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Saga of the Half-timbered Skyscraper:

What Does Half-Timbered Construction have to do with the Chicago Frame?

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Introduction

What does half-timbered construction have in common with the first generation of American skyscrapers? The answer is that both structural systems use masonry engaged and confined within a structural frame, rather than masonry walls carried to the ground independent of any internal framing. The English term "half-timber" refers to only a small subset of this structural typology, which can be characterized as *thin-wall composite construction*.

Figure 1. (L) Undamaged *himis* construction in Gölcük, Turkey. (R) 1913 Woolworth Tower by Cass Gilbert, is now the tallest building in Lower Manhattan after the collapse of the World Trade Towers.

Tall buildings have been constructed in load-bearing unreinforced masonry, but building multi-story buildings efficiently and economically has always required alternatives to masonry alone. For buildings constructed before the advent of iron, steel, and reinforced concrete, this usually meant the use of timber. Timber has sometimes been used inside of the masonry walls themselves to bind them together, and although rare in monumental buildings, timber lacing of masonry as a means to keep the masonry from separating has been common for domestic and commercial buildings throughout history. In the most common form of this kind of construction, the timber forms a complete frame, and masonry is used for infill to form walls. Regional manifestations of this construction type have been called "*colombage*" in France, "*fachwerk*" in Germany, and, of course, "half-timber" in Britain. In Turkey, it has been called "*himis*" and in Kashmir, is called *"Dhajji Dewari."*

Reinforced concrete now has been adopted for the structural frame of buildings in most parts of the world, with the exception of North America, Scandinavia, and a few other areas where timber remains plentiful. In a few places, in Iran for example, light weight steel frames are more commonly used. Low to mid-rise steel and concrete buildings are still most commonly constructed with brick or hollow clay tile (HCT) masonry infill forming the partitions and exterior walls.

Figure 2. (L) Juarez Hospital after 1985 Mexico City earthquake with neighboring (C) undamaged infill-frame RC building. (R) Steel building after 2003 Bam, Iran earthquake.

At the 13th WCEE, Fouad Bendimerad 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"* – and earthquakes over the past half-century supports this finding. The critical question, therefore, is how a technology of building construction based on these promising new strong materials of steel and reinforced concrete could ultimately be connected to such searing catastrophes as these recent earthquakes during which tens-of-thousands have died? Is it sufficient to explain such pervasive and repeated calamities by pointing at bad quality construction practices, or can one also learn something from the performance of frame and infill-wall construction over the centuries? This paper will explore this issue by looking at construction methods and building performance from an historical perspective.

Chicago and the First ‘Skyscraper’

The earliest buildings that were called “skyscrapers,” a term previously applied to the top sails on clipper ships, given not simply because they were tall, but because they had metal skeleton frames. Thus, while the 10 story 1884 Home Insurance Company Building with an almost complete iron frame is often referred to as the first “skyscraper”, the 17 story 1891 Monadnock Building with unreinforced masonry bearing walls is not a “skyscraper.”

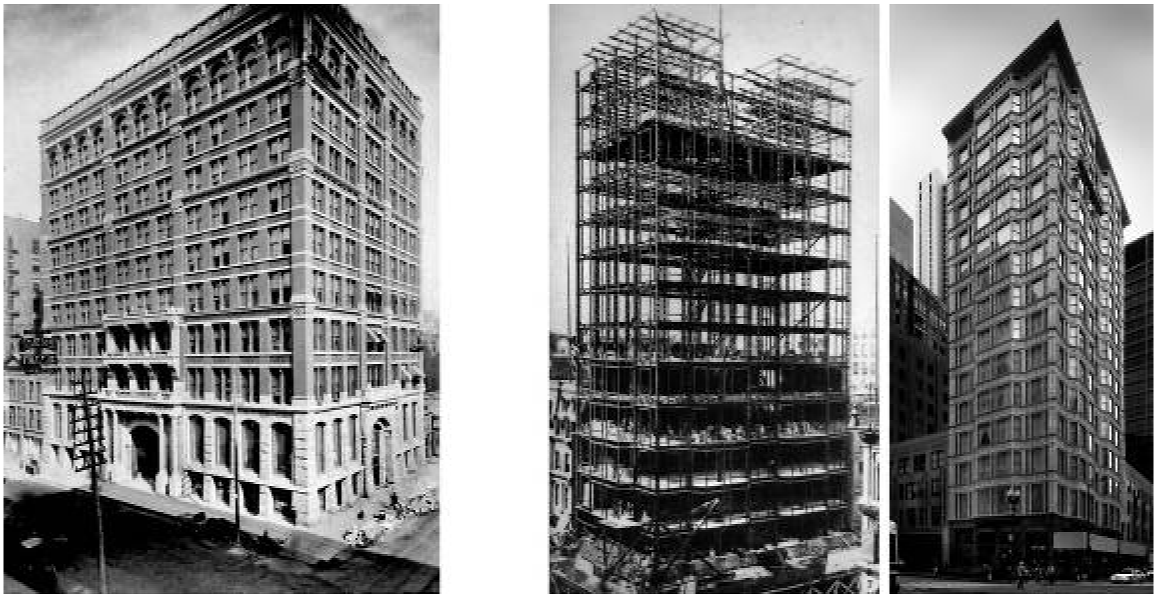

Figure 3. (L) Home Insurance Co. Building (1884) (Univ.Melbourne).
(R) Reliance Bldg, 1894-5 showing steel frame, and 2005 view of renovated building.

A debate has long-since raged among scholars and architects as to who “invented” the skeleton frame form of construction, and which building was the first to have this seminal new form of construction and thus earn the imprimatur “skyscraper.”

Iron post and beam frames had been used for building construction for several decades before its use for tall commercial buildings in Chicago and New York. Factory construction with cast iron columns and wrought iron beams date back almost to the early 19th century in England, and the Crystal Palace by Paxton constructed for the 1851 Exhibition in London was a multi-story structure constructed almost completely with an iron frame clad only with glass. The 19th Century height record, of course, goes to Gustave Eiffel’s tower in Paris, a wrought iron frame structure that was the equivalent of a 100 story building, but it was in Chicago that this technology was first applied to tall office building construction.

The critical step in this evolution is that the exterior and interior walls were supported by the frame so that *“each floor is independent of the other, so that the entire framework could be put up and then the mason[s] begin laying the walls at the sixteenth instead of the basement story…”*(Boston Journal, 1891, p. 5/6, cited in Webster,1959). In fact, this change did not happen all at once. The Home Insurance Company Building of 1884-5 by

William Le Baron Jenney, the building most often cited as the first true “skyscraper ” (even though of a mere 10 stories later expanded to 12), was designed to transfer only a portion of the weight of the exterior masonry walls onto the frame. Jenny designed the firewalls and exterior masonry piers that extended from foundation to the roof to carry their own weight directly to the ground, while the spandrels rested on the iron columns that were imbedded in the brick piers with a clever design that could accommodate differential settlement without cracking.

Figure 4. (L) Flatiron Bldg (1902), NYC. Masonry façade with construction beginning on upper floors at same time as at foundation (vazyvite.com). (C) Flatiron Bldg. (R) 343 Sansome, San Francisco.

The issue of Home Insurance Company Building’s claim of this title remained enough of an issue that, in 1931 when the building was demolished, a special committee was formed to examine the revealed frame to determine whether it could be considered a skeleton frame building. After investigation, the Committee concluded that the building possessed a true skeleton frame and could “claim the title of ‘Father of the Skyscraper’ (Tallmadge 1931, p. 113), but this finding did not deal with the question of what role the infill masonry is intended to have in resisting lateral forces.

The Structural Role of Masonry in Skeleton Frame Skyscrapers

Historians have focused almost exclusively on the historical shift from load bearing walls to the use of a skeleton frame to carry wall loads. This question was frequently debated in the early part of the 20th Century as if it was a moral imperative, rather than simply a watershed event:

> Metal construction may be raised hundreds of feet from foundation to roof without the aid of any masonry – a great metal structure, strong in its own strength, not only to carry the direct loads which may be placed upon it, but also to resist all lateral strains to which it may be subjected.
>
> (Birkmire 1894, P2)

However, like many other early Chicago Frame buildings, the Home Insurance Company Building had no wind braces – as there was believed to be no need for them because the masonry of the exterior and the hollow clay tile partitions was believed to be sufficient to take the lateral loads on the building (Condit 1968, p.125).

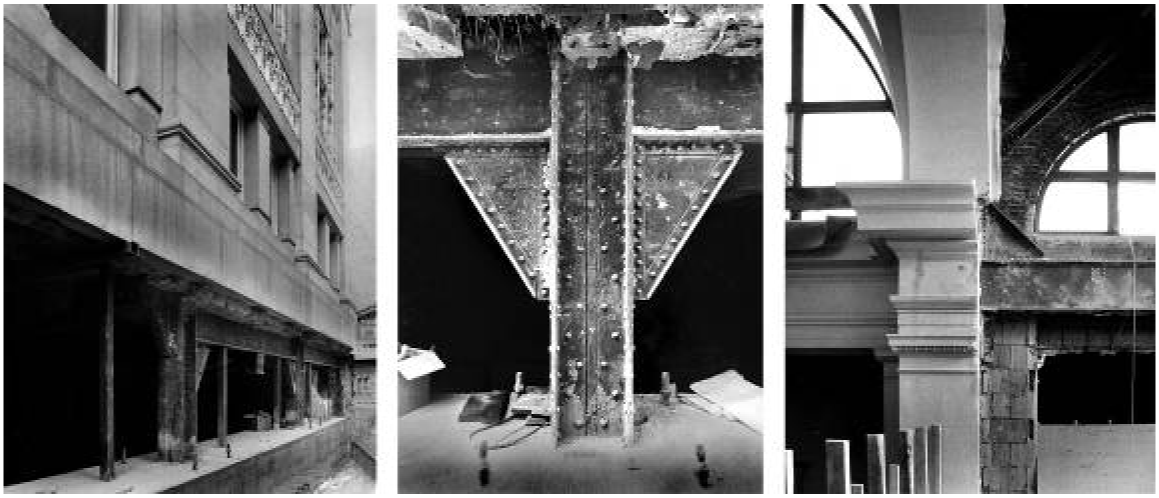

Figure 5. Oakland, Calif. City Hall (1911-14) showing imbedded steel frame revealed at base and in interior during seismic retrofit project in 1993.

As late as 1901, a contemporary structural engineer, Joseph Kendall Freitag, in: Architectural Engineering with Especial Reference to High Building Construction, observed:

> "'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 (to borrow a comparison used by various writers) make possible the effective service of the component bones"
>
> (Freitag 1901, p 9)

In both the 1895 and 1901 editions, Freitag elaborates on this by saying that a skeleton frame building *"should be safe…if the exterior of the iron framework is covered with well built masonry walls of sufficient thickness"* in lieu of diagonal rods for sway braces because *"the rigidity of the solid walls would exceed that of a braced frame to such an extent that were the building to sway sufficiently to bring …bracing rods into play, the walls would be damaged before the rods could be brought into action."* (Freitag 1895, p.137 & 1901, p. 250)

Freitag, however, is critical of the total reliance on the infill masonry for lateral support: *"This method of filling in the rectangles of the frame by light partitions may be efficient wind bracing, but the best practice would certainly indicate that it cannot be relied upon, or even vaguely estimated"* (1895, p137 & 1901, p249) What is most significant in terms of later developments is that he raises the problem of the need to calculate the contribution of the masonry infill, a problem that plagues engineers even today: *"While the steel frame is more or less reinforced by the weight and stiffening effects of the other materials, still no definite or even approximate values can be given to such items, except their purely static resistance or weight"* (1901, p256).

Figure 6. (L) Portal arch wind bracing in Monadnock Building, South Half (1891-3). (R) Cladding on 90 West Street (1907) damaged by World Trade Towers collapse showing steel shelf angles.

Despite the early efforts to reduce weight and transfer all loads to the skeleton frames, masonry continued to be commonly used for the enclosure and partitions in high-rise buildings until about the middle of the 20th Century. These masonry walls were designed to be *"thin curtain walls"* supported by the frame "*12 to 20 inches in thickness*" (Birkmire 1894, p.2). This amount of masonry is still a considerable amount of weight, but it could provide added resistance in a high wind or earthquake, even if the original designers had disregarded it in their calculations. For example, a 1938 report on the tallest, and one of the last, examples of this type, the 1931 Empire State Building in New York City, reveals that the infill masonry at the 29th and 41st floors cracked during a storm with wind speeds of 90MPH. Strain gauges that had been placed on the steel only began to register strain in the steel frame after the masonry cracked, thus showing that it was the "non-structural" masonry infill that bore 100% of the lateral loads until cracking (Rathbun 1938, pp. 1335-1375, reported in Eldakhakhni 2002).

The Great San Francisco Earthquake and Fire of 1906

While the lateral force on tall buildings in the "windy city" was that of wind, the ultimate test of the capacity of skeleton frame buildings would come during the 1906 San Francisco earthquake where Chicago Frame buildings (some even by Chicago architects) had already been constructed.

The fire burned through the city for three days after the earthquake, burning out the interiors of almost every one of these "fireproof" buildings. Distinguishing earthquake damage from that of the fire is thus particularly challenging, but contemporary reports agree on the fact that their performance ranged from good to extraordinary. This is demonstrated by the fact that many of these buildings are still in existence for the 100th anniversary of the earthquake. The steel frames were rarely found to be damaged, except as a direct result of the subsequent fire.

Figure 7. San Francisco in 1906 showing Chicago Frame buildings that burned out but remained standing. All of the taller buildings in these images are still extant in 2006. (Bancroft Library)

An engineer for The Roebling Construction Company of New York City that had patents on some of the pre-fire floor systems, reported in 1906:

> The successful manner in which the tall, steel skeleton frame buildings withstood the effects of the earthquake and the fire is most reassuring, in fact wonderful, and proves conclusively that the best modern practice is directed along correct and efficacious lines. …These buildings had never before been subjected to violent earthquake shocks, and many architects and engineers doubted their ability to withstand such surface movements without injury. …In all cases when the structural details were designed in accordance with the best modern practice and executed with skill and workmanship of only fair quality, the buildings passed through the earthquake without structural injury.
>
> (Himmelwright 1906, p.7)

Figure 8. St Francis Hotel lobby after the 1906 earthquake and fire, and same space still extant 100 years later. (Roebling, 1906)

When evaluating these buildings, it is important to realize that for earthquakes, unlike for wind where maximum forces are used, the forces are so large that even today, the codes are based on an expectation that damage will occur. Thus, proper comparative evaluation of these 1890-1905 buildings in the '06 earthquake must include an assumption that some damage is expected even for good performance.

Interestingly, the 1906 damage can be compared to the fate of downtown Oakland in the 1989 Loma Prieta earthquake, where a number of early 20th century Chicago Frame construction buildings suffered the cracking of the infill masonry. In this later earthquake, the only skeleton frame building to suffer significant exterior wall collapse was the Oakland Hotel – ironically, the only large skeleton frame building that had been given a seismic upgrade. As part of this work, all of its original masonry interior partitions had been removed and replaced with light wallboard, making the building more flexible (Langenbach 1992), which resulted in greater damage than can be seen in the photographs of San Francisco's skeleton frame buildings in 1906, which helps to confirm Freitag's 1895 (p.137) observation about the interplay between braced frames and masonry infill.

Figure 9. (L) The Oakland Hotel showing damage to façade, and later during repairs. (R) The Touraine Hotel, Oakland, California showing masonry exterior infill during upgrade work.

The Roebling Company also made prescient observation about reinforced concrete construction, which in 1906 had only just begun to be used:

> Enthusiastic persons…have [been]…advocating buildings constructed entirely of reinforced concrete as a type well adapted to resist earthquake shocks. …Many of the statements so published are misleading. It would therefore seem appropriate and necessary to sound a note of warning and conservativism to those who contemplate the erection of buildings of this class in sections subject to earthquake disturbances. …It is well known that the standard connections in a well executed structural steel design will bear a considerable amount of distortion before being damaged or weakened to any serious degree. …In reinforced concrete construction, however, slight displacements or settlements are of vital importance and a menace to the safety and integrity of the building. The light rods and bars which are ordinarily employed for reinforcing and which are anchored in the concrete or simply hooked together, lack the positive rigidity, strength and tenacity of the standard steel connections, and would in no case withstand the same distortion without failure.
>
> (Himmelwright 1906, p. 261-2)

Modern Movement – Structure as Architectural Expression

When one reads about the contest over which building was the first “true” skeleton steel frame” skyscraper, one gets the impression that the introduction of shelf angles (Figure 6) supporting the exterior cladding and the eventual elimination of masonry all together would lead not only to a new building type, but to a better way of building. For architects, it would mean the opening up of the interiors and the elimination of the thick membrane that had historically separated the interior from the world outside. This provided the basis for what would become a major philosophical shift in architecture, marking the emergence of what came to be termed “Modern Architecture,” or what Swiss architect Le Corbusier (1887-1965) called the “New Architecture.”

From the influential writings of a contemporary of Le Corbusier, Sigfried Giedion, one can gain an idea of how architectural design philosophy was influenced by changes in structural form, and then in turn helped to further those changes in profound ways. For example, in the caption to a 1927 construction photograph (Figure 10) of a multi-story housing block in Stuttgart by Mies van der Rohe, Giedion says:

> “It took more than half a century before the importance of the iron skeleton for apartment houses was recognized. The conclusion to be drawn here from the construction is: fixed interior walls are senseless in this type of construction! Each tenant should be given the opportunity to arrange his dividing walls freely according to his own needs.”
>
> (Giedion 1927, p. 131)

The photo shows the building supported by a steel frame of thin steel members that subdivide the thin exterior masonry wall into panels, with an absence of interior structural walls or shear walls – remarkably similar to many steel infill-frame buildings which collapsed in the Bam, Iran earthquake of 2004.

Later in his book, Giedion turns with an embracing excitement to the work in reinforced concrete of Le Corbusier, beginning with Le Corbusier’s 1915 iconographic drawing of the prototype structural form for multi-story residences known as the “Dom-Ino” house. Le Corbusier’s image of the bare concrete skeleton of the Dom-Ino House (Figure 10) stands as an icon of the “New Architecture” of which he was a chief proponent. Le Corbusier succeeded in making this simple diagram a symbol that remains powerful and pervasive today:

> Out of the possibility of hanging the whole weight of a building on a few ferroconcrete pillars, of omitting the enclosing wall wherever one so desires, Corbusier created…a single, indivisible space. The shells fall away between interior and exterior. … There arises…that dematerialization of solid demarcation…that gradually produces the feeling of walking in clouds.
>
> (Giedion 1927 p. 168-9)

The Modern Movement not only brought skeleton frame construction into the realm of mid-rise housing, but established the philosophical basis for the removal of the walls from the structural system. The “Dom-Ino” frame became the basic structural system for housing construction that spread, first through Europe, and then the rest of the world, including earthquake hazard areas.

What seems to have been missed in this philosophical embrace of *"the eternally open house,"* is that the dematerialization of the walls that lay at the philosophical center of the "New Architecture" collides directly with the enclosure requirements of completed buildings. As a result, masonry did not disappear. The problem was that the robust multi-wythe thick infill walls that served as both enclosure systems and wind braces for the first skyscrapers had evolved into thin single-wythe membranes of insufficient strength to provide much supplemental resistance in the event of earthquakes, yet their weight added significantly to the lateral forces that had to be resisted by the frame.

Figure 10. (L) Construction in 1927 of Stuttgart Werkbundsiedlung (Giedion, 1928). (C) Le Corbusier's Dom-Ino House, 1915. (R) Gölcük, Turkey building under construction at time of 1999 earthquakes.

Compounding this problem was the frequent use of open "piloti" or shop fronts on the ground floor, as Le Corbusier had advocated, which caused a risk that became defined as a "soft story" (see Figure 15 for soft story collapse). It is in these kinds of buildings in which tens of thousands have died in earthquakes in different countries around the world, including recently in Turkey and Taiwan in 1999, India in 2001, Morocco in 2003, Pakistan in 2005, as well as other countries.

Figure 11. Mexico City 1985 earthquake: (L) Collapsed RC Parking garage. (C) RC frame showing column damage and loss of infill. (R) Bent steel frame in ca.1940 building with too little masonry to help.

Building in Earthquake Country

How can it be that the introduction of steel and reinforced concrete could be implicated as a cause, rather than a mitigation, of recent earthquake catastrophes? Is it appropriate to blame this all on bad construction, or is there a fundamental difference between the original invention of the skeletal frame, and the later decision to make such frames do *all* the work of holding a building up, even in large earthquakes? For an answer to these questions, it is worth looking at the historical precedent for modern infill-frame construction.

In 1883, noted Chicago architect, Irving K. Pond, writing for the Inland Architect and Builder wrote an article about his European travels in which he focused on the timber frame and masonry infill construction he observed in Spain where it was still being practiced:

> There is a tendency, from the very first days of Spanish building, to treat the wall, not as a homogeneous mass of masonry or brickwork, but rather as a frame filled in…with…mud, clay, or brick. …In some cities rolled iron beams are used for the frame, though timber frames are more common. Even minor partitions are so constructed; so that it is not uncommon to see the frame complete to the height of three or four stories, before the masonry has been carried above the foundation.”
>
> (quoted in Condit 1968, p. 129 & Look 1972)

Today, the historic center of Madrid is known for its solid masonry five to seven story façades, but this is an illusion. Almost all of these 18th and 19th Century buildings are in fact timber infill-frame structures hidden behind a single layer of masonry and stucco (Langenbach, 2003; Gonzales Redondo, 2003).

Figure 12. Historical center, Madrid showing front façades and infill masonry timber frame construction revealed on rear walls after demolition of adjacent structures in 2002.

It is intriguing to think of the possibility that the subject of this article may have influenced William Le Baron Jenney when he designed the Home Insurance Co. Building constructed a year later. While it may seem to stretch credibility to draw a connection between the traditional way of building that in 1883 was still being practiced in Spain as Irving Pond had reported, and the design of the first skeleton frame skyscrapers, the connection is not so remote as today one may imagine. Timber frame with masonry infill construction is a form of composite skeletal frame construction that dates back almost to the beginning of recorded history, and perhaps even beyond that. 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 2 story "half-timber" house which Archeologist Amadeo Maiuri referred to by what Vitruvius called "Craticii." (Langenbach, 2003a&b) This 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, because the 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 (http://mars.acnet.wnec.edu).

Thus, the Chicago architects and engineers did not invent infill-frame construction; but rather, they adapted it for skyscrapers by wrapping iron and steel frames with masonry. While the later theorists placed importance on the purity of having the skeleton frame support all loads, heaping criticism on those practitioners who continued to rely on masonry, the first skyscraper engineers were conscious of the fact that the infill walls, which they needed anyway for enclosure and fireproofing, provided the most efficient means to resist wind. In 1906, in San Francisco, these same walls were called upon to resist large earthquake forces as well.

The Legacy of the Infill-Frame

Madrid is not subject to earthquakes, but Lisbon is. What is believed to be the largest known earthquake to hit Europe struck Lisbon in 1755, also causing a tsunami and fire. In planning for the rebuilding of the central area, Chief Minister Sabastiao Jose de Carvalho e Melo (who later became the Marquis of Pombal), gathered a group of military engineers led by Manuel da Maia to determine the best manner of earthquake-resistant construction to use for the rebuilding. They developed the *gaiola* ("cage") a well-braced form of half-timber construction that has become know as Pombalino construction. After testing a prototype, they made its incorporation into the reconstructed buildings a requirement (Penn, et al, 1995).

Figure 13. Interior of late 18th Century building with Pombalino walls revealed during renovation work in 2003. This example has does not have the *gaiola* frame extending into the exterior masonry.

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

The inspiration to use this system was most likely from the observation of surviving half-timbered structures after the earthquake (Figure 14). This is consistent with the eyewitness report by Reverend Charles Davy, who alluded to the distinction between what stood and what fell in his comment: *"With regard to the buildings, it was observed that the solidest in general fell the first."* (Tappan 1914) The significance of the Pombalino system lies in the fact that it was *deliberately* developed and selected as earthquake-resistant construction for a major multi-story urban area.

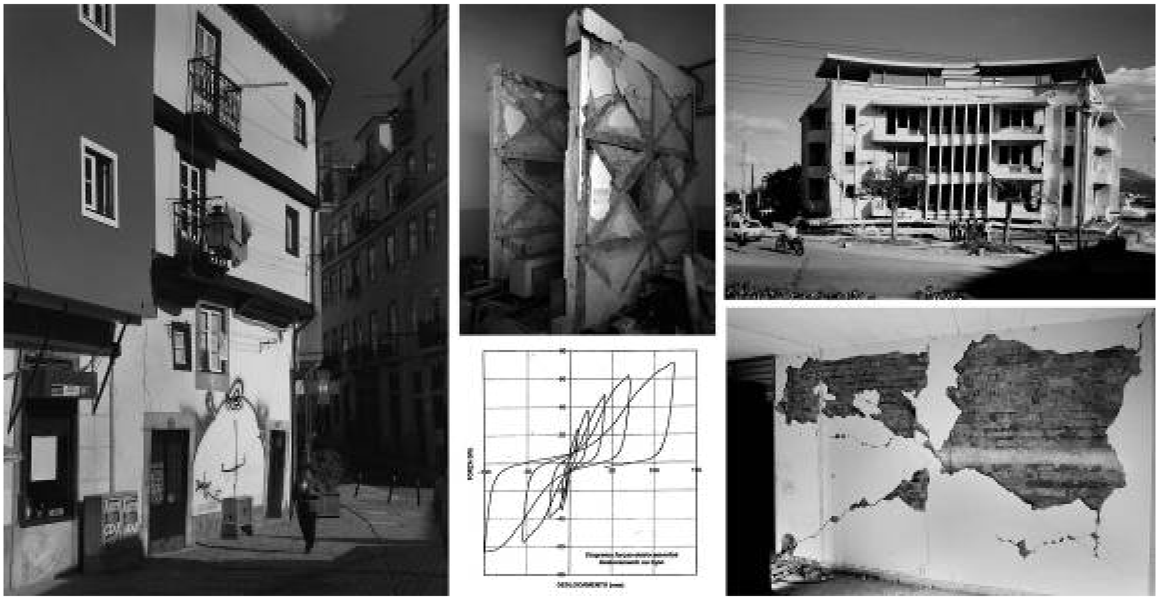

Figure 14. (L) Pre-1755 timber infill-frame building. (C) Lab test of *Gaiola* with hysteresis. (R) El Salvador building after soft-story collapse in 1986 earthquake with upper floors held up by strong infill.

The only other example known where this type of construction was developed specifically for earthquake resistance is in Calabria and Sicily, where there had been frequent devastating earthquakes including one in Calabria 28 years after the Lisbon earthquake. This Italian system was known as *"Casa Baraccata,"* which was likely influenced by the Portuguese "Gaiola." In Italy, the *Casa Baraccata* (Figure 21) became the underlying basis for a whole series of manuals of practice, and even of patent applications for seismic resistive construction techniques up until the beginning of the 20th Century. (Barucci, 1990).

For recent earthquake tests of this kind of construction, one can turn to Turkey and India. Most recently, the October 8, 2005 earthquake killed approximately 80,000 in Pakistani Kashmir. Traditional infill-frame construction, known locally as *Dhajji Dewari* ("patchquilt wall") is common in Indian Kashmir (Figure 15), but has not been found on the Pakistan side where the shaking was greatest. This type of construction performed better than the conventional masonry buildings of more recent construction. The high mortality was almost exclusively from the collapse of relatively new concrete and rubble stone buildings that lacked any form of timber lacing. Indian Institute of Technology, Kanpur Professors Rai and Murty in their reconnaissance report on the earthquake, observed:

> 'Dhajji-dewari'…has excellent earthquake-resistant features. No collapse was observed for such masonry even in the areas of higher shaking. The presence of timber studs, which

> subdivides the infill, arrests the loss of the portion or all of several masonry panels and resists progressive destruction of the rest of the wall. Moreover, the closely spaced studs prevent propagation of diagonal shear cracks within any single panel, and reduce the possibility of out-of-plane failure of masonry of thin half-brick walls even in the higher stories and the gable portion of the walls… Timber-laced masonry can maintain its integrity even when the supporting masonry walls in lower stories are severely damaged [as seen in Figure 15].
>
> (Rai and Murty 2005)

Similar construction affected by the 2001 Gujarat earthquake also showed minor damage, whereas many nearby RC new multi-story apartment blocks collapsed (Langenbach 2003a&b; see also www.conservationtech.com). Both Kashmir and Ahmedabad shared a timber-laced masonry building tradition with Turkey, where timber-with-brick-infill vernacular construction is documented to have first appeared as early as the eighth century (perhaps as a result of the reach and influence of the Ottoman Empire) and continued to be common until the latter half of the 20th Century, when it was rapidly replaced with reinforced concrete (Gülhan and Güney, 2000). .

Figure 15. (L) Herculaneum "*Craticii*" construction. (C) *Himis* Construction, Turkey. (R) New *Dhajji Dewari* construction, Srinagar, in 1981, and house in Baramula after 2005 Kashmir earthquake.

In Turkey itself during 1999, the Kocaeli and Duzce earthquakes killed over 25,000. In amongst the collapsed reinforced concrete buildings from both earthquakes were the unassuming infill-frame masonry buildings, known as *himis* construction, which had survived the earthquake, often with only minor damage (Figures 1&15). So too, in the former Yugoslavia, Greece, and Central America, variations on this construction system have demonstrated resilience in past earthquakes. (For a full description of these observations, see Langenbach, 2000, 2003, 2004). The way these pre-modern infill wall buildings responded to the earthquake vibrations is not unlike the way that the Chicago Frame structures behaved in the 1906 San Francisco earthquake. As with the traditional construction, the infill masonry, which was confined by the relatively closely spaced members of the early steel frames, served to protect the underlying frames by yielding first, and then dissipating energy without falling out.

CONCLUSION

Steel and concrete skeleton frame construction began at the end of the 19th Century and evolved with remarkable rapidity through the 20th Century until it has become standard around most of the globe. Its widespread acceptance is more than just a result of an abstract notion of people doing what is seen as "modern;" it is also because it is believed to be stronger and safer than pre-existing local forms of traditional construction. In fact, the unfortunate legacy of the multitude of pancake collapses of concrete frame buildings in large earthquakes belies this confidence.

To lay the blame for this on Le Corbusier and his contemporaries is not entirely fair. Many engineers claim that RC moment frames are strong and would have worked had they been constructed correctly, but this goes to the very heart of the problem. Many of the buildings constructed nowadays *cannot* be expected to meet exacting earthquake engineering standards, especially for reinforced concrete, where common construction mistakes remain hidden. Light steel frames have also suffered from poor field welding. If seagoing vessels are poorly designed or constructed, they sink, like the Swedish Galleon Vasa did only a few minutes after beginning its maiden voyage in 1628 (www.vasamuseet.se). Bad buildings, on the other hand can sit there for years or decades before they experience large but rare environmental force they should be able to resist, but cannot.

Structural Engineering has gone through its own revolution over the past century. The 19th Century was an era of enormous ferment, producing engineering giants like Brunel and 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 to 20 stories to over 100 stories. To accomplish this, engineering practice shifted from a largely empirical process to one of rigorous mathematics. Portal frame analysis based on the contraflexure methodology of isolating moments was invented and became the standard methodology for code conforming building design. This calculation method was both simple and accurate enough for it to have remained in use through the entire 20th Century, up until the present for the design of most skyscrapers (Robison, 1989). Not only is the inelastic behavior of masonry very difficult to quantify mathematically, it also does not fit conveniently with portal frame analysis, so there was a technical as well as a philosophical reason for its elimination from the structural design calculations.

The solution was, unfortunately, to simply ignore the masonry in the calculations (except as dead weight). The seemingly reasonable explanation for this was that by including only its weight, the design would be more conservative than if it also were included as part of the lateral resisting system. Walls could then be moved at will, and the frame (in theory) would be strong enough. The experience with low to mid-rise frame buildings 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 building structures are expected to deflect into the nonlinear range. In other words, the structure of the building (that is the skeleton frame) will go inelastic in a design-level earthquake, which means that structural damage is expected to occur. For frames, this has been recognized in codes through the use of ductility factors which are assigned based on the individual elements that make up a structural frame, but such factors are unresponsive to the conditions that exist when "non-structural" infill masonry is added to the system, as this masonry is usually a stiff and brittle membrane contained and restrained by the frame that changes the behavior of the frame, sometimes with catastrophic results.

The masonry infill commonly found today in the modern vulnerable buildings is much weaker and less densely packed into the frames than in the early Chicago Frame buildings. It can interfere with the idealized performance of the frames by throwing stresses onto portions of buildings that are not capable of resisting because of localized crushing and falling out of the frame (Figure 11). For skyscrapers this was not a common problem, because both the frame and the infill walls had to be robust and well constructed enough to support the much higher dead, live, and wind loads (Figures 4&5).

This description of the historical context for modern construction practice is not meant to advocate a return to an empirical form of engineering design, or the jettisoning of modern ways of building, but simply to focus on what has worked in the past as a lesson for the future. (For a proposal for seismic hazard mitigation based on traditional infill-wall construction known as "Armature Crosswalls" see Langenbach 2003b). Modern construction materials and methods have brought with them extraordinary opportunities for new spaces, forms, and ways of building, but in many parts of the world they have also been disruptive of local culture, resulting in building forms and ways of building that are alien to the local society. The earthquake risk is just one way that we can observe what this disruption represents in terms of a loss of cultural and technical memory, when the new ways of building are not sufficiently well enough understood or respected to give any confidence that they will be carried out to an acceptable level of safety. By opening up to learning from indigenous pre-modern examples of earthquake resistant technologies, we also can learn to preserve the surviving examples of these now seemingly ancient ways of building in a way that respects what these buildings are, not just how they look.

Recent catastrophes show there is much to learn about how to build in a safe and durable manner. Well engineered and constructed modern buildings have fared well in earthquakes, but good public policy challenges us to meet the needs of a broader range of rural and urban populations than have access to well-trained engineers and builders. It is in this realm that the construction methods developed before the introduction of modern materials and modern computational tools have much to teach us. Old ways of building based empirical wisdom passed down through the ages will probably defy most attempts to rationalize them into systems that can be fully calculated, but the evidence remains that some of these systems nevertheless worked quite well. This was true despite the extreme and unpredictable forces experienced in earthquakes that have confounded many efforts to fully predict or protect against the impact of these forces on the plethora of buildings that make up the contemporary city.

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