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## **RECOVERING THE LOST 'MOMENT': HOW TIMBER-LACED MASONRY MAY HOLD THE SECRET TO STOPPING PANCAKE COLLAPSE OF CONCRETE MOMENT FRAMES**

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### **ABSTRACT**

This paper examines the effects of the 2005 Kashmir earthquake on traditional timber and masonry construction in the Pakistan and Indian parts of Kashmir and the Pakistan Khyber Pakhtunkhwa (KPK). The effects of this earthquake are then compared to other earthquakes that have affected similar types of construction, which have also demonstrated a high degree of resilience against collapse, especially when compared with buildings which lack the timber reinforcements within stone or brick masonry walls. Two types of construction are examined: bhatar which consists of timber ring beams within masonry bearing walls, and dhajji dewari which consists of a timber framework with panels with a single layer of brick nogging. It has been shown that certain counterintuitive features in these indigenous building systems can account for this result. A new system named Armature Crosswalls has been proposed which can adapt these features to work in moment frame reinforced concrete buildings. The paper concludes with another technical adaptation named Gabion Bands. This is intended for bearing-wall rubble stone masonry buildings with mud mortar. Gabion Bands are designed to enable the safe reconstruction of these houses with the rubble stone and mud mortar that are often the only locally available materials in villages located distant from roads.

### **KEYWORDS**

Dhajji Dewari; Bhatar; Taq; Traditional; Masonry; Moment Frame.

### **1. INTRODUCTION**

I begin this paper with a personal story of my second trip to Pakistan as part of a UNESCO reconnaissance team. This was not for an earthquake, but for the 2010 Indus River Valley Floods. When I described the 1900 to 2500 BCE Bronze Age urban settlement of Mohenjo-Daro for the UNESCO report after the Indus Valley site visits, I included some of what we found in modern-day agrarian villages surrounding this remarkable archeological site. In addition to farming and growing cattle, some of the villagers took advantage of their location on the alluvial plain of the Indus River to make pottery from the clay – using ancient time-honored design and craftsmanship to produce pots in our current era which have an uncanny resemblance to the prehistoric vessels which had been found in the archeological diggings now housed in the museum (**Figure 1**).



**Figure 1: Potter in village near Mohenjo-Daro**

For me, this experience brought the archeological site alive in a way that further archeological digging and more displays in the museum could only touch. The people, their tools and their crafts spoke volumes about the site and its past history. They were true representatives of the rural and agricultural population of modern Pakistan, yet they stood there as teachers to us of the ancient world and its civilizations and the continuity of human life away from cars, computers, and the plastic containers that fill grocery stores. Thus I felt it important to include these villages and the effects of the 2010 flooding on them in the UNESCO Report (This report was given to the Government of Pakistan, but has not been published online). This included a description of how their population may contribute to the conservation and interpretation of the larger site around the ruins of Mohenjo-Daro. My notes from the expedition record that the inclusion of this material “was the very thing that got Pir Aftab Hussain Shah Jilani (Minister of Culture) most enthusiastic during our meeting.”

Despite this endorsement, when I received what was to be the final draft of the document from UNESCO, I found that all of the references to these closely surrounding communities at Mohenjo-Daro with their traditional crafts and life-style had been deleted from the document. The explanation in an email from the UNESCO head of the mission was the following:

*“The proposal to include the villages as part of the experience of Moenjodaro – life like 3000-5000 years ago – is culturally very sensitive and we have to be very cautious about this – UNESCO could be highly criticized [sic] making such comparisons.”*

I mention this because this shows an interpretive boundary between conservation of an artifact of ancient (in this case pre-historic) human culture, and, in the deepest historical sense, the human culture in the present day to which these artifacts are connected.

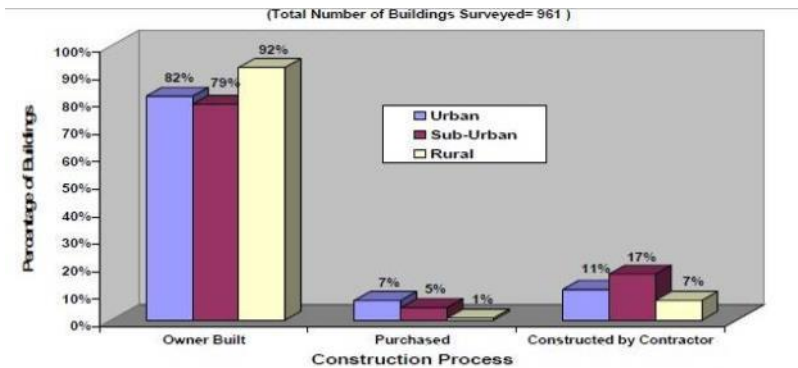


Figure courtesy: Building Inventory Survey under the SEDM (2000)

**Figure 2: Construction comparison between owner-built and contractor-built (courtesy of Dr Amod Dixit)**

## 2. TRADITIONAL CONSTRUCTION AS CULTURAL HERITAGE

What I describe in the rest of my paper comes from people like those whom I met in Mohenjo-Daro almost a decade ago, here in Pakistan. I did not learn about traditional construction at Harvard University, nor at the Institute of Advanced Architectural Studies in York, England, but rather in Kashmir on both sides of the Line of Control. I found it also in Turkey, Iran, Afghanistan, Nepal, Bhutan, and in Gujarat, India, and in Italy, Portugal, Mexico, Nicaragua, and El Salvador. My teachers were the masons and carpenters in these countries.

When I was invited to give lectures in Srinagar, in Ahmedabad, in Istanbul and in other heritage cities, my talks focused on the local traditional construction that I had found to exist in those very same places, but which I found was either disdained or unrecognized - particularly by the engineers and architects who lived there. In some of these places, for example, in Srinagar, students came up to me afterwards to tell me that I was the first to show them their own traditional construction in a positive light and convince them that it was resilient in earthquakes.

Indeed, when confronted with the evidence laid before me by earthquakes, I have come to realize that it is not enough to know how to design and calculate structures from lessons and codes written on the opposite side of the planet. We must learn from the affected people themselves how they build, before we can then turn around and teach them not only how to make their homes more resilient, but also to convince them to continue do that which they already know and have done well. We must encourage them to carry on those cultural traditions that have proven to be resilient in a recent earthquake, and to give these traditions the respect that they deserve.

This recommendation calls to mind the words written by the leading engineer of the team responsible for the drafting of the Nepal Building Code (DUDBC (2018) over 20 years earlier, Richard Sharpe of BECA in New Zealand. He stated in a Letter to the Editor of Bulletin of the New Zealand Society for Earthquake Engineering (Sharpe, 2016) that *“A year on [after the Gorkha earthquake of 2015], there are moves to revise the [Nepal] building code - perhaps to “international” levels seismically. A number of those who have called for such a lift appear to be ignorant of the rationale and careful consideration/consultation undertaken in the drafting of the Code. The level of design loads is, obviously, almost irrelevant if there is little compliance with the Code”* Mr. Sharpe’s comments were made because he understands the socio-economics of the country and its almost total reliance on owner-builders for almost all rural and much of the urban building construction in the country (**Figure 2**).

### 3. 2005 KASHMIR 7.6 M<sub>w</sub> EARTHQUAKE

The epicentre of October 2005 Kashmir earthquake was close to Muzaffarabad in the Pakistan portion of Kashmir (in Pakistan named *Azad Kashmir* (Free Kashmir)), where eighty thousand people died in both reinforced concrete (RC) buildings (including one modern high-rise residential complex in Islamabad), buildings of mixed concrete slab and block masonry walls, and unreinforced stone masonry buildings. It also affected India across the Line of Control, with approximately 2,000 fatalities (**Figure 3**).

There are two basic types of traditional construction with earthquake resistance capabilities found in Kashmir. One, of solid bearing-wall masonry with timber lacing, is known as *taq* and the other, a brick-nogged timber frame construction, is known as *dhajji-dewari* from the Persian words for patch quilt wall. In Pakistan, *dhajji dewari* is often referred to with only the single word, *dhajji*, (**Figure 4**) and *taq* is called *bhatar* (**Figure 5**). According to the structural engineering professors Durgesh Rai and Challa Murty (Rai and Murty 2005) of the Indian Institute of Technology-Kanpur:

*“In Kashmir, traditional timber-brick masonry (dhajji-dewari) construction consists of burnt clay bricks filling in a framework of timber to create a patchwork of masonry, which is confined in small panels by the surrounding timber elements. The resulting masonry is quite different from typical brick masonry and its performance in this earthquake has once again been shown to be superior with no or very little damage.”*

They cited the fact that “the timber studs ... resist progressive destruction of the ... wall ... and prevent propagation of diagonal shear cracks ... and out-of-plane failure.” They went on to suggest that: “there is an urgent need to revive these traditional masonry practices which have proven their ability to resist earthquake loads” (Durgesh and Murty, 2005).

My first trip to Pakistan was in 2006, one year following the Kashmir earthquake of 2005. We visited remote rural areas including two agrarian hamlets of Topi and Thub high in the foothills. Then we passed through the earthquake devastated towns of Muzaffarabad and Balakot to the Swat Valley in the Khyber Pakhtunkhwa (KPK). After a visit to the University of Engineering and Technology in Peshawar, we returned to Islamabad where UN-HABITAT had arranged for me to give a talk to Earthquake Reconstruction & Rehabilitation Authority (ERRA) and National Engineering Services Pakistan (NESPAC). ERRA had been established only 16 days after the October 8, 2005 Kashmir earthquake, while NESPAK was established in 1973 as a private limited liability company by the Government of Pakistan.



**Figure 3: Collapsed School, Uri, Indian Kashmir. Written on the blackboard before the earthquake, is “*Ramazan Mubarak*” (Blessed Ramadan), which now is all that remains.**



**Figure 4: *Dhajji* in Pakistan**



**Figure 5: *Bhatar* in Pakistan**

Within a week of this talk in Islamabad, ERRA and NESPAK approved *dhajji* construction as compliant for Government support, and the following year approved *bhatar*. Since those approvals, as reported by the International Federation of Red Cross and Red Crescent Societies, by 2009, at least 150,000 new homes had been constructed using one of these two traditional typologies in this region of northern Pakistan. The credit for the Government's acceptance of these traditional forms of construction belongs to generations of the rural farmers and home builders themselves. They taught both the *dhajji* and *bhatar* construction systems to me and my colleagues when we arrived for the first time after the earthquake. In fact, both of these traditional construction typologies had already been recognized by engineering professors in India by being included in the Indian building code for non-engineered construction as well as the Nepal Building Code, well before I began my own research. Even better than simply knowing these forms of construction was the fact that, in Topi and Thub, as well presumably in many other remote

villages, the citizens resurrected these forms of construction from their own past after the 2005 earthquake left such buildings standing, when the newer and more common unreinforced rubble stone buildings had collapsed across the region.

The people themselves had made a decision to rebuild with *dhajji dewari* or *bhatar* walls despite the fact that the Government had told them that they would have to build with RC or reinforced concrete block to get any government assistance, and it was their faces that appeared on the screen in my talk at ERRA. These self-motivated rural citizens provide a modern-day example of the characteristic empirical process that has affected the way building construction has evolved over many millennia, long before complex calculations have come to dominate engineering, which has evolved into a separate and distinct professional field. Teddy Boen, an expert on Non-engineered Buildings, working in Indonesia, wrote in 2008:

“It is not advisable for experts to try to "teach" local people, but instead they must try to absorb and understand the local wisdom regarding why it was done the way it is. Having understood the local way of thinking, experts must try to facilitate locals in among others making their houses earthquake resistant but without introducing abrupt changes or use new alien materials” (UNCRD, 2009).

Back in Pakistan in the rural village of Topi there was only one house of the older *dhajji* construction, but the more recent homes were all simply of unreinforced rubble stone. All of these newer URM homes had collapsed (**Figure 6**), but that one earlier *dhajji* home remained standing. During the year following the earthquake, it had provided a model for all the villagers to follow when setting out to reconstruct their homes.

On the road to the next village, called Thub, is a large 2 ½ story country store building of *dhajji* construction (**Figure 7**). This structure had remained almost completely intact, only losing a few infill panels, but in the village itself, a much more recent three story store structure of reinforced concrete suffered complete collapse of its ground floor (**Figure 8**). From what we observed, it was the only reinforced concrete structure, not only in this village, but in the whole larger area.



**Figure 6: New *dhajji* next to ruins of URM house**



**Figure 7: Large *dhajji* country store block on road to Thub**



**Figure 8: Collapsed RC country store in Thub**



**Figure 9: URM wall on left and bhatar wall on right after earthquake**



**Figures 10: Buildings of *bhatar* construction in Bahrain**

After passing through the devastated towns of Muzaffarabad and Balakot towards Besham and then over the mountains to Bahrain in the Swat Valley, we passed a settlement that had examples of *bhatar* construction not far from a partially collapsed building of reinforced concrete. One interconnected wall was particularly interesting in that the unreinforced portion of it was totally collapsed, and a very crudely constructed timber laced section of it with dry laid stonework was entirely intact (**Figure 9**).

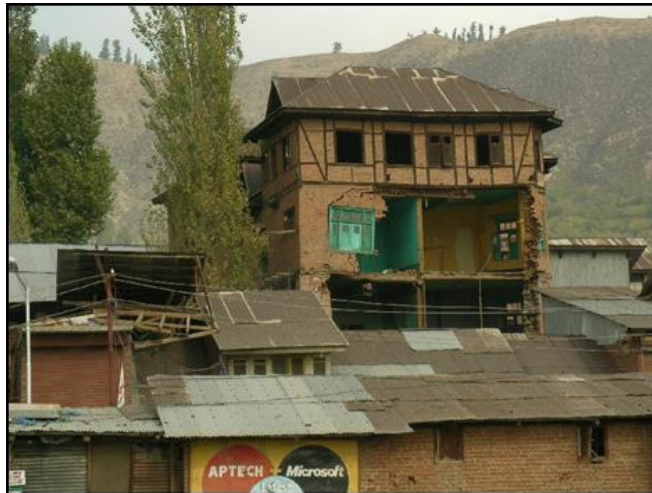
Proceeding to Bahrain in the Swat Valley, KPK, there were many structures of *bhatar* construction which had also stood up well in the earthquake (**Figures 10**).

#### **4. INDIAN KASHMIR AFTER THE 2005 EARTHQUAKE**

The trip to the hills of northern Pakistan was almost exactly a year following a trip to Indian Kashmir only two weeks after the 8<sup>th</sup> of October Kashmir earthquake. It was Srinagar, where I had been so impressed beginning in 1981 with its rich vernacular architecture, that I was stimulated to begin my research on structural aspects of *dhajji dewari* and *taq/bhatar*. The 2005 earthquake and this earlier research led to the publication by UNESCO of my book, *Don't Tear It Down! Preserving the Earthquake Resistant Vernacular Construction of Kashmir* (Langenbach, 2009).

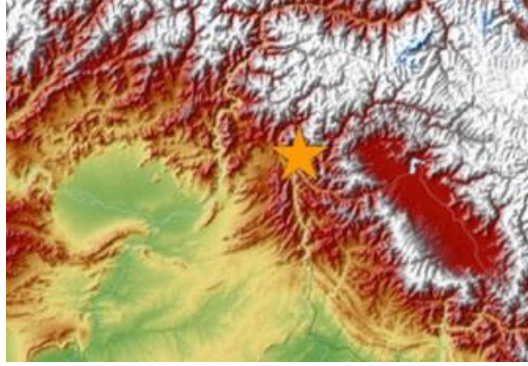


**Figure 11: Collapsed School, Uri**



**Figure 12: *Dhajji dewari* top floor showing ability of *dhajji* to span the wide gap left by collapse of unreinforced brick wall below in Baramulla**

By coincidence, I happened to be in Delhi at the time of the earthquake for the “8<sup>th</sup> Convention on Construction,” and thus was able to fly to Srinagar on the 24<sup>th</sup> of October, only 16 days after the earthquake. Of course the damage was much less than nearer the epicenter in Pakistan, but my reconnaissance of Indian Kashmir took me not only to Srinagar, but also nearer the border with Pakistan, where in Uri there were many collapses (**Figure 11**) and extensive damage in Baramulla (**Figure 12**). Before describing the earthquake damage, it is important to mention how the prehistoric geography has defined the building construction in this region of both India and Pakistan (**Figure 13**). The area around Srinagar is a giant alluvial basin of what had once been a land-locked lake surrounded by the mountains (**Figure 14**). Interestingly, this area is higher in elevation than is the mountain landscape of Pakistan Kashmir (**Figure 15**). At 5,200 ft, Srinagar is more than twice the elevation of Muzaffarabad, which is at 2,400 ft.



**Figure 13: Geography of Indian and Pakistan Kashmir. The large red area between snow covered peaks is the Vale of Kashmir. The star is the EQ epicenter**



**Figure 14: The setting sun on Dal Lake near Srinagar**



**Figure 15: River and mountains of Kashmir near Muzaffarabad**

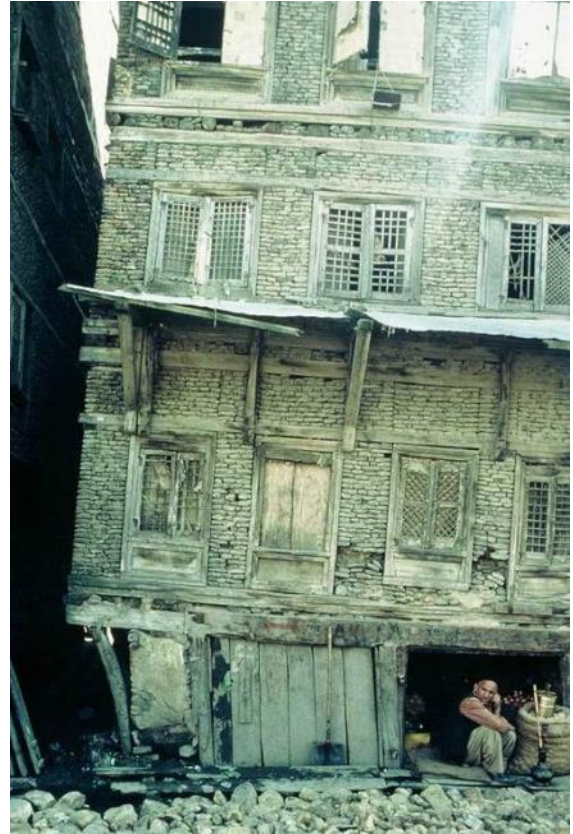
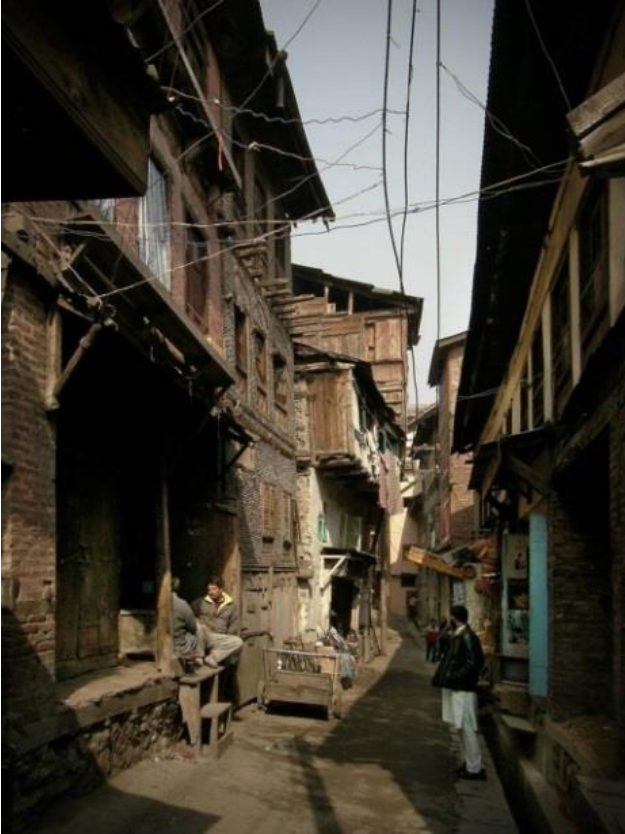
The deep alluvium of the pre-historic lake bed that surrounds Srinagar provides the principle masonry building material in the region around Srinagar - a unique handmade fired brick known as “Maharaja Brick.” In the lower elevations of Pakistan Kashmir and in the Swat Valley, the locally available material is stone, which unfortunately is often a rounded river stone rather than freshly quarried rock.

As will be shown, despite this significant difference in masonry materials, there are some remarkable continuities to be found when comparing the traditional construction practices across this geographic region. This is easily explained by the fact that, until the creation of India and Pakistan as separate countries after British withdrawal from India, and the concurrent demise of what had been the princely state of Jammu and Kashmir under the British Empire ruled by a Hindu Rajput prince, this region had been one continuous mountain state without a fortified border. The last prince, Maharaja Hari Singh, attempted to remain independent with friendly relations with both countries, but this noble effort eventually failed with the unfortunate result that this historic and remarkably beautiful mountain kingdom has been plagued by civil conflict that continues to this day.

Almost forty of the eighty years of this divided state’s history have now passed since my first arrival in Indian Kashmir in 1981 – a time when Srinagar resembled an historic and picturesque medieval city (**Figures 16** and **17**). My research on the subject of the question of comparative vulnerability and resilience of traditional masonry construction with and without timber lacing began during that first visit to Srinagar. In the decade to follow, it was only written reports by traveling British authors after an earthquake in 1885 that affected Srinagar that provided observations of the resilience of Srinagar’s traditional *dhajji dewari* and what is now referred to as *taq* construction. Note that while the term *dhajji dewari* has long been in use to describe timber frame with infill masonry construction, the term *taq* it turned out became used to identify timber laced masonry bearing wall construction after I had been told the term by a young Kashmiri architect – but I later learned that *taq* was an architectural term describing how many window bays such a masonry house had. When I prepared the book *Don’t Tear It Down!* (Langenbach, 2009) published by UNESCO in 2009, I was told by my Kashmiri colleagues that the term had now been adopted from my earlier publications, and it was best to keep it because there was no other term for describing its traditional timber-laced masonry construction.



**Figure 16: Rainiwari Canal, the only canal not filled in and turned into a road in central Srinagar**



**Figure 17: A typical lane in old Srinagar, not yet widened into a motor vehicle road**

**Figure 18: An old formerly canal-side *taq* (*bhatar*) building in Srinagar with timber lacing. Notice that the windows do not line up one above the other, a structural feature only possible with the timber ring beams**

While the 19<sup>th</sup> century reports about the earthquake of 1885 give a strong proof of the resilience of the timber-laced bearing wall masonry and timber frame with infill (*dhajji dewari*) construction, they did not provide definitive evidence of the origins of the systems. The origin of these systems is actually most likely not for earthquake resilience, as earthquakes are themselves quite rare, with time between them exceeding the life-span of the people who would carry the memories. It is most likely a product of the location of Srinagar and surrounding villages on the water-laden alluvial soil of the Vale of Kashmir. Absent the ring-beams of timber in *taq* connected together with what has become known as “Kashmiri” scarf joints along the walls and notched timbers at the corners (**Figure 18**, or absent the *dhajji* framework (**Figure 19**), the buildings would simply split apart from differential settlement in much the same way as seen in **Figure 20** taken in Kathmandu Nepal which is also located in an alluvial basin.

One must ask why one can find *dhajji* and *bhatar* construction on the Pakistan side of the Line of Control in the mountain regions where the ground is firm and the masonry building material is stone, not fired or unfired brick? This is a more difficult question to answer definitively. Earthquakes may have had something to do with it just as we have witnessed after the 2005 quake in Topi and Thub, but at the same time, such traditional timber reinforced construction may be a product of the practicality, when trees were plentiful, of using cut timber to reduce the amount of the more time consuming masonry construction work including the lifting of such heavy stones. This is particularly the case with *dhajji* timber frame

construction in which the walls are a thin single layer of stone, but also with *bhatar*, the timber ring beams reduce the wall thickness, and thus the weight of masonry that is needed for stability. This is especially true when *dhajji* is used for the upper stories of multi-story buildings, thus providing overburden weight on the masonry walls below, while the *dhajji* itself is well tied together.



**Figure 19: A dhajji dewari building in Srinagar**



**Figure 20: A similar sized building in Kathmandu, Nepal, showing effects of differential settlement without timber lacing causing the building to begin to split apart**



**Figure 21: the Bhuj branch of the Ahmedabad-based Swaminarayan Temple, the construction is of timber frame with masonry infill which was common in Ahmedabad, but rare in Bhuj, is located in the heart of the walled city of Bhuj, yet it survived almost undamaged, while the modern concrete pavilion seen on the right collapsed**



**Figure 22: A view within the historic walled city area of Bhuj after the 2001 Gujarat earthquake. Most of the historic buildings were of rubble stone masonry construction and the modern buildings were of reinforced concrete. The earthquake destroyed many of both types of construction**

In this way, the system resembles that found in Turkey, and further west in Greece, Hungary, Romania and other Eastern European countries. This also provides cultural evidence that it may have come into Kashmir through the spread of the influence of the Ottoman Empire into the Indian subcontinent during the Mogul Empire (1526-1857) with its connection with the Persian Empire. The Gujarat earthquake of 2001 has reinforced this hypothesis because it revealed a profound difference between the construction heritage found in the Mogul city of Ahmedabad (**Figure 21**) with that of the Hindu princely cities in western Gujarat and Kutch, such as Bhuj (**Figure 22**), where these construction systems were very rare. As a consequence, during the 2001 Gujarat earthquake, the destruction was much more extensive.

## 5. TIMBER-LACED MASONRY CONSTRUCTION IN HISTORY

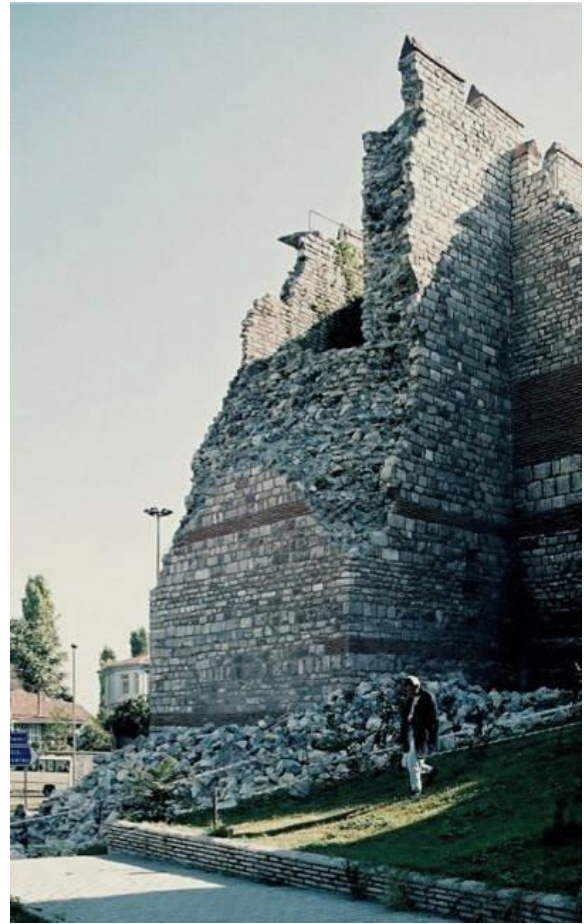
The question of whether timber-laced masonry construction evolved in response to the earthquake risk is difficult to answer, as there were other compelling economic and cultural reasons for the evolution of these systems. In addition to Kashmir's *dhajji dewari*, regional manifestations are called *colombage* in France, *fachwerk* in Germany, *hımsı* in Turkey, and *half-timber* in Britain, all of which are in areas of low earthquake risk. Variations that used earthen plaster and sticks or reeds (wattle and daub) include Turkish *Bağdadi* and Peruvian *quincha*. Despite the ephemeral nature of the material, 5,000 year old *quincha* construction has been unearthed at the Peruvian archeological site Caral. 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* (Langenbach, 2007).

When archeologists dug up the port town of Herculaneum that had been buried in a hot pyroclastic flow from Mount Vesuvius in 79AD, they found an entire two story half-timber house which was identified as one of the masonry construction typologies described by Vitruvius as “*Craticii*” or “*Opus Craticium*” (**Figure 23**). This example in Herculaneum may provide us with the only surviving example of the form of construction that had been used in ancient Rome for the seven or eight story tenements (*insulae*) that filled that city of a million and a half people. Masonry bearing walls would have been too thick at the base to fit on the known footprints of these ancient buildings with space for rooms left over, so it is likely that the Romans constructed many of these tall buildings with timber frames and infill masonry (Langenbach, 2007).

Laced-bearing wall construction may have had its origins in ancient times as well. This kind of construction can be found in the 5th Century AD Theodosian city walls of Istanbul, where the belts of red brick are an integral part of the architecture (**Figure 24**). Modern restorers reconstructing a portion of the walls mistakenly treated this only as an architectural element by applying a brick band as thin layer on the surface, rather than as a structural layer extending through the masonry. When the 1999 Kocaeli earthquake struck, this newly constructed section collapsed, while the surviving 1600-year-old heavily deteriorated portions of the wall were largely unaffected by the earthquake, despite the pre-existing damage (Langenbach, 2007) (**Figure 25**). It was this system of what I have called “crack-stopper” courses that evolved into the timber-laced system known as *hatil* in Turkey, which is similar to *taq* and *bhatar* described here.



**Figure 23: House of the Opus Craticium, Herculaneum, Italy**



**Figure 24: Unrestored section of the Theodosian City Walls of Constantinople showing brick courses extend into core of the wall**

**Figure 25: A modern reconstruction of a section of the city walls where the brick courses were only on surface**

After the fall of Rome, infill-frame construction became widespread throughout Europe. Timber-with-brick-infill vernacular construction is documented to have first appeared in Turkey as early as the eighth century. Thus, the adoption and continued use of this system until the present time was most likely the successful by-product of a technology developed as much for its economy as for its strength, rather than specifically because of earthquake risk.

## **6. KOCAELI EARTHQUAKE OF AUGUST 17, 1999**

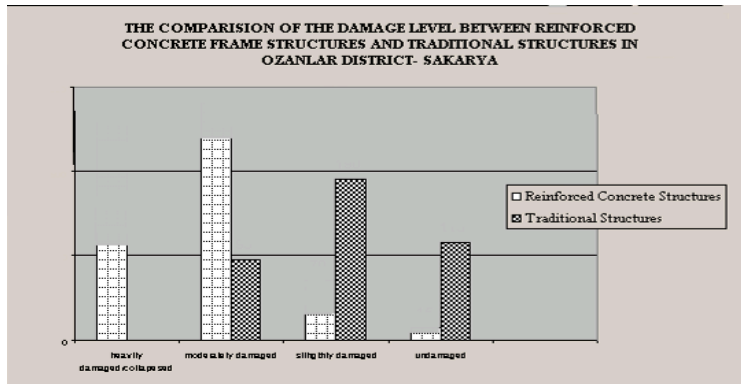
Moving east from Istanbul to those regions affected by the 1999 Kocaeli and Düzce earthquakes, most of the settlements were industrial towns developed mainly in the 20th century. The Kocaeli earthquake of August 17, 1999 killed approximately thirty thousand people. The epicenter was just 200 kilometers east of Istanbul. In some areas of Gölcük and Adapazari, the earthquake destroyed more than a third of all housing units, almost all of them in reinforced concrete buildings (Kandilli Earthquake Research Institute, 2000). While the laced bearing wall type was rare, there were clusters of *hımsı* (which is the Turkish word

for *dhajji*) buildings in the heart of these districts. The houses were constructed of *humiş* from the ground up. These houses, mostly dating from the early part of the twentieth century, often only pre-dated the ruined reinforced-concrete apartment blocks nearby by a few years. Most of these older *humiş* houses remained intact, with only a few heavily damaged, with damage almost always a result of wood rot, or badly done alterations (Figure 26).

This finding was confirmed by researchers who conducted a detailed statistical study in several areas of the damage district. They found a wide difference in the percentage of modern reinforced concrete buildings that collapsed, compared to those of traditional construction. Gülhan and Güney documented that in one district in the hills above Gölcük, of the 814 reinforced-concrete four-to-seven-story structures, 60 collapsed or were heavily damaged, while only 4 of the 789 two-to-three-story traditional structures collapsed or were heavily damaged. The reinforced-concrete buildings accounted for 287 deaths compared to only 3 in the traditional structures. In the heart of the damage district in Adapazari, where the soil was poorer, research shows that, of the 930 reinforced concrete structures, 257 collapsed or were heavily damaged and 558 were moderately damaged, while none of the 400 traditional structures collapsed or were heavily damaged and 95 were moderately damaged (Figure 27) (Gülhan and Güney, 2000).



**Figure 26: Formerly 4 story RC building next to dhajji building with very little damage from 1999 earthquake. (reproduced with permission from Adem Doğangün (Doğangün et al., 2006))**



**Figure 27: Comparison by Gülhan and Güney of damage to RC buildings with traditional timber and masonry buildings of all types**



**Figure 28: Margalla Towers, Islamabad (courtesy of Express Tribune)**

## 7. REINFORCED CONCRETE MOMENT FRAMES

Returning to Pakistan, while there were a very large number of fatalities in the 2005 earthquake, the effort to distinguish the body count in reinforced concrete buildings is complicated by the fact that so many buildings were of mixed construction with concrete block masonry together with reinforced concrete slabs for floors and roofs. Whereas in Turkey, the 1999 earthquake affected a highly urbanized area with large numbers of multi-story concrete buildings, the one iconic modern multi-story reinforced concrete building complex to experience a pancake collapse in Pakistan was one part of the Margalla Towers complex in Islamabad (**Figure 28**). Both of the small cities of Muzaffarabad and Balakot were almost totally destroyed, with many buildings of reinforced concrete structural frames having collapsed (**Figure 29**).

At the 13th World Conference on Earthquake Engineering in August, 2004, Fouad Bendimerad, Director of the Earthquakes and Megacities Initiative said that roughly 80% of the people at risk of losing their lives in earthquakes in the world today are subjected to risk from collapse of reinforced concrete frame with masonry infill buildings. This is a remarkable statistic because such buildings are entirely of recent origin, and often considered safer than the masonry buildings they replace. As we can see from the statistics in Turkey and other recent earthquakes, there is a pattern emerging where the promised strength and resilience of reinforced concrete has often been found to be less than expected.



**Figure 29: This is a remarkable photo taken in Balakot of an open air prayer meeting on the floor slab of the collapsed main Balakot mosque. Every building in the city was reported to have been destroyed, but the strength of this reinforced concrete floor slab to hold this many worshippers is amazing (courtesy IIEES)**



**Figure 30: 5+ story RC moment frame building under construction in Kabul, Afghanistan**

**Figure 31: 10 story moment frame building under construction in Karachi showing infill masonry (cement block) finished up to the 7th floor**

There is a discrepancy between the current state of earthquake engineering knowledge and the actual performance of many contemporary buildings. The myth that this construction is earthquake-safe is gradually declining from a promise to that of folklore, yet even after the 2015 Gorkha earthquake in Nepal one hears people saying they wish to have a pillar building by which they mean a building with a concrete frame. In India, the term *pucca* building refers to a ‘strong’ building. It is used in comparison to a *katcha* building meaning a ‘weak’ and insubstantial building. *Pucca* is reinforced concrete that is thought to be strong, and *katcha* is weak, which now means timber and masonry or mud brick construction.

In 2011, having found the opposite to be the case in regards to earthquake risks, I entitled my talk at the World Bank in Washington DC: *Katcha is Pucca & Pucca is Katcha*. This was to highlight my findings from the decades of my research that began as an effort to find what I hoped would be at least a minimum level of earthquake safety in the traditional construction so that I could argue in favor of preserving the buildings without that effort being defeated by earthquake safety efforts. Little did I then expect to find the situation now, after several earthquakes in different countries, where these traditional buildings have

out-performed what were believed to be the safer and more modern reinforced concrete alternatives. This comes at a time when concrete construction dominates the market throughout most earthquake hazard zones around the entire planet (**Figures 30 and 31**), except where construction quality timber is widely available – which includes the United States and Canada, and parts of Turkey, Eastern Europe and Russia. It also, quite fortunately, includes parts of Indian and Pakistan Kashmir.

The problem with concrete construction is not the concrete, if it is properly mixed, placed and cured correctly. If this were so, then the Pantheon in Rome – a 2,000 year-old-building – would not be standing today. However, had it been reinforced with steel, it would not have lasted for two millennia. The corrosion of steel reinforcing is definitely a problem and in future years it will become more of a problem, as the rusting of the steel reinforcing has proven to shorten the lifespan of buildings to only decades or at most a century in the modern era. This was evident, for example, in Haiti where both the National Palace and the Cathedral collapsed in the 2010 earthquake because the steel reinforcing had largely rusted away.

However, the risk presented by the corrosion of steel reinforcing is a subject for another paper. The other RC building failures in Haiti, in Turkey and in other recent earthquakes around the world, including that in Pakistan, were not from rust, but from structural failure. If one steps back and looks at these collapses as group, rather than individually, a pattern begins to emerge. This pattern brings one to what turns out to be the most significant revolutionary change that has occurred, not only in building construction technology, but also in structural engineering (Langenbach, 2012; 2013).

## **8. FROM WALLS TO FRAMES**

Structural engineering has gone through a revolution over the past century. The 19th century was an era of enormous ferment, producing engineering giants like Brunel and Eiffel, along with William Le Baron Jenney and the other engineers of the first skeleton frame iron and steel highrise buildings in Chicago, New York City, and San Francisco. In the first decades of the 20th century buildings what became known as skyscrapers went from a height of 10 to 20 stories to over 100 stories. This achievement required a shift in engineering practice from a largely empirical process to one of rigorous mathematics.

The teaching and practice of the structural engineering of buildings moved away from the design of solid wall structures with post and beam interiors to the analysis and design of frames. To fully understand the implications of this change, we must first isolate what is meant by the term “frame” in structural engineering in order to distinguish between a framework of columns with simply supported beams and a moment frame where the beams and columns are interconnected sufficiently to allow the frame alone to resist lateral forces as well as to carry loads to the ground. Until the nineteenth century, frame structures and the internal framework of buildings were most often made of timber, with the lateral forces resisted by masonry walls acting in shear and/or by braces within the heavy timber framework.

The advent of steel and steel reinforced concrete has allowed for the creation of moment frames. These no longer need to rely on braces or masonry shear walls. In terms of engineering practice, the linear-elastic portal frame analysis of such structures has come to define most of the day-to-day professional engineering work for multi-story buildings. Moment frames provide lateral resistance by both shear and flexure of the framing members. Their lateral capacity is primarily determined by the strength and ductility of the joints between the beams and the columns. The enclosure and partition walls that turn this open framework into a useable building are routinely ignored in the structural calculations except as dead weight. The advantage of this approach is that it has allowed for a coherent mathematics-based engineering approach to building design by separating the infinite complexity of a finished building with all of its parts from that of the primary structural system – the frame.

An interesting fact about the historical development of the modern skeleton frame construction and portal frame analysis at the late 19<sup>th</sup> and early 20<sup>th</sup> centuries is that thick masonry infill and cladding was very much an accepted part of the early iron, and then steel and reinforced concrete buildings, even though it was then, as now, not considered in the engineering calculations for lateral resistance (**Figure 32**). This is made clear by the author of one of the first textbooks on the subject of skeleton frame construction (Freitag, 1901)

*“‘Skeleton Construction’ ... suggests a skeleton or simple framework of beams and columns, dependent largely for its efficiency upon the exterior and interior [masonry] walls and partitions which serve to brace the structure, and which render the skeleton efficient, much as the muscles and covering of the human skeleton...make possible the effective service of the component bones....While the steel frame is more or less reinforced by the weight and stiffening effects of the [masonry infill], still no definite or even approximate values can be given to such items, except their purely static resistance or weight.”*

The 1906 earthquake in San Francisco put skeleton frame buildings – even some done by the same architects as those in Chicago – to the test. As it turned out, they passed that test remarkably well (**Figures 33** and **34**). Indeed, one must ask why these first generation steel skeleton skyscrapers in San Francisco remained standing with undamaged frames and repairable damage to the masonry walls, when so many frames with infill masonry buildings have been collapsed by earthquakes a century later. Even two of our most distinguished earthquake engineers in practice in California today, Ronald O. Hamburger, and John D. Meyer, both principals and structural engineers at Simpson Gumpertz & Heger, Engineers based in San Francisco, asked the same question in their article on the centennial of the 1906 earthquake in EERI Earthquake Spectra: *“Evaluation of these buildings using modern methods of seismic analysis would not suggest such outstanding performance would occur. This raises the obvious question as to why the performance would be so much better than predicted using modern evaluation techniques (Hamburger and Meyer, 2006).”*



**Figure 32: Flatiron Building in New York City under construction in 1902 showing the stone masonry façade resting on the steel frame. The upper walls are constructed separately from the walls below, most probably to ensure their weight is bearing on the steel frame rather than the lower masonry walls.**



**Figure 33: View of San Francisco after the 1906 earthquake and fire. The three tall buildings in this view were burned out by the fire that followed the earthquake, but all were in good enough condition despite this to be repaired, and they are still extant today.**



**Figure 34: The Flood Building, San Francisco, constructed in 1904, It is twelve stories with a steel frame and thick infill masonry. (Left) after the Great 1906 earthquake and fire, and (right) its appearance today. It was simply repaired from the earthquake and fire damage after the earthquake. It did not have to be rebuilt.**

Hamburger and Meyer go on to examine three contributing factors that may explain the greater than expected resilience of these steel frame buildings during the 1906 earthquake, and their survival of the fire that followed. While their explanations were thoughtful and convincing, together they point out the difficulty that exists with the forensics that generally surrounds the issue of isolating the causes of successes as well as failures after such overwhelming disasters. That is that determining the reasons for successes is usually more difficult than for failures. This is especially conspicuous when one of Hamburger and Meyer's colleagues said that one explanation could be simply that the good performance may not have seemed so remarkable had the fire not happened. Then these buildings would not have been surrounded by burnt out and collapsed ruins. Had the surrounding buildings been only earthquake damaged the difference would have been less apparent.



**Figure 35: Collapsed RC Buildings in Gölcük, Turkey after 1999 Kocaeli earthquake**



**Figure 36: Collapsed steel frame building after 2003 Bam, Iran earthquake**

For the purpose of this paper, however, the question is whether there is anything that can be learned from the good performance of these first generation frame skyscrapers which carry the heavy load of masonry infill and stone or terracotta cladding with hollow clay tile interior walls, and which have “soft stories” of open shop fronts and many large windows on all floors. None of these buildings even came close to collapsing even though the earthquake had caused some of the fireproofing of the steel columns to fall away before the fire swept through them. By comparison with the collapse in subsequent earthquakes of hundreds of reinforced concrete (**Figure 35**) (and in Iran, steel (**Figure 36**) frame structures constructed over the last fifty years, the difference is profound.



**Figure 37: Hotel Oakland, Oakland, California after 1989 earthquake which caused much of this end façade to fall off**

After having experienced a seemingly medieval world in Srinagar, Kashmir, I found that the answer lies where one least expects it – with the infill masonry. This leads to another observation by Ronald Hamburger – who wrote that he is “*not aware of any [structural evaluation] models that incorporated the effects of the [interior masonry] hollow clay tile partitions.*” These interior partitions are, of course, in addition to the exterior brick and stone masonry in the engineering assessment of these buildings (Hamburger and Meyer, 2006).

The questions raised by Hamburger and Meyer point to the fact that the masonry in general, and the hollow clay tile interior walls in particular, fall outside of modern seismic analysis models, such that in a seismic retrofit project the typical decision has been simply to replace the hollow clay tile interior walls with lightweight materials. It is worth recalling the quote by Freitag, where he uses the human body as a metaphor for the structural role that the infill masonry must have had in steel frame high-rise buildings, yet “*while the steel frame is more or less reinforced by the weight and stiffening effects of the [masonry infill], still no definite or even approximate values can be given to such items, except their purely static resistance or weight* (Freitag, 1901).”

Hamburger and Meyer’s comments are particularly interesting in light of what happened during the 1989 Loma Prieta earthquake in Oakland, across the bay from San Francisco. That earthquake affected a number of early 20th-century skeleton-frame mid-rise buildings with masonry curtain walls. None of these buildings came close to collapse during the earthquake, but, as expected, many manifested cracks in their masonry exterior walls, as they did in San Francisco in 1906. However, one such building, the former Hotel Oakland, an eight-story block-sized building recently converted to housing, sustained considerably more damage to its façade than did any of the others. After the earthquake, it was surprising to find out that of all of the buildings of this type, this one building had been the only one that had been

seismically upgraded (**Figure 37**). As part of that upgrade, all of the interior hollow clay tile masonry walls had been demolished and replaced with gypsum plasterboard on light weight steel studs.

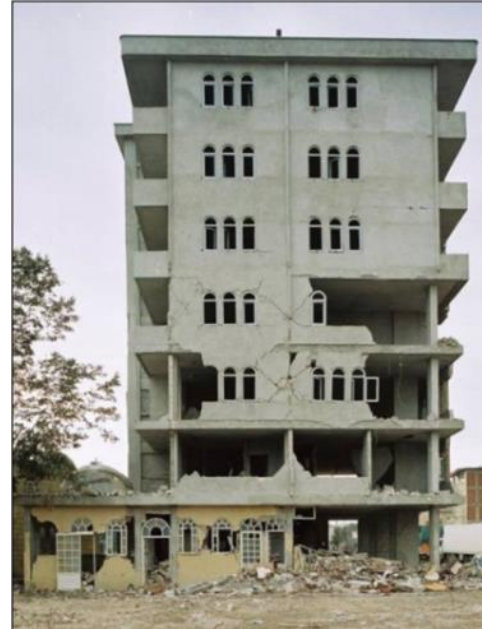
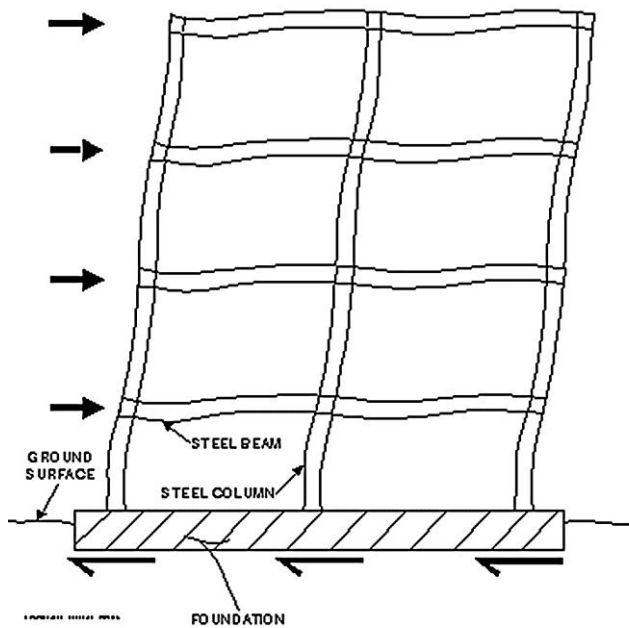
Thus, this building confirmed that Freitag's instructions in 1901 were as valid as is Hamburger and Meyer's observation that *modern methods of seismic analysis* fail to predict the good performance of the 1906 steel framed buildings in the San Francisco earthquake. It also is another example of how engineers continue to have difficulty finding a way to incorporate infill masonry into their calculations and wish to remove it whenever possible.



**Figure 38: Margalla Towers, Islamabad (middle) after debris removal exposes the basement level 'soft story' and (right) base of the section next to that which collapsed showing evidence of onset of short column failure**

Returning to the Margalla Towers in Islamabad, together with the thousands of other reinforced concrete moment frame buildings with infill masonry walls which have collapsed in earthquakes, one is forced to ask why for so long these moment frame structures are constructed with masonry infill walls which are largely ignored in their design calculations. Note in the USA and Canada, the use of masonry for infill was banned in the building code more than half a century ago, but in much of the rest of the world, it is still commonly used. In the case of the Margalla Towers as late as 10 years after the earthquake, the Pakistan Express Tribune reported that there was “no answer yet” as to why the Margalla Towers collapsed, but my own photos taken in 2006, a year after the earthquake seem to me to show good evidence that the collapse may have been a soft story failure combined with some short column failures (**Figure 38**) (Usman, 2015).

There are two changes which have taken place, one in engineering and the other in construction. In engineering, most of my historical focus above was on the transition to the use of iron, and then, later, steel and reinforced concrete frames for taller buildings. To accomplish this, engineering practice shifted from a largely empirical process to one of rigorous mathematics. One of the watershed events in this transition is the invention of a way of doing a portal frame analysis using what is called the contraflexure methodology for isolating moments. This method allowed the calculation of the capacity and bending stresses on multi-story frames by mathematically separating a moment frame into parts at each neutral point of bending reversal of the columns and beams. This allows the forces to be calculated using the three equations of equilibrium. Multi-story modern moment-frame steel and concrete buildings as we continue to see them built today in every practical sense date their origin to this change in engineering analysis methodology (Robison, 1989; Langenbach, 2006) (**Figure 39**).



**Figure 39: Moment frame under lateral load showing the rigid connections of the beam/column connections which then produce the flexural shapes of the beams and columns. This is an idealized shape of the ‘frame action’ which engineering calculations are predicated on, whereas the beams are often much deeper, which can more easily lead to rupture of the beam/column connections.**

**Figure 40: The infill walls can prevent this ‘frame action’ from happening altogether as can be seen in taken in Gölcük, Turkey after the 1999 earthquake. This photograph shows how the building was brought almost to collapse as the infill walls failed in shear at the lowest levels, causing a soft story condition**

While the contraflexure methodology for calculating the forces on a frame for tall buildings allowed for greater accuracy and simplicity, one of the interesting results is that the greater efficiency in the calculations meant the frames were no longer as overdesigned as they had to be prior to the adoption of the contraflexure methodology for moment frames for high-rise buildings, which is reported to have occurred around 1910 to 1915 (Robison, 1989). Thus the sizes of the beams and, particularly, the columns are reduced and a bending ‘pin’ connection at each floor level is eliminated.

The solution also was to change the construction rather than the mathematics by reducing the amount of masonry used to a single thin layer, while still deliberately leaving the masonry out of the engineering calculations. The seemingly reasonable theory was that by including only the weight of the masonry in the calculations, but not relying on it for lateral strength, the design would be more conservative than if it were included as part of the lateral resistance. Experience has shown that there is a fundamental flaw with this approach. The standard analysis method is based on linear elastic behavior which contradicts the fact that, even under current seismic design regulations, structures are allowed and expected to incur into the nonlinear range. This fact has been recognized in codes through the use of ductility factors which are assigned based on the individual elements that make up a structural frame, but such factors are unresponsive to the conditions that exist when the non-structural infill masonry is added to the system.

The problem is that the masonry is not eliminated, but instead became thin and weak. What had been the strong multiple layers of infill masonry laid in lime mortar that contributed to keeping San Francisco’s

early skyscrapers standing was in later buildings attenuated into a single layer of brick or hollow clay tile laid in cement mortar that is stiff, yet brittle (**Figure 40**). While these single layer brick infills have proven in recent earthquakes to be strong enough during an earthquake to sometimes rupture the RC moment frames, they then collapse or fall out of the frame, which can cause a pancake collapse of the buildings (**Figure 41**).



**Figure 41: Research on the effects of conventional infill walls at Middle East Technical University, Ankara, Turkey. The photos on the right show how the infill can cause the rupture of the surrounding RC frame when pushed laterally parallel to the wall**



**Figure 42: Buildings in Mingora, Pakistan. On left, what appears to be a very weak RC frame building under construction, and on the right an infill wall building with no visible attempt to give it a cultural or architectural quality**

## 9. FROM SOLID WALLS TO FRAMES

Many historians of the early skyscraper era viewed the evolution of skeleton frame building design like 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 floor plans of open spaces and moveable walls. Unfortunately, as can be seen in these illustrations above, the creativity and vision of the first architects such as Le Corbusier, is missing from many of the manifestations of what had been a promising new structural system in the first decades of the 20<sup>th</sup> century (**Figure 42**).

This transition to the nearly ubiquitous use of reinforced concrete frame construction led to increasing numbers of failures of such buildings in each successive earthquake, presenting a dilemma which only becomes evident when certain disrespected and forgotten examples of traditional timber and masonry construction such as *dhajji* and *himis* are found to have a better statistical record of collapse prevention in certain large earthquakes than the modern frame structures. While timber lacing and timber frames with infill masonry intuitively are better than plain unreinforced masonry, *how can these, nevertheless, be better than reinforced concrete?* In other words, how can the failure of what is often determined after an earthquake to be bad construction be considered to be an indictment against the RC frame systems themselves? This question is especially difficult to answer, when it can also be seen that better built RC buildings have survived with little or no damage.



**Figure 43: Buildings that were intended to be identical when finished, located near Bhuj, India after the 2001 Gujarat earthquake**

**Figure 44: Large RC infill wall building after 1985 earthquake in Mexico City showing ruptured columns**

In my observations of the behavior of these systems in the Turkey, Kashmir and Gujarat earthquakes, the use of weak rather than strong mortars in combination with the timber framing allows the masonry to shift and slide early in the onset of earthquake shaking, rather than crack through the masonry units and fall out of the framework. The combination of the framework with the masonry thus is interactive, rather than one working against the other. Frame action, the independent working of the frame as a structural system, is neither what exists nor what is important. Although a framework of timbers is constructed, it is imbedded in the masonry wall and “works” in the engineering sense of the term together with the masonry in the wall.

However, with reinforced concrete moment frames, now for more than 100 years, the universally excepted engineering calculations based on frame analysis are based on a fundamentally false premise. Instead, for what is now an entire century, buildings constructed with moment frames, but enclosed and subdivided into rooms with infill masonry walls, and thus cannot actually undergo the “frame action” during earthquakes on which their design calculations are predicated.

I have seen evidence of this many times after a number of earthquakes, but the photograph in **Figure 43** illustrates this in a particularly clear and dramatic way. The two buildings seen were, when finished, intended to be identical, but only the one on the left was finished and occupied, while the bare frame on the right was clearly the only one of the two frames in which the frame action on which all of the structural design calculations were based could occur. Need I say more? The frame is standing, but the finished building has collapsed.

**Figure 44** gives a clear view of what the collapse mechanism is for the collapsed building in **Figure 43**. It shows a large infill wall RC building in Mexico City after the 1985 earthquake that was very close to being collapsed by the action of the infill masonry on the frame. The photo shows the rupturing of the corner column on the right in two places in the same story. It is remarkable that it was still standing when photographed.

## 10. ARMATURE CROSSWALLS

How can this situation be fixed? For decades, researchers have worked on ways to structurally separate the infill walls from the frames, but still have walls that provide acoustic and fire safety separation between rooms, and a weather separation from the outside. While sophisticated hangers and clips or lightweight materials and composites of different types are all possible, few are as economical or practical as brick or hollow clay tile infill.

The best alternative that I can propose is to do what should have been done over 100 years ago –make the infill masonry an integral part of the engineering of the building. The goal is to make it work, in the engineering sense of the term, together with the frame such that “frame action” will still occur.

I will describe now what I propose, which I have named **Armature Crosswalls**. The term crosswall has been drawn from the terminology used in the Uniform Code for Building Construction (UCBC) Chapter 1 as applied to unreinforced masonry construction. In that code, a “*crosswall decreases the displacement ... and will provide damping of the response of the diaphragm to earthquake shaking.*” For the purposes of this proposal, a crosswall is an infill wall inserted into the building’s structural frame, rather than only connecting floor diaphragms, and thus it is not limited to interior partitions. The word is chosen because of the similar emphasis on its reduction of deflections of the structure and its provision of damping through hysteretic behavior of the crosswalls themselves. Part of the research on the Turkish *hımış* construction has been accomplished with a 2003 EERI Lessons Learned over Time grant. The research and publication of the papers referenced on the last page was supported by this grant). The Armature Crosswall (ACW) technology is founded upon the assumption that (1) vulnerable RC frame structures will continue to be constructed in great numbers, and (2) weak existing RC buildings will continue to be occupied. RC infill construction has become the default form of construction in many countries even though it has proved to be particularly deadly in earthquakes except where engineering design and construction quality control is rigorous. Rapid urbanization and development continues to lead to severe compromises in engineering and construction quality. The technical knowledge and the equipment necessary for construction of acceptable quality simply do not exist in many regions, and proper enforcement and inspection in many locations is simply not possible. The problem with most RC Infill construction in many parts of the world thus is not an engineering problem; it is a socio-economic problem in building delivery (Langenbach, 2003).

The Armature Crosswall concept is focused on the infill walls themselves, rather than the frame. It is based on the idea that the masonry infill walls may hold the key to the prevention of such wide-spread collapses of RC buildings, just as they did for the Chicago Frame buildings in San Francisco in the 1906 earthquake. Previous efforts to reduce the negative effect of the infill walls have included separating them

from the frame or reinforcing them, but these approaches do not help to protect against collapse when the RC frames prove to be deficient - especially when supporting the weight imposed when masonry is used for all exterior walls and partitions.

An Armature Crosswall (ACW) is a masonry infill wall that has been constructed or retrofitted with studs and horizontal members (the armature) that subdivide the masonry infill, and surround all openings. The goal is to develop a design for the ACW that is capable of sustaining inelastic deformation with consequential friction over many cycles. To do this, the concept is to make the walls more flexible and less subject to collapse by dividing the masonry into panels, and also by using a mortar that is significantly weaker than the masonry units. The objective is to reduce their elastic stiffness compared to non ACW walls, while making them more stable and robust in their inelastic behavior. The ACW concept is based on the goal of making the infill walls serve both as a secondary means of support and as economical energy dissipaters. The energy dissipation results from the friction from the controlled cracking through only the mortar joints (not the masonry units) and sliding of the masonry within the armature framework. I have also found examples of buildings with a de-facto version of ACWs that have demonstrated their potential resilience in reconnaissance trips to Mexico after the 1985 earthquake, El Salvador after the 1986 earthquake (**Figures 45-47**), and Iran after the 2003 earthquake.

The armature in an ACW consists of a series of studs and cross-beams that divide the infill wall masonry into a series of panels. Although traditionally of timber, the materials to be used for armatures are not critical. It can be timber, steel, precast concrete, or combinations thereof. The ACW is intended to be tightly fitted within the building frame so as to provide sustained friction and energy dissipation over repeated cycles. ACWs will be designed to accommodate doors and windows, and also allow for partitions that are not confined within the frame together with those that are. Since these are crosswalls, rather than shear walls, they do not have to extend unbroken from foundation to roof or have their own foundations or boundary elements.



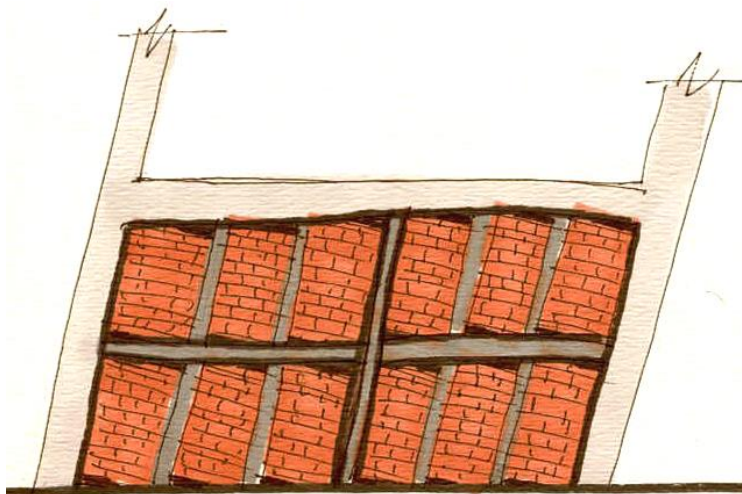
**Figure 45: The brick wall of a power station showing an ‘armature’ of light steel reinforcement that subdivides the wall into panels. This building suffered no damage in the 1985 Mexico City earthquake while Figure 45 (b) shows RC building under construction just across the street has collapsed.**



**Figure 46: Photos of a soft story collapse of an apartment building in El Salvador in the 1987 earthquake**

**Figure 47: Upper story walls had been subdivided with an RC ‘armature’ which prevented the soft story collapse becoming a complete pancake collapse. This kept the occupants of the upper 3 stories from being killed**

One important attribute of ACWs is the use of weaker mortar such as lime mortar, rather than stronger, but brittle, cement-based mortar. The objective is that the masonry units be stronger than the mortar, so that any movement within the walls occurs easily within the mortar joints, and between the masonry panels and the armature. The ACW technology can thus avoid the initial stiffness of infill walls in earthquakes by allowing the building frame to deflect uniformly across its entire height. This also will serve to reduce the effect of soft stories at the shop front level, which is now one of the most prevalent reasons for building collapse. The energy dissipation that results reduces the building’s resonance with the earthquake. As the story drift of a building with ACWs increases over the course of an earthquake, the individual crosswalls, held up and reinforced by the armature, are squeezed within the deflecting frame of the building, thus serving to brace the frame from collapse.



**Figure 48: Diagram of the Armature Crosswall in an RC frame**

Although the lateral distortion is less than shown, this sketch in **Figure 48** is meant to show the stability of an ACW under shear forces. It contrasts with **Figure 49** where a typical RC frame infill wall of brittle hollow clay tiles has collapsed out of its frame. This view is from inside a building that was partially collapsed by the 1999 Turkey EQ, but was not far from **Figure 50** of a *hımış* wall in a building shaken by the same earthquake forces but which remained undamaged except for the plaster surfaces. The house was immediately adjacent to several RC buildings that had collapsed in Düzce, Turkey.



**Figure 49: Photograph taken in an upper story of a partially collapsed RC building in Gölçük**

**Figure 50: Masonry with timber armature *hımış* wall in Düzce, Turkey after 1999 Düzce earthquake**

In summary, the purpose of the armature is to change the behavior of the wall when subjected to earthquake shaking so that the infill masonry will: (1) remain in place without falling out of the frame from either in-plane or out-of-plane forces, (2) add substantially to the lateral capacity of the building, (3) avoid development of an equivalent diagonal strut that can impose excessive loads onto the beam/column joint, (4) avoid propagation of diagonal tension cracks that can cause the infill wall to fall out of the frame, (5) allow increased flexibility within narrowly defined limits compared to standard infill walls, while resisting extreme excursions that place the stability of the frame at risk, and (6) dissipate substantial amounts of energy over many cycles of severe shaking, and by so doing, reduce the resonance of the structure with the earthquake vibrations (Langenbach, 2008; Langenbach et al., 2006). More information is available at <http://www.conservationtech.com/armaturecrosswalls.html>

## 11. NEPAL AND GABION BANDS

To conclude, I leave the discussion of frame constructions and turn to some of the most remote Himalayan village settlements in Nepal that were affected by the 2015 Gorkha earthquake. The 7.8 $M_w$  Gorkha earthquake of 25 April 2015 caused devastation over a wide area in Nepal, including Kathmandu where it devastated the most intact heritage sites of Patan Durbar Square and Bhaktapur. In Sindhupalchok District, it collapsed and destroyed many modern concrete buildings. There were approximately 9,000 fatalities. The 25<sup>th</sup> of April quake was followed by a Mw 7.3 aftershock on the 12<sup>th</sup> of May further to the east that killed an additional 200 people and caused damage in additional areas further to the east.



**Figure 51: A role of Polypropylene geogrid sufficient for a small house is this easily carried on one's back, making the Gabion Band technology practical for reconstruction of houses remote from the roads high in the Himalayan foothills**

**Figure 52 (a&b): Construction of this first Gabion Band house with wire mesh bands is shown with the village mason together with the family whose house had fallen down. My instructions to the owner-builders and mason with translation by Nepali volunteers took less than an hour, and the construction of the walls to the roof-line took only 4 days.**

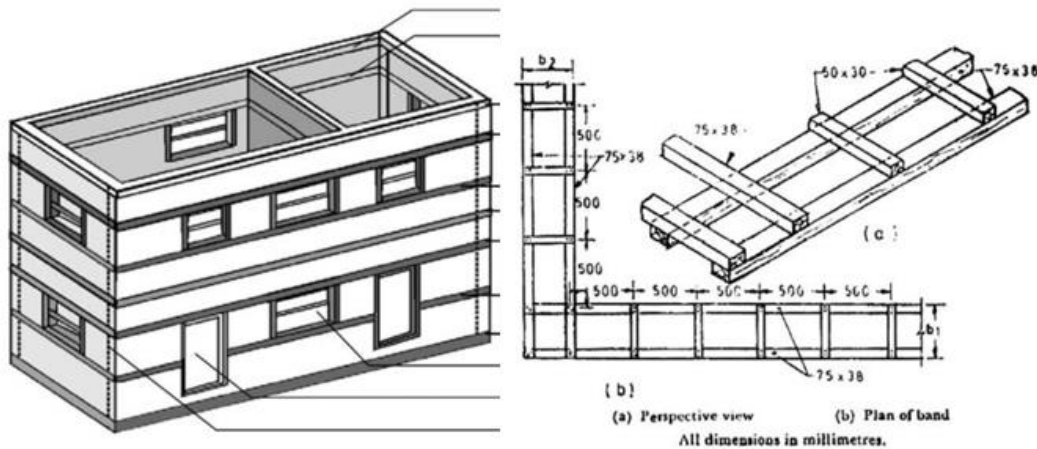
Not unlike that which struck Pakistan Kashmir in 2005, the Gorkha earthquake bore the signature characteristic of rural earthquakes everywhere. However, for the reconstruction of the rural residential infrastructure, the situation in northern Nepal was even more extreme because many of the more rural settlements were high in the foothills of the Himalayas, the tallest mountains in the world, and thus many of these settlements were off the road network. This meant that they could not be reached by vehicles capable of carrying the loads of concrete and steel rebars that had been mandated as necessary for safe construction by the more urban-based professional engineers, architects, and building officials. It is for this reason that I have proposed a technology which I have named Gabion Bands (**Figures 51+52+53**).

The idea for Gabion Bands came about after an Australian colleague wrote an essay in which she said that construction-grade timber was in short supply and very costly in Nepal. While there are many trees in the foothills in northern Nepal where the earthquake damage was most extensive, these were often young softwood trees, which are particularly vulnerable to rot and termite attack. Moreover, they would have to be milled after they are cut, so that in many communities the timbers would have to be transported twice, even if grown near to the construction site.



**Figure 53: Construction of the 1st Gabion Band house in Mankhu, Nepal showing the laying of the mesh and after it is wrapped around one course. (see also Figure 52)**

As I have mentioned above, Nepal had already adopted a building code for non-engineered construction that very closely paralleled the one in India, complete with many of the same graphic images (**Figure 54**). In fact, one of the principal authors of the Indian code, Prof. Anand Arya of IIT-Roorkee had also consulted on the Nepal code. Thus the use of timber ring beams in bearing-wall masonry construction was already an accepted construction typology. When confronted with the problem with having enough affordable timber, I considered what could work as an alternative that would still provide the same or better seismic hazard mitigation provided by the timber ring beams embedded into the walls.



**Figure 54: Illustration of timber bands from the Indian and the Nepal Building Codes for non-engineered buildings**

Of course, timber would still be needed for the roofs and any floors (should the houses have elevated floors rather than the common simple gravel, dirt and cow dung floor laid on the ground) but the timber for these would most probably be available from the earthquake damaged or collapsed ruins of the previous houses. In addition, the wood to be embedded in the rubble masonry walls had to be more resistant to decay than does the wood (or bamboo) to be used for a roof, as it cannot be replaced or maintained without rebuilding the masonry walls – a strenuous and time consuming project.

The Gabion Bands concept is a simple one. In the same way as does the timber ring beams in the Code, it adds tensile resistance to lateral forces to a one or at most, a two story rubble stone wall by adding a series of ring beams over the height of the wall that are one to three feet apart over the height of the wall. Each of these ring beams consists of a single course (layer) of stones wrapped tightly in the wire or geogrid mesh. At first, I proposed to use a wire mesh (**Figure 52+53**), but after finding the welded wire mesh to be subject to corrosion because of low quality manufacturing, I switched to recommending the use of polypropylene geogrid, which has a long lifespan, especially in a dark environment, and also is very strong with low elasticity.

The idea behind the wrapping of single courses of stone, instead of wrapping the whole wall, is that (1) the polypropylene geogrid is within the wall where it is less subjected to exposure and other causes of breakage or deterioration, and (2) the geogrid forms what is effectively a beam laid into the wall that is flexible enough to remain bearing on the masonry should earthquake vibrations cause some of the stones below it to compress together or fall out.

The geogrid also provides a way of tying and confining the corners of a building with stone walls by being folded back to wrap and tie the corners in a way that is potentially much stronger and more effective than are the notched timbers of the timber ring beams in the code. At the top of the wall, a double layer or more of the wrapped stonework can be used to prevent the tops of the masonry walls from overturning, thus using the parapets or the upper wall courses that are embraced by the eaves to provide the overburden weight that can help turn the attic floor into an effective diaphragm without the hazard of masonry falling off from the tops of the walls.



**Figure 55: After learning of my Gabion Bands technology when it was featured on the US Public TV science documentary NOVA about the earthquake, a former Peace Corps volunteer John Vavruska of Santa Fe, NM, with Nepali expats from the village of Chupar, Nepal constructed this school building**

Gabion Bands have also been proposed for one-story rural schools (**Figure 55**). Unreinforced stone masonry schools have been shown to suffer from two significant problems in addition to the lack of tensile reinforcement. One is that they do not have attics, so the stone walls that surround the classrooms are effectively like garden walls without being securely stabilized at the top, and second, the windows and doors in schools are most often only or mostly on the south sides of the building, resulting in what is in effect is a partial wooden framework on one side of the building which can resonate differently than the rest of the building, throwing the stones around it down.



**Figure 56: School building totally collapsed in 2015 Ghorka Earthquake with sheet metal roof.**



**Figure 57: School building with front and rear walls still standing with a ceramic tile roof. (photos courtesy Nepal School Projects NGO)**

In addition to these problems, over the recent years the customary stone slab or clay tile shingle roofs have now most frequently been replaced with galvanized corrugated steel (GCI) sheets which are extremely light. Engineers have frequently embraced this lightening of the tops of the buildings, but in actual fact, masonry must have overburden weight to have any hope of surviving being shaken apart in earthquakes. **Figure 56** shows a school collapsed in 2005 with a GCI sheet metal roof. The front stone wall is entirely destroyed. By contrast, **Figure 57** shows another unreinforced masonry school with both gable ends and all interior crosswalls collapsed, but the roof is a heavier ceramic tile which appears to have helped maintain the front and rear walls from crumbling down.

A report “*GABION BANDS*”: *A Proposed Technology for Reconstructing Rural Rubble Stone Houses after the 2015 Nepal Earthquakes*,” with a more complete description of the Gabion Band technology, can be found on the web by clicking the title, or by going to <http://traditional-is-modern.net/Nepal.html> and finding it on that webpage.

The story of the Gabion Bands technology is an on-going one because, unlike the Government of Pakistan, through ERRA and NESPAK, which embraced *dhajji dewari* and *bhatar* construction after the wisdom of it became apparent in the remote rural areas of Kashmir, the Government of Nepal has continued to insist on reinforced concrete for bands if stone masonry construction is used, despite the difficulties of delivering such materials needed for it to remote rural locations and its high costs. Engineers connected with the Government of Nepal (Department of Urban Development and Building Construction (DUDBC), the Department of Education, and Nepal Reconstruction Agency (NRA) have been resistant to such technologies by citing the need for calculations when such technologies based on the reinforcement of all sorts of differently configured masonry walls of rubble stone with mud mortar do not lend themselves to being calculated, other than for the statics of dead weight.

Even the principal author of the Nepal Building Code, Richard Sharpe, has expressed opposition to this requirement by simply pointing out that the relevant code is specifically for non-engineered buildings, so requiring calculations for buildings even with what is intended to be a modification to the code, such as Gabion Bands instead of timber bands, is not appropriate. Specifically, the buildings to be reconstructed in rural areas of Nepal, just as they have been in Pakistan Kashmir, are almost all owner-built - which is why it is so important that the applicable code be for non-engineered construction. That is also why its instructions are identified and presented as rules of thumb.

The technology of Gabion Bands harkens back to an earlier age when a more empirical approach to engineering ruled the discipline. It is the approach which lay at the root of the design of the great structures of the world over the centuries of masonry construction and even unreinforced concrete construction, such as the Parthenon in Rome – a 2000 year old structure that would not be there today, had it been reinforced with steel. The need for calculations is an engineering approach that is caught on the fence of time. Mathematics has always existed in engineering, but for the most part it has been the statics of dealing with weight, while the calculations of the modern era are those used to calculate dynamic forces on frames rather than on masonry, including lateral forces on moment frames (The “equivalent diagonal strut” analogy for calculating the potential disruption to a reinforced concrete frame from the infill masonry is a good example of this modern method of using frame theory even for solid walls).

## 12. CONCLUSIONS

The government of Pakistan's endorsement of traditional construction techniques after the 2005 earthquake, described at the beginning of this paper, was not immediate. In May of 2006, only seven months after the earthquake, ERRA published a manual, "*Guidelines For Earthquake Resistant Construction Of Non-Engineered Rural And Suburban Masonry Houses In Cement Sand Mortar In Earthquake Affected Areas*," in order show that what would be considered "compliant" with the government-approved standard for earthquake-resistant construction necessary for financial reimbursement would have to be cement concrete reinforced.

As in Nepal, the affected houses were predominantly rural, with urban housing accounting for only 10 percent of the total. A requirement that government assistance be limited to reinforced masonry with cement mortar would mean that the materials would have to be transported deep into the countryside where, as in Nepal, there are often no roads on which to deliver heavy materials as seen in **Figure 58** below. As described above, many of the families rendered homeless began rebuilding destroyed rubble masonry houses using their own locally grown timbers and stones from the fallen down houses, despite knowing that they would be ineligible for government financial assistance because the transport of required materials was impossible.

One of the difficulties, as reported by UN-HABITAT, was the fact that *dhajji* and *bhatar* construction had not been the subject of engineering research and no generally accepted analytical tools had been developed for it. This explains why many engineers, including those representing the World Bank and other donor agencies have difficulty accepting traditional construction, but it also explains why these traditional masonry-based systems need to be recognized and valued by engineers who have the people's cultural and financial needs at heart. In an effort to provide some professional credibility for the systems, UN-HABITAT prepared a report called *Build Back Better – Bhatar* authored by two structural engineers and an architect, which makes a strong case for the viability of *bhatar* as an earthquake resistant form of construction. It describes the structural characteristics of *bhatar* that give it its resilience. In brief, it says "*The fundamental principle of the bhatar system is dissipation of energy through friction (shear)*." In this report they deal with the argument over the conventional wisdom that calculations are needed by saying:

"Because of the inherent variability and complexity of the individual materials...it is not possible to accurately calculate or model the structural behaviour of the bhatar system. As the bhatar system relies on structural stability and energy dissipation rather than strength characteristics, standard calculation techniques appropriate for dynamic analysis of engineered structures have limited validity when applied to bhatar construction. Of greater value is the vast amount of empirical data available from post-earthquake reconnaissance, and historical evidence."

With the support of Army personnel who could see the practicality of using local vernacular techniques in the mountain areas and the urgency of the need for disaster assistance funding in this historically volatile region, *bhatar* was approved by ERRA in July 2007. While overseeing a program covering the construction of 630,000 new and repaired houses, Waqas Hanif, the ERRA Programme Manager for Rural Housing, came to embrace both *dhajji* and *bhatar* and thus was key in ensuring both were approved as compliant.

Despite the time and effort that it took, architect Tom Schacher observed that "the readiness of the engineering consultants to the government to review their dogmas and approve construction practices hitherto unknown to them, and for which they often didn't have the required scientific evidence, was extraordinary" (Schacher, 2008) (**Figure 59-61**). His finding is certainly confirmed by the contrast between what he observed in Pakistan with that which I have described that is still on-going in Nepal.

PLEASE NOTE that I recommend against the use of diagonals that tightly confined in a box shape in the framework as shown in **Figure 61(a)** because they prevent the masonry from yielding in the way described above, which then allows the movement and energy dissipation that are intended to be features of the Armature Crosswall system. **Figures 4** and **61(b)** illustrates a more traditional, and in my opinion, more effective, arrangement of cross-bracing between the studs.

This history in Pakistan is significant for a number of reasons. Not only has the earthquake made it clear to the government and affected citizens alike that there is a need for more structurally sound and earthquake resistant construction, even in rural areas, it has also served to bring urbanized and university-educated architects and engineers into contact with the culture and indigenous building crafts characteristic of the rural regions.



**Figure 58: Hand carrying of cement blocks to a reconstruction site remote from the road in Pakistan after the 2005 earthquake (Photo courtesy of ERR)**

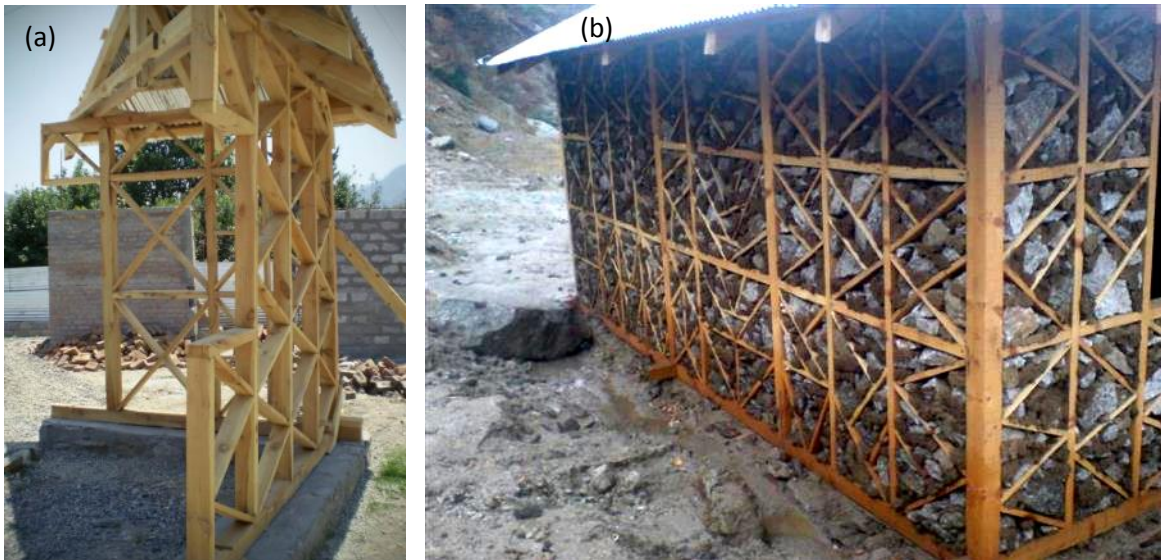


**Figure 59: Teaching improved anti-seismic masonry construction to rural masons in Pakistan by SDC and UN-HABITAT with support from ERR**

Most observers had long identified non-engineered traditional masonry construction of all types as archaic and unsuitable for contemporary living, particularly in an earthquake area, but after such a devastating earthquake, they could witness for themselves what survived and what failed. The interaction between the foreign humanitarian technical support teams both with the local engineers and government officials and the local population was crucial in what actually became a creative two-way technology transfer. Before either dhajji or bhatar could be adopted, both the foreign and the Pakistani professionals had to jettison their pre-existing prejudices to accept and improve upon premodern systems that were taught to them by the local people themselves. This stands as a remarkable example of openness, creativity, and acceptance at all levels (Schacher, 2008).



**Figure 60: Sample *bhatar* structure for masons training as described for Figure 59**



**Figure 61: Samples dhajji structure for masons training as described for Figure 59. As mentioned in the paper, I have recommended against the use of such rigidly inserted diagonals as seen in (a), in preference to those which are less likely to jack apart the corners as seen in (b) and also in the traditional construction shown in Figure 4 allows more lateral movement of the masonry infilled frame without breaking apart of the frame**

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