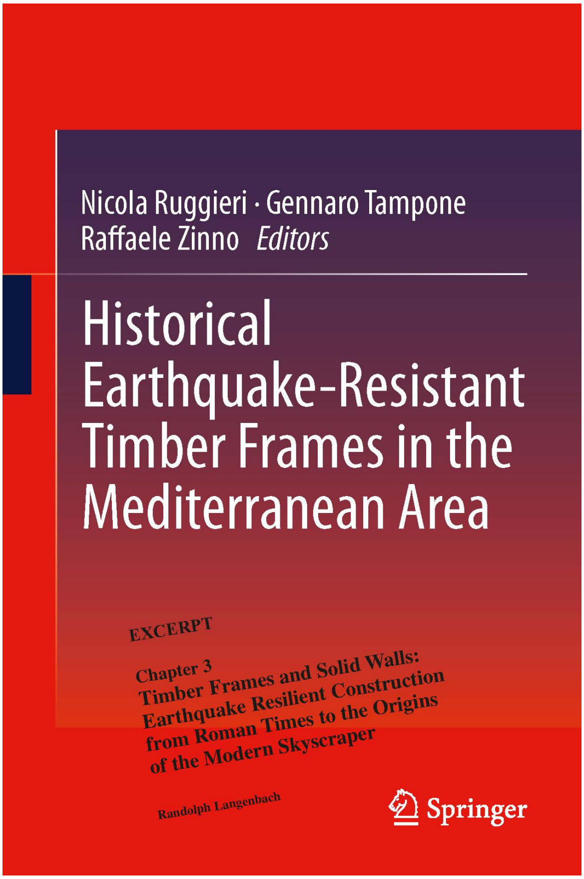

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Chapter 3
Timber Frames and Solid Walls: Earthquake Resilient Construction from Roman Times to the Origins of the Modern Skyscraper

Randolph Langenbach

Abstract This paper explores what can be learned from the earthquake performance of simple, unsophisticated, non-engineered timber and masonry historical construction that resists earthquakes compared to that of modern reinforced concrete frame buildings of varying construction quality that are common in much of the world's seismically active areas. The paper includes an analysis of the observations in the 1930s by American seismic engineer, John Ripley Freeman, about the 1908 Messina-Reggio earthquake and the comparative performance of the 18th century *baraccata* construction mandated by the Bourbon government after the 1783 Calabria earthquake.

Keywords Traditional construction · Timber · Masonry · Reinforced concrete · Earthquakes · Seismic · Earthquake engineering · *Hımış* · Dhajji dewari

The 1999 Earthquakes in Turkey

In November 2000, 1 year after two devastating earthquakes struck near the Sea of Marmara in Turkey, a conference was convened by UNESCO, ICOMOS and the Turkish Government in Istanbul, called "Earthquake-Safe, Lessons to be Learned from Traditional Construction" [1]. The 1999 earthquakes in Turkey, as well as more recent earthquakes worldwide, have demonstrated that in spite of all of the knowledge of seismology and earthquake engineering gained over the last century in the science and practice, the death toll in such events has continued to rise. It has become apparent that steel and concrete, even when built according to modern codes, have not been able to guarantee seismic safety (Fig. 3.1).

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Fig. 3.1 A traditional *hımış* construction house still standing next to a row as far as one can see of reinforced concrete apartment buildings in Adapazari, Turkey after the 1999 Kocaeli earthquake. Photograph by © Randolph Langenbach

At the time of the conference, few would have thought that traditional construction could provide any meaningful lessons to address the dilemma of death and destruction in modern buildings of reinforced concrete (RC). Yet conspicuous among the ruins of the RC buildings were many traditional buildings (known in Turkish as *hımış* construction) with timber frames and infill masonry that had remained standing.

At the 13th World Conference on Earthquake Engineering in August 2004, Fouad Bendimerad, Director of the Earthquakes and Megacities Initiative, reported that "*approximately* 80 % *of the people at risk of death or injury in earthquakes in the world today are the occupants of reinforced concrete frame infill-masonry buildings.*" In fact, a new term has emerged in recent years to describe the problem with reinforced concrete buildings: "*pancake collapse*."

It is reasonable to ask: how can a technology of building construction based on the new strong materials of steel and reinforced concrete be linked to such deadly catastrophes? At the beginning of the last century both steel and reinforced concrete held great promise for earthquake-safe buildings, yet, 100 years later, in Turkey in 1999, in India and Pakistan Kashmir in 2005, and in Haiti in 2010, the pre-modern buildings of timber and masonry remained standing surrounded by collapsed concrete buildings. Clearly the original promise of these new materials has not been fully realized.

After the 1999 earthquakes in Turkey, the world's scholars and engineers descended on the ruins of the buildings that took the lives of 30,000 people. They made frequent pronouncements that the collapses were caused by bad design and poor construction, pointing to those that did not suffer major damage or collapse to prove their point. Inspection, quality control, better training was what was said to be needed. Some experts even asserted that nothing new can be learned because

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the myriad observed faults had previously been well documented, and that some well-engineered and constructed buildings, of which there were many in Turkey, had survived. From their perspective it may seem that justice had been served, and that bad construction met its rightful fate. Contractors were arrested and developers chased out of town, in the hope that in the future people could be taught to pay attention to building codes, and graft and corruption would cease. “Only then,” they say, “can we expect that earthquakes will not result in such massive mortality and the promise of earthquake resistance of RC construction be fully realized.”

Kashmir

Srinagar has been, and continues to be, a city largely unknown in the rest of the world by decades of regional civil strife. When first viewed by the author in the 1980s, it appeared as a magical world—a city beside a mountain lake with a way of life that seemed unchanged for a 1000 years. The construction practices used for the traditional houses in Srinagar, which stand in contrast to today’s codes, include (1) the use of mortar of negligible strength, (2) the lack of any bonding between the infill walls and the piers, (3) the weakness of the bond between the wythes of the masonry in the walls and (4) the traditional use of heavy sod roofs (now mostly replaced with corrugated steel sheets).

These buildings were observed almost a century earlier by Arthur Neve, a British visitor to Kashmir, when he witnessed the 1885 Kashmir earthquake: “*Part of the Palace and some other massive old buildings collapsed … [but] it was remarkable how few houses fell …. The general construction in the city of Srinagar is suitable for an earthquake country; wood is freely used, and well jointed; clay is employed instead of mortar, and gives a somewhat elastic bonding to the bricks, which are often arranged in thick square pillars, with thinner filling in. If well built in this style the whole house, even if three or four stories high, sways together, whereas more heavy rigid buildings would split and fall*” [2] (Figs. 3.2, 3.3 and 3.4).

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” that is similar to the *hımış* found in Turkey [3]. The October 2005 Kashmir earthquake was centered on the Pakistan portion of Kashmir where 80,000 people died in both reinforced concrete buildings (including one modern highrise residential complex in Islamabad) and traditional unreinforced stone masonry buildings. It also affected India across the Line of Control, with approximately 2,000 fatalities. According to the structural engineering professors Durgesh Rai and Challa Murty 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*

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Fig. 3.2 Four story building of *taq* construction in Srinagar, Kashmir, India. The timbers are on the inside and outside face of the wall. Photograph by © Randolph Langenbach

Fig. 3.3 Buildings in Srinagar, Kashmir. The building on the left is of *taq* construction, and on the right is of *dhajji dewari* construction. Photograph by © Randolph Langenbach

Fig. 3.4 A partially demolished *dhajji dewari* building showing timber frame with typical single layer of infill masonry construction. Photograph by © Randolph Langenbach

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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"* [4].

Timber-Laced Construction in History

The origin of both types of timber-laced masonry systems dates as far back as the ancient world. The palaces at Knossos have been identified as having possessed timber lacing of both the horizontal and the infill frame variety [5]. This suggests that timber-laced masonry construction dates 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. They found an entire two story half-timber house and interior walls in other houses believed by the archaeologists to be examples of what Vitruvius has called *Opus Craticium*. 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 [6] (Figs. 3.5 and 3.6).

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 well 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*.

Other systems from around the world, including *hımış* and *dhajji dewari,* are described at length in my earlier papers that can be found at www.conservationtech.com, but of all of them, I have only found two historical examples of the frame and infill masonry typology which were invented specifically in response to earthquakes: Portuguese *Gaiola* and Italian *casa baraccata*. The *Gaiola* was developed in Portugal after the 1755 Lisbon earthquake under the direction of the Marquis de Pombal (which is why it is also called *Pombalino* construction). The *baraccata* or *la casa baraccata* was developed in Italy after the Calabria earthquake of 1783, and later was even registered for a patent as an invention [7].

While I have discussed the *gaiola* at length in several papers also to be found on www.conservationtech.com, I have not, prior to the HEaRT 2013 conference, had the opportunity to see on site examples of *casa baraccata*. Much work on *casa baraccata* has been done by other scholars, including our conference host, Nicola Ruggieri [8], and also another Italian Scholar, Alessia Bianco [9], and in

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Fig. 3.5 A building in the ancient Roman town of Herculaneum uncovered after having been buried in the eruption of Vesuvius showing an example of timber frame with masonry infill that is thought to have been called Opus Craticium. Photograph by © Randolph Langenbach

addition by my own former academic colleague, Stephen Tobriner [10]. Rather than commenting on or attempting to add to this considerable work, I wish here to focus on a particular document written more than 80 years ago in English by an American engineer, John Ripley Freeman, who undertook a remarkably comprehensive study of earthquake damage and earthquake resistant construction around the world [11]. His section on Italian earthquakes makes up 75 pages of his 900-page book, and early on in his treatise on Italy, he states "Italy, more than any other country, was the early home of scientific research of many kinds, and in its great engineering schools of today, offspring of its ancient universities, the sacred flame of learning still burns brightly" [11, p. 564] (Figs. 3.7 and 3.8).

What is remarkable about Freeman's treatise is that, rather than simply documenting the damage from the earthquakes, he focused on the post-earthquake reports by Italian engineers who had developed post-earthquake building ordinances after arranging for the translation of many Italian documents. His work provides documentation of the evolution of the field of earthquake engineering from its empirical origins to a discipline based on the rigorous mathematics, a process that also traces the shift from traditional Italian stone masonry construction to the increasing use of reinforced concrete frames with masonry infill.

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Fig. 3.6 A single family middle class house of colombage timber frame with single layer infill masonry construction near downtown Port-au-Prince photographed after the 2010 earthquake. This house was in the heart of the damage district with collapsed reinforced concrete buildings nearby. Photograph by © Randolph Langenbach

Beginning with the 1930 earthquake near to Naples, he then turns back to the December 28, 1908 Messina-Reggio earthquake, which he cites as *one of the greatest catastrophes since the dawn of history.* It was the engineering reports following this earthquake that has enabled him to cite the post-1783 earthquake provisions enacted by the Bourbon Government that then controlled this part of the Italian peninsula and Sicily—the provisions which established the *casa baraccata* form of construction as a requirement for reconstruction of buildings throughout 18th and 19th century Calabria. These provisions were based on guidelines written by Francesco La Vega, an engineer described by Tobriner as "*engaged in evaluating seismic damage to the sites of cities throughout southern Calabria*" [10, p. 134].

Freeman cites that the Report of the Italian Royal Committee of 1909 on the Messina-Reggio Earthquake [11, p. 564] which said that "*the Bourbon Government issued provisions on March 20, 1786, which even today … still show great sagacity, and the Committee deplores that in the space of a few decades these excellent provisions and suggestions should have been allowed to fall into oblivion, when their strict observance … would have saved to Italy the tremendous losses of 1894, 1905, and of 1908. The Committee stated that it knows of houses built under these Bourbon rules that had resisted all of the successive earthquakes. The system of wood-framed dwellings known as Baraccata, originated from these ordinances issued by the Bourbon Government, and … proved very successful so that the system is even today under certain circumstances highly commendable*" [11, p. 569].

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Fig. 3.7 An early 20th century building in Mileto, Calabria, Italy constructed with a baraccata timber frame embedded on the inside face of the wall, with a photo of it taken during its construction. *Photo* courtesy of the owner

The Sub-Committee reports on the facts of 1908 earthquake and an earlier earthquake in 1905 documented that "*the experience in the Messina quake proved that the system of wood-framed houses known as "Baraccata," built according to the ordinances of the Bourbon Government, established immediately after the earthquake of 1783, is a system that may be considered good and advisable for all those cases where materials were lacking for a more nearly perfect system of construction, but where it is possible to obtain, cheaply, good quality of timber of proper dimensions for the framework, and bricks, or regularly shaped stones with at least two planes of repose, and good lime and sand*." [11, p. 568].

Noting the report's reference to "*cases where materials were lacking for a more nearly perfect system of construction*", it is interesting to speculate on what, in 1909, the committee members may have been referring to. The report on the 1908 earthquake stated that "*the greatest resistance was presented by houses of one or two stories in height, constructed of the best brick masonry and resting on rock or firm soil,*" but the sub-committee on the 1905 earthquake made an interesting observation about a new form of construction—reinforced concrete stating that "*… four structures of reinforced concrete in Messina, which remained wholly unharmed*" which "*the sub-committee cited as examples of the capabilities of this material when properly used*" [11, p. 568] (Figs. 3.9, 3.10 and 3.11).

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Fig. 3.8 A vertical column of the timber frame in the building in Fig. 3.7 showing through holes in the brickwork. Photograph by © Randolph Langenbach

This observation, however, followed a longer description of other reinforced concrete buildings that "*were nearly all tumbled down, in spite of the fact that … the shocks were less violent than elsewhere.*" They said that these buildings were "*improperly classed as reinforced concrete … because of the poor quality of material used, and lack of proper joints or connections between various members*."

This quote not only documents what was seen in this earthquake, but stands as a prescient observation of the extreme dialectic between good and bad performance that continues to bedevil reinforced concrete frame construction in 21st century earthquakes. The sub-committee's insistence that the failed structures were "*improperly classed as reinforced concrete …*" provides a record of how reinforced concrete was already by 1909 viewed as a modern system capable of great strength and resilience, but which if done badly, not only will be vulnerable to collapse, but should not even be identified as "*reinforced concrete.*" The seemingly odd categorization only would make sense if one would similarly insist that a brick building found to be collapsed in an earthquake because of poor construction should not be entitled to be classed as 'masonry construction', which of course is ridiculous.

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Fig. 3.9 Side view of exterior wall showing the thickness of masonry in the Bishop's House in Mileto, Calabria, Italy constructed after the 1783 earthquake showing *casa baraccata* framework embedded in the inside face of the masonry wall. The house has been abandoned for many years. Photograph by © Randolph Langenbach

Fig. 3.10 Interior elevation view of the same wall as shown in Fig. 3.9 of the embedded *casa baraccata* framework in the Bishop's House in Mileto, Calabria, Italy. Photograph by © Randolph Langenbach

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Fig. 3.11 This view of Messina as rebuilt after 1908 was identified by Freeman as "*built under the new building laws.*" In the caption to the image, Freeman states "*In some [buildings] the framework is concealed, and in others [such as these shown] it is revealed and made an architectural feature*" [11, p. 562] Photograph by © Randolph Langenbach

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 Jenny and the other engineers of the first skyscrapers. In the first decades of the 20th century buildings went from a height of 10–20 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 structure as a whole 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 either by masonry walls or by braces within the heavy timber framework.

The advent of steel and steel reinforced concrete has allowed for the creation of moment frames which 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 work. While most of the historical focus is on the transition to the use of frames for taller buildings, the watershed event in this transition is the "invention" of a way of doing a portal frame analysis using the contraflexure methodology for isolating moments. This method allowed the calculation of the bending stresses on multi-story frames by mathematically separating the frame into parts at each neutral point of bending reversal of the columns and beams. This allows the forces to be calculated using

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the three equations of equilibrium. Modern skyscrapers in every practical sense date their origin to this change in engineering analysis methodology [12, 13].

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 mathematically-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 19th and early 20th centuries is that thick masonry infill and cladding was very much an accepted part of early steel and RC building construction, even though it was then, as now, not considered in the engineering calculations for lateral resistance. This is made clear by the author of one of the first textbooks on the subject of skeleton frame construction, Joseph Freitag when in both the 1895 and 1901 editions, he writes that "*'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*" [13] (Figs. 3.12 and 3.13).

It was only a little over two decades after the construction of the first skeleton frame "skyscraper" in Chicago, the 10 story Home Insurance Co. Building by William Le Baron Jenney, that 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. 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. As clearly stated by Freitag, it was not the frame alone, but the masonry in partnership with the frame that was responsible. Many of these buildings are now more than 100 years old, and despite having been burnt out by the subsequent fire, they were repaired and continue in service today.

In spite of the noteworthy evidence from this famous earthquake, it was after the 'invention' of portal frame analysis based on contraflexure methodology when the essential incompatibility between the masonry infill and cladding and the engineering of the underlying frames came into both theoretical and practical conflict. And so, over the years to follow, the masonry walls were made thinner and weaker. Standard portal frame analysis is predicated on the existence of "frame action." In other words, the building design is based on the assumption that the frame will deform in a geometrically coherent way, so that all of the beams and columns can share the loads.

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Fig. 3.12 Flatiron Building in New York City under construction in 1902 showing the heavy stone masonry façade resting on the steel frame. The upper walls were constructed separately probably to ensure the weight is bearing on the frame rather than the lower masonry walls. U.S.Library of Congress Photograph

In most parts of the world today, the enclosure and partition walls are most often of weak, but stiff brittle masonry. This has not been considered a problem for wind, as the system together with the masonry was designed to remain elastic, and the addition of the masonry simply made it stiffer and thus likely to be more resistant. Design-level earthquakes though were another matter because a building's structural system is expected to deflect into the nonlinear range. In other words, structural damage is expected to occur. Because these walls are considered by the design engineers to be "non-structural," these infill masonry walls are often not themselves designed to resist the lateral forces of an earthquake. Thus, their impact on the overall deformation of the building is not properly considered, especially after the point where some infill walls in the lower stories of the frame have broken, while others above continue to resist the deformation of the frame (Fig. 3.14).

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, with the open

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Fig. 3.13 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. Photograph courtesy Bancroft Library, U.C.Berkeley

Fig. 3.14 "Frame action" of a moment frame shown here with the uniform elastic bending of the framing members unimpeded by the effects of infill walls

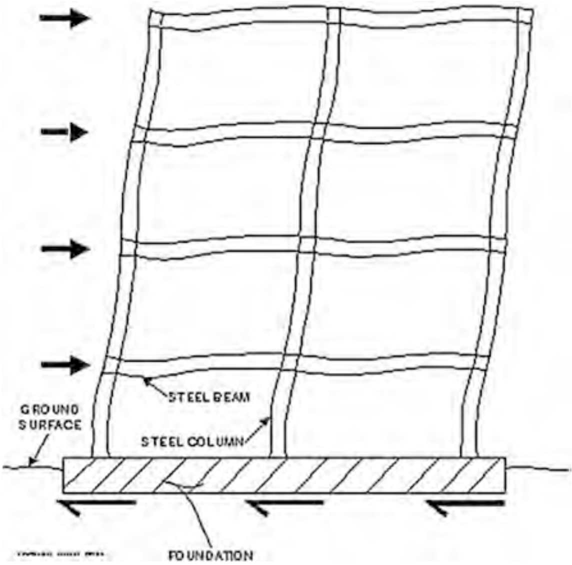

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Fig. 3.15 The interior of the historic structure of this Middle Eastern house has been demolished and is being replaced in RC, with the stone façade to be reconstructed around the new frame. This photo provides a graphic image of the difference between the open self-supporting framework of a reinforced concrete moment frame structure and a masonry solid wall structure. Photograph by © Randolph Langenbach

frame itself made the basis for the architectural expression with flexible systems of open spaces and moveable walls [12]. 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. The revolutionary change to building construction traditions that the adoption of RC moment frames for ordinary building construction represents can be seen particularly well in Fig. 3.15 of a Middle Eastern 3 story house where the remnant of the historic load-bearing stone masonry is relegated to be just a fragment while the self-supporting interior frame stands behind no longer dependent on it for support. The Dom-Ino house structural system 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*" [14].

From the Dom-Ino prototype, the reinforced concrete moment frame spread throughout Europe and 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, although still not included in the engineering designs except as dead weight, masonry, the increasingly attenuated and weakened masonry walls did not disappear. This resulted in the problems specific to earthquakes enumerated above. Compounding this problem was the frequent use of open 'piloti' on the ground floor, as advocated by Le Corbusier. In earthquake engineering parlance, this became known as a soft or weak storey, which has become perhaps the single greatest threat to the safety of these buildings.

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This transition to the nearly ubiquitous use of reinforced concrete frame construction with evidence of increasing numbers of failures of such buildings in each successive earthquake has presented a dilemma—a dilemma which only becomes evident when, as described above, certain disrespected and forgotten examples of traditional timber and masonry construction are found to have a better statistical record of collapse prevention in certain large earthquakes than the modern frame structures [6]. 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 flawed design and/or construction be considered to be an indictment against the RC frame systems themselves, when better designed and built RC buildings can be shown to have survived with little or no damage?

The issue can perhaps be seen as a basic dialectic that exists between the engineering of frames and walls. Engineering tools and methodologies—and code provisions—are used for both frames and walls, but the integration of the two systems in a single structure presents complexities. This is especially true when designing for design-level earthquakes for which inelastic yielding is not only probable, but fundamentally expected to occur. This behavior is accounted for in the building codes by ductility factors—factors which have been derived from extensive physical testing of what are now common modern materials and systems such as steel and RC, but not for archaic systems with combinations of timber and masonry that have better behavior than unreinforced masonry alone.

The most dramatic recent example of this is perhaps the 2010 earthquake in Haiti—where recent research shows that both late 19th century traditional timber and masonry houses of *colombage* construction and even more remarkably, the multi-story cement-block and concrete floor slab houses constructed in the informal settlements by itinerant owner-builders, out-performed the formal, contractor-built and often engineered buildings in the city center [15].

The performance of *dhajji* and *hımış* actually may provide insight into the better performance of the Haiti 19th century middle-class houses as well as large areas of the Haiti slum settlement houses. In my observations of the behavior of these systems in the Turkey earthquakes and the 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 (Figs. 3.16 and 3.17).

This is exactly what John Ripley Freeman found when in 1932 he translated the 1909 Italian engineers Committee Report which includes a description of “*houses in Favellioni Piemonte [damaged in the 1905 earthquake were of] reinforced concrete framework … having walls of small hollow concrete blocks … while the framework remained intact the walls were damaged … in places detached from frame and*

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Fig. 3.16 Two RC frame buildings in Bhuj, India after the 2001 Gujarat earthquake. The building on the left had been completed, while the frame only of an identical building had been completed on the right. The earthquake collapsed the one where the frame was restrained by the masonry infill walls, while the bare frame survived. Photograph by © Randolph Langenbach

Fig. 3.17 A collapsed RC building next to a surviving *hımış* building in Turkey after the 1999 earthquakes showing the resilience of the timber frame with masonry infill compared to that of a new RC frame building of modest height next door. It is interesting to compare this view with Fig. 3.16, where the infill probably caused the collapse, while here the infill and timber frame worked well together. Photograph courtesy of Adem Doğangün

collapsed," next to the report that "*wood-framed houses known as "Baraccata," built according to the ordinances of the Bourbon Government, … that had resisted all of the successive earthquakes … proved very successful*" [11, p. 568].

Thus, many buildings that we call "frame" structures are not frames in the engineering meaning of the term. More importantly, for earthquake resilience, it is important that they be understood not as frames, but as composite systems working more as solid walls that yield inelastically without collapse. The significance of this is that even if the framework is weak, the overall system can prove—as examples have already proved—to be resilient in large earthquakes.

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Conclusion

The importance of *dhajji dewari* itself as an earthquake-safe form of construction has already been proven, at least in 2005 earthquake epicentral area in Pakistan. Following the earthquake, the Government of Pakistan's post-earthquake emergency management agency ERRA mandated reinforced concrete or concrete block construction for anyone receiving financial assistance for reconstruction of their houses. Despite this limitation, many local people—especially those in remote settlements where access to concrete blocks and steel was difficult—proceeded to build *dhajji* houses despite the lack of government assistance (Figs. 3.18 and 3.19). After a little over a year, through the recommendations of international relief workers in the field, the government approved *dhajji dewari*, and a year later approved the masonry bearing wall construction which in Pakistan is known as *bhatar*. In the half-decade that has followed these approvals, UN-HABITAT reports that 150,000 to 250,000 new houses in these traditional systems have been constructed in northern Pakistan throughout what are mainly rural areas.

Why is this better than to continue to require reinforced concrete? First, *dhajji* and *bhatar* are more economical and affordable—largely because they

Fig. 3.18 A rural general store building near Thub, Kashmir, Pakistan in the damage district after the 2005 earthquake. Photograph by © Randolph Langenbach

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Fig. 3.19 The owner standing in front of his house under construction showing the light timber frame of *dhajji* construction before the rubble stone masonry with mud mortar infilling. His unreinforced rubble stone house had collapsed in the earthquake and he and his neighbors proceeded to rebuild with *dhajji* when they saw that the only house to survive in the village was the only one of *dhajji* construction and that the one building of RC construction had also collapsed. Photograph by © Randolph Langenbach

are primarily constructed of locally available materials: mud, stone and timber. Second, they are safer on average than RC houses for a simple reason: the safe construction of a multi-story RC moment frame requires a level of training and expertise that is not to be found even in most urban areas of Pakistan, and certainly not in the rural regions.

Not even the 1860 provision that "*imposed corporal punishment upon workmen who assisted in building structures which violated the provisions of the ordinance*" enacted in the Italian town of Norcia by the Pontifical government that controlled that part of Italy at that time—cited by Freeman—would be sufficient to assure the safety of all such buildings once RC construction became common even if re-enacted to cover such construction [11, p. 569]. With this, one can only imagine the scene of workmen, with their overalls dropped to their knees, being spanked for bad workmanship, and how often after earthquakes around the world where we may wish this had been done. Freeman did not include any further information on whether this was ever enforced in the Umbrian town of Norcia, which is located not far from the damage district of the devastating 2009 L'Aquila earthquake. More seriously, he did repeatedly emphasize the importance of the need for earthquake resistant construction that provides "*safety to human life, with greatest practicable economy … sought through use of local materials with which the people were familiar*" [11, p. 562].

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Finally, although timber, which has traditionally been over-harvested in Pakistan, is used in these houses, most of it could be salvaged from the damaged and collapsed houses, and the amount needed for the rest meets sustainability quotas on the local forests. 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. Wood is nature's most versatile renewable building material. Stone and unfired earth, together with wood, represent the most energy efficient materials that can be used for building construction. In addition, fired brick and lime mortar are materials which require far less energy to manufacture than Portland cement. Thus, identifying traditional vernacular construction practices that have performed well against one of the strongest forces that nature can throw at structures also can serve to provide a lens through which to 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, with a minimum of formal education, traditionally had learned how to build successfully for themselves with materials readily at hand.

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