the masonry only as "architectural finishes" is also a product of the well-recognized fact that the infill masonry is very difficult to quantify mathematically and it certainly does not fit with portal frame analysis. Under wind loading, ignoring the effects of the infill rarely causes a failure because the value of the load sharing that occurs in reality between the frame and the infill can offset any unaccounted for behavior of the frame resulting from the infill. In a design-level earthquake, however, the situation is very different, because a building's structural system is expected to deflect into the nonlinear range. For frames, this has been recognized in codes through the use of ductility factors which are assigned based on the individual elements that make up a structural frame. Such factors, however, are unresponsive to the conditions that exist when non-structural infill masonry is added to the system, as this masonry is usually a stiff and brittle membrane confined and restrained by the frame. The rigid diagonal strut provided by the masonry changes the behavior of the frame, sometimes with catastrophic results. The standard linear-elastic analysis method for code-conforming design is thus remote from the actual inelastic behavior of the infilled frame for the structural engineer's calculations, so as to fully account for the effects of the forces on it.

7 LESSONS FROM *HIMIŞ* CONSTRUCTION — ARMATURE CROSSWALLS

Returning to the aftermath of the 1999 Kocaeli earthquake in Gölcük, one answer to this problem may lie hidden behind the heaps of rubble from the collapsed concrete apartment houses. As different as they are from their concrete cousins, the *hımış* houses that remained standing amongst the ruins also have masonry infill confined within a frame, and their survival has provided a source for one idea on how to keep reinforced concrete buildings from collapsing — a concept called "Armature Crosswalls." The Armature Crosswall concept is based on using the ancient infill-wall masonry technology for modern reinforced concrete construction. Instead of the existing method of constructing infill walls in reinforced concrete buildings totally out of hollow clay tile or brick, they are constructed with a sub-frame of studs and cross-pieces with the masonry infilling this sub-frame. The material chosen for these studs need not be limited to one type - it may be timber, steel, or concrete. The mortar for the masonry, however, is best if it is of low strength, rather than of high strength Portland cement. This is best accomplished by using a lime-based mix that is less strong, stiff, and brittle than ordinary cement mortar. [13]

Figure 12. **left**: Interior of a traditional house in Yuva, Turkey of after the 2000 Orta earthquake showing evidence of the working of the *hımış* walls. **middle**: Typical hollow clay tile masonry wall in a reinforced concrete apartment building in Gölcük, Turkey collapsed by the 1999 Kocaeli earthquake. **right**: Typical infill masonry wall found inside the upper stories of a four story building that suffered a soft story collapse during the 1986 San Salvador earthquake showing that the infill wall was subdivided with a concrete beam and column similar to that advocated for Armature Crosswalls. These sub-frames prevented the collapse of the ground floor from progressing to a complete pancake collapse, saving the lives of the occupants.

The intention behind the assembly of these elements is that the infill walls would have less initial stiffness and more frictional damping than standard infill masonry walls. The reduced initial stiffness can avoid the potentially destructive development of the “equivalent diagonal strut,” thus, allowing the frame-action to occur, on which the portal frame analysis is based. In addition, the energy dissipation from the working of the combination of timber, bricks and mortar against each other serves to dampen the excitation of the building by the earthquake. As demonstrated by the *hımış* buildings in the epicentral region of the 1999 earthquakes in Turkey, this working of the composite structure during an earthquake can continue for a long period before the degradation advances to a destructive level. This was not the case with the nearby reinforced concrete buildings. Interestingly, the same phenomenon can be observed with the bearing wall masonry buildings in Haiti, where the enframing brick piers and subdividing brick courses often prevented total collapse - even when the panels of rubble had completely crumbled.

Two fundamental questions are raised by this proposal: (1) why traditional buildings, with their seemingly weak and fragile construction, survive earthquakes that felled their newer counterparts, and (2) is it reasonable to expect that such a technology could be exported for use in multistory concrete buildings, which are often much heavier and larger than their traditional counterparts?

The answer to these questions lies in an understanding of phenomena that have been repeatedly observed in earthquakes. The subdivision of walls into many smaller panels with studs and horizontal members and the use of low-strength mortar has prevented the formation of large cracks that can lead to the collapse of an entire infill wall. As stresses on the individual masonry panels increase, shifting and cracking first begins along the interface between the panels and the sub-frame members before degradation of the masonry panels themselves. When the mortar is weaker than the masonry units, cracking occurs in the mortar joints, allowing the masonry units (which are held in place by the studs and cross-pieces) to remain in place and stable. The resulting mesh of hairline cracking produces many working interfaces, all of which allow the building to dissipate energy without experiencing a sudden drop-off in lateral resistance. By comparison, standard brittle masonry infill walls without the “armature” lose their strength soon after the initial development of diagonal tension X cracks and the separation of the infill wall panels from its surrounding frames, which can rapidly lead to their collapse, precipitating a progressive collapse of the building.

This difference in configuration, material strength, and system ductility (including the counter-intuitive fact that weaker mortar is likely to be better) explains why traditional infill-frame buildings are capable of surviving repeated major earthquakes that have felled modern reinforced concrete buildings. The basic structural principle is that there are no strong and rigid elements to attract the full lateral force of the earthquake. The buildings survive the earthquake by not fully engaging with it - in much the same way that a palm tree can survive a hurricane. Although the masonry and mortar is brittle the system displays ductile behavior. Ductility is not a quality normally used to describe the structural behavior of unfired brick masonry, however, what is being described here is ductile behaviour of a system, not of a single material. For example, Prof. Alkut Aytun credited the timber bond beams in unfired clay masonry walls in Turkey with *"incorporating ductility [in] to the adobe walls, substantially increasing their earthquake resistant qualities."* [14]

Even though reinforced concrete buildings are often much larger and taller, their performance with Armature Crosswalls is predicated on the same phenomenon observed by Prof. Aytun because larger residential buildings have more walls in each direction, in direct proportion to their size. Since the Armature Crosswall system is based on flexibility and on a reduction in initial stiffness compared to standard infill walls, the building's deflection in an earthquake is likely to engage all of the crosswalls parallel to its deflection in rapid succession. Because the initial cracking of each wall does not represent the loss of the ultimate strength of any given wall, the load shedding is interactive, with loads passed along from one wall to another and back again as the overall deflection increases, until all of the walls have been engaged relatively uniformly.

While this behavior in traditional construction during earthquakes may seem relatively easy to comprehend, few disaster recovery engineers or other experts have understood its significance when evaluating the performance of damaged timber and masonry vernacular buildings—with sad consequences in terms of the loss of cultural heritage. This failure has also seriously harmed relief efforts to provide safe and livable housing after earthquake disasters, by leading at times to the replacement or relocation of whole villages after earthquakes, which in turn brings about destruction of the social fabric of the communities as well as an extraordinary waste of resources. Many such new villages in Turkey and other countries have eventually been abandoned. [15]

All too often, cultural heritage takes an unnecessary hit in the post-earthquake inspection process, especially with vernacular cultural properties that are not officially recognized. Inspectors sent into areas after a disaster often have no training and even less sympathy for vernacular buildings and archaic construction simply because their training is remote from that which would be relevant to understanding of how such buildings can competently resist earthquakes. The existence of damage in these buildings is not necessarily reflective of a significant loss of ultimate structural capacity. Thus, the standards applicable to reinforced concrete, where a small crack can be indicative of a significant weakness, are often wrongly applied to archaic systems where even large cracks may not represent the same degree of degradation or future risk of collapse.

8 CONCLUSION

The assessment of existing buildings and the archaic structural systems used for non-engineered buildings reveals the basic difficulty of establishing a norm for earthquake safety and performance when "no damage" is not a viable objective. With earthquakes, however, it has been determined that requiring all buildings to remain within their elastic range for design-level earthquakes is economically infeasible for such a large but infrequent event and so, the codes have been drafted with reduced forces to be used for linear elastic analyses with ductility factors to account for the expected non-linear response. Thus, in this context it is difficult to properly recognize the post-elastic performance of archaic non-engineered structural systems constructed of materials that do not appear in the codes, and for which there are little or no codified test results.

This problem is not merely academic; rather, it is integrally connected to the longer-term issues of post-disaster recovery and regional development. Old ways of building that are based on an empirical wisdom passed down through the ages will probably defy most attempts to be rationalized into systems that can be calculated, but the evidence remains that some of these systems nevertheless have worked well even in large earthquakes. Because of this lack of set rules and methodologies for quantification, the evaluation of older structures after earthquakes can lead to broadly divergent views on the significance of particular damage and on the reparability of the structures, which inevitably has led to the unnecessary destruction of traditional houses and even whole city districts and rural villages – at tremendous social costs.

Modern construction materials and methods have brought with them extraordinary opportunities for new spaces, forms, and ways of building, and for lower-cost housing for great numbers of residents. But in many parts of the world they have also been disruptive of local culture, resulting in building forms and ways of building that are alien to the local society, even where promoted as safe and modern. Earthquakes have proven to be particularly unforgiving when the new ways of building are not well enough understood locally or carried out at an acceptably safe level of quality. Surprisingly, by learning from indigenous pre-modern examples of earthquake resistant technologies, we can also help preserve the surviving examples of these now seemingly ancient ways of building in ways that respect what these buildings are, not just how they look.

As the world moves from an era of profligate energy use to one where fossil fuels are gradually depleted, sustainability and “green” have become the catchwords in building design and construction. In this respect, wood is nature’s most versatile renewable building material, and stone and unfired earth, together with wood, represent the most energy efficient materials available. To this can be added fired brick and lime mortar, which require far less energy to manufacture than Portland cement. Thus, honoring traditional vernacular construction practices that have performed well against one of the strongest forces of nature can provide a lens through which one can see that the preservation of vernacular buildings represents far more than the saving of frozen artifacts. It is an opportunity for cultural regeneration — a reconnection with a way of building by people who traditionally had learned how to build successfully for themselves with materials readily at hand.

Figure 13. **left**: This is the only house to survive the 2005 Kashmir earthquake in the remote Pakistani village of Topi. It is of *dhajji* construction. **right**: Also in Topi, the owner (right) is standing next to his carpenter in the half-completed *dhajji* house he was building next to the ruins of the rubble stone house that collapsed in the earthquake seen on the right. He is using *dhajji* after seeing that the house on the left is the only one that survived. By proceeding with *dhajji* for his reconstruction, the owner was forgoing government disaster assistance which mandated using their reinforced concrete specifications. One year after the earthquake, shortly after this picture was taken, the government approved *dhajji* construction for as qualifying for disaster assistance. [16]

Now, in Haiti, some of the same people who were strong advocates for the acceptance of this and other types of indigenous earthquake resistant construction using sustainable materials and technology are leading the UN reconstruction effort.

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