



The Great Counterintuitive: Re-evaluating Historic and Contemporary Building Construction for Earthquake Collapse Prevention

Randolph Langenbach
Conservationtech Consulting

ABSTRACT: This paper discusses a way of classifying the differences in construction typology of buildings from around the world and of all ages. This classification is intended to focus on building performance in earthquakes, with pre-modern as well as contemporary code conforming construction materials and systems. Instead of using the classic subdivisions found in most building codes which are organized around construction materials and structural systems, the author explores an organization of structural systems along a continuum from ‘solid walls’ to ‘frames,’ with ‘mixed-wall dominant’ and ‘mixed-frame dominant’ in the middle. The discussion of this provides a platform for exploring different approaches towards the analysis of buildings that is more responsive to the inherent resilience of certain forms of archaic construction. This can also lead to the recognition of retrofit alternatives that utilize certain traditional masonry construction practices in more effective combination with steel and reinforced concrete than often has been seen in recent years, where such combinations have contributed to collapses.

1 INTRODUCTION: SLAYING THE GREAT GOD OF “PROGRESS”

My work in the field of Architecture and Heritage Conservation began in New England when I became interested in the 19th century architecture and town planning of the first planned industrial towns in North America. Driven at first by water power, these large but uniform interconnected rows of giant multi-story timber and brick textile mills along canals merged together, appearing from a distance like medieval walled cities – except that their walls were penetrated by the large double or triple hung sash windows necessary to let in the light for the workers to see their work in the days before the electric light (Figures 1 & 2).



Figure 1. Crown and Eagle Mill, Uxbridge, MA., USA, ca. 1825.
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Figure 2. Interior of Mill showing typical “slow burning” heavy timber construction and brick masonry walls, Amoskeag Millyard, Manchester, NH, USA, Ca. 1835.

At the same time, my interests gravitated towards pre-industrial historic structures of the colonial era in the USA, or even from earlier eras in Britain and in Europe. This included rural and urban vernacular construction that was also of masonry with timber, but very different from the 19th century factory buildings. When I later moved to the West Coast of the United States and confronted the issue of earthquakes, these two seemingly distant typologies provided the basis for what would then become an exploration not only in space, but in time. It has taken me around the globe a number of times, and forced me to consider more than just the architectural attributes of the industrial and pre-industrial heritage structures, but also to explore the question of what people knew in the past – about construction – about structure – and about forces on buildings. The lateral forces in one setting were from the vibrating machines, and in the other, from earthquakes – natural forces that continue to this day to bewilder mankind, in spite of all that modern materials and technology has provided.

Many of us were brought up in the post-war era of the ubiquitous belief in “progress.” The U.S. Government’s program called “Urban Renewal” was promised as a fast step into a future of modernity and a better life – a program that in retrospect is better characterized as having achieved with bulldozers the kind of destruction of the central core of some cities not unlike that experienced from the air in Europe during World War II.

Now – only a short 30 to 50 years later – many of the new buildings built during “Urban Renewal” to replace the old are themselves being torn down because of their obsolescence and rapid deterioration, and even the widely held view now that they are ugly. Heritage preservation in recent years has been more widely embraced as a part of urban development plans.

One now must wonder whether the “progress” that we were led to believe is the consummation of the sum total of all that was worthwhile, and whether the supposed scientific and technical know-how is really that, especially as it fails to recognize what has been forgotten. This is more than just recognizing and recalling history; it is an understanding that knowledge as broad and extensive as our own is embedded in the artifacts of the past.

This is particularly true with buildings, which at their best are a product of art, science, and craft - a knowledge that is different from the conventional wisdom of our own day. Most crucially, embedded in this ancient knowledge are the embryos of ideas and technologies that can solve critical building design and construction problems in the modern day. From my current vantage point in California, it is the impact of earthquakes on masonry buildings that has led me to explore this insight.

2 THE GLOBAL EARTHQUAKE MODEL (GEM) TAXONOMY

2.1 *A comprehensive ranking*

I recently consulted on a part of the European-based multi-national Global Earthquake Model (GEM) earthquake hazard awareness and mitigation project as part of a team convened to produce a taxonomy of worldwide building typologies based on their seismic performance. This seemingly impossible task proved to be quite an interesting challenge. It involved placing existing buildings of all ages, uses, sizes, construction systems and regional cultures side-by-side for analysis, to be used as the foundation of the vulnerability factors to be used in the GEM software. It is not often that one is asked to graph the earthquake performance and resilience attributes of skyscrapers together with medieval masonry houses, or even bamboo or wattle and daub construction in different parts of the world. .

This task makes one confront and question the conventional wisdom that pervades the fields of disaster mitigation and earthquake engineering. For example, on the GEM webpage on the Ontology and Taxonomy leads off with the following: *The GEM taxonomy should be able to distinguish differences in seismic performance between different building types, ranging from highly vulnerable stone masonry buildings to modern buildings designed in compliance with the latest building codes. (GEM Foundation, N.D.)*

To graph this on a vulnerability table, it seems logical that the line between these two typologies would, as the statement says, be from vulnerable to safe. Yet, where along this line would one place the Hagia Sophia in Istanbul (Figure 3), which has survived many earthquakes, when

many modern and presumed to be code-conforming reinforced concrete buildings in Gölcük in 1999 failed in just one? Even more to the point is the view of the stone mosque in Gölcük with its tall thin stone minarets standing intact after the 1999 Kocaeli Earthquake surrounded by the collapsed ruins of almost every modern reinforced concrete (RC) building around it. (Figure 4). How can one create a taxonomy that can be effectively used for a global vulnerability analysis if one fails to recognize and account for such potential departures from standard expectations that are only visible after an earthquake?



Figure 3. The Hagia Sophia in Istanbul has existed for over one and a half millennia. Repairs have been done and buttresses added after repeated earthquakes.



Figure 4. This intact unreinforced masonry mosque with its tall minaret in Gölcük, Turkey is surrounded by many RC buildings collapsed by the 1999 Kocaeli earthquake. *Photo: Enric Marti, Associated Press*

A recent quote published in the New York Times is illuminating here: *“A ranking can be heterogeneous, in other words, as long as it doesn’t try to be too comprehensive. And it can be comprehensive as long as it doesn’t try to measure things that are heterogeneous. But it’s an act of real audacity when a ranking system tries to be comprehensive AND heterogeneous.”* (Gladwell, 2011) This quote well describes both the parsing of the structural attributes of building typologies around the world, but also for the creation of the vulnerability codes to be used in the GEM software. *“Audacity”* in this case is not far from the truth. Earthquakes are heterogeneous, and buildings – even those with the same kind of structural systems – are often idiosyncratic enough to have very different performance when subject to forces which, even for code-conforming modern buildings, take them beyond their elastic limit. Even within a single structural typology and proximate years of construction, the breath between good and poor performance can be very wide indeed.

2.2 A heterogeneous ranking

Earthquakes are unique among natural forces for which buildings are specifically designed to resist, because the presumption in modern code-conforming design is that inelastic behavior (i.e. structural damage) will occur. Most code analysis is based on linear elastic methodologies which are proxies for inelastic behavior of the structural system. This can be problematic when these tools are applied to archaic systems for which these codes were not specifically written. The results can lead to over-conservative interpretations for the simple reason that the inherent capacities of archaic systems are either left out of the calculations, or reinterpreted in ways that do not conform to their inherent properties. For example, steel or concrete frame buildings with masonry infill often have been analyzed as bare frames with the infill treated as dead weight, rather than a structural membrane of confined masonry with the properties of one part – the frame – dependent on the properties of the other part – the masonry. However, many such buildings (such as the City Hall in Oakland, California, USA shown in Figure 5.) have demonstrated a greater resilience in actual earthquakes than had been predicted.

Ironically, and at times tragically for structures recognized in the code, this can lead to the opposite situation when, for example, the architectural finishes that are not required to be part of the engineering analysis actually cause or contribute to the collapse of buildings. The primary example of this is when the infill material prevents “frame action,” on which the original engineering design is predicated, but is too brittle and weak to contribute to the lateral capacity of the structure once the system goes inelastic (Figure 6).



Figure 5. Oakland City Hall, Oakland, California, USA constructed in 1914. This is a steel frame, infill brick masonry building with a glazed terra cotta exterior.



Figure 6. A typical view of a pancake collapse of a 5 story reinforced concrete infill masonry building in Adapazari, Turkey after the 1999 Kocaeli Earthquake.

Earthquakes have only rarely succeeded in destroying every building of any given typology within a single event at one site. More often instead, vastly different performance has been observed in buildings that are found to be within the same construction typology. Sometimes there are subtle differences in their structural design, quality of construction, and orientation on the ground. While the aggregated loss predictions may be adjusted by defining a range and seeking the middle of the bell curve of building performance within each typology, doing so can be problematic if the outliers in one or both extremes may encompass a majority of the buildings of a particular typology at a particular locale. In many situations, this cannot be predicted in advance simply by examining the exteriors and interiors of the buildings because the design and construction characteristics or flaws are hidden (see Figures 6-9 for illustrations of this range).



Figure 7. An RC pavilion in Port-au-Prince, Haiti after the 2010 earthquake shows that the earthquake which caused such devastation could not collapse this, in spite of the fact that it has thin columns, a heavy roof and masonry infill in only a single bay – behind the photographer.



Figure 8. A boat on the roof of the only surviving building in this view in Otsuchi, Japan after the 2011 Tsunami demonstrates the remarkable resilience a well-constructed RC building. *Photo: Kimimasa Mayama/EPA published by the Boston Globe.*

One issue that adds even more heterogeneity to the GEM project that must be dealt with is the difference between anticipated risks of injury and loss of life on one hand, and economic losses on the other. Some damage results in economic loss but is of less risk to human life, while other earthquake-caused building collapses have resulted in many fatalities with small numbers of survivors. Also, some types of hazards can result in injuries which are less lethal, while others more so. With the pancake collapse of RC buildings, for example, human survival followed by timely rescue is less likely (Figure 9), whereas many survivors have been extracted from collapsed wooden buildings (Figure 10).



Figure 9. Aerial view of collapsed apartment houses in Golcuk, Turkey after 1999 earthquake. Most of the 17,000 fatalities (the unofficial estimate is over 25,000) in this earthquake were in pancake collapsed RC buildings. *Photo UN*



Figure 10. Collapsed timber framed multi-story apartment house in San Francisco after the 1989 Loma Prieta earthquake. There were only 3 fatalities in this earthquake caused by the collapse of timber frame buildings.

2.3 The 2003 Bam, Iran Earthquake

One poignant example is from the 2003 Bam Earthquake in Iran. Many of the buildings that collapsed with lethal consequences were not pancaked RC buildings, but rather, buildings with a combination of archaic and contemporary construction – adobe walls with steel and fired brick jack-arched roofs (figure 10). After the earthquake, hospitals in the nearby city of Kerman prepared for a flood of injured survivors, yet few came.



Figure 10. Collapsed building with adobe walls and steel and fired brick jack arch roof in Bam, Iran after the 2003 earthquake.



Figure 11. Partially collapsed adobe building of traditional unreinforced construction in Bam, Iran with most of its vaulted roofs still standing.

The reason was that the adobe walls surmounted by a steel and firebrick roofs turned out to have a greater likelihood of crushing the occupants, and the dust suffocated the few survivors.

The walls of most of these structures were not secured to the roofs, and as a consequence, the heavy steel and brick roofs would fall when the walls separated from them. Ironically, earthen buildings with the traditional construction of masonry vaulted roofs were observed to have done better on average than did those with the modern steel beamed roofs, although many of those did collapse as well (Figure 11).

2.4 *Frames and Solid Walls*

What can be gleaned from these examples with regard to the local hazard mitigation efforts for which the GEM is intended? Are they simply a confirmation that such efforts to identify hazards is futile, or that their diversity is simply too large, or that our ability to predict future performance based on descriptions of building structural typologies is too superficial to be effective? More importantly, is there any pattern in what has been observed in actual earthquakes that can lead to better construction in the future in a range of socio-economic and cultural environments, to avoid the kind of catastrophe witnessed recently in Haiti...in Iran...in Turkey...in Pakistan...in India...in China, and even in Italy and New Zealand?

It is easy to assume that the default approach would be to parse the data by structural material and system in standard curves from weak masonry to modern steel and concrete – but these fail to consider the problems described above. Instead, I have explored a concept that is emblematic of essential differences that may underlie ways to better mitigate against the kinds of extreme losses that have torn apart communities as diverse as Sichuan, China and Christchurch, New Zealand. It is to place the world's buildings into a single structural continuum with structural *frames* at one end and *solid walls* at the other. (The reason for not using the term “bearing wall” instead of “solid wall” is that a solid wall may or may not be bearing the floor and roof loads, but it still shares earthquake response characteristics with other solid walls, both bearing and non-bearing.) This is a typological, not a hierarchical, continuum. In other words, the placement of a system into this table under “frames” or “solid walls” is not a value judgment as to its resilience, but only a description of its type.

In a simplistic way this approach is believed to better capture an essential historical difference between buildings, compared to the more common building code focus on principle materials used in the construction of their structural systems – such as rammed earth, stone masonry, concrete, timber, steel, etc. Solid walls and frames distinguish between, for example, masonry buildings from timber frame or bamboo frame buildings, even though timber may span between masonry walls to support the floors and roof of a masonry building. It also allows modern steel skeleton frame skyscrapers to be recognized for an essential structural characteristic together with the smallest of frame structures –allowing in both instances the addition of descriptors and modifiers that can be used to parse the data into categories of seismic performance. Moreover, in between these two categories – structural frames and solid walls - are variations that encompass attributes of both typologies, and it is with these mixed typologies that the structural issues become particularly interesting.

It is in this mixed category that one can place such as historical building types as ‘half-timber’ buildings, such as the Turkish *hımış* houses, the Kashmiri *dhajji dewari* buildings in both India and Pakistan, and even the *colombage* houses in Haiti. Moreover, at a different location on the continuum, one finds the contemporary buildings with RC frames with masonry infills as well as the late 19th and early 20th century steel skeleton frame buildings with thick infill masonry and masonry cladding first found in Chicago, New York and San Francisco, which themselves followed iron framed masonry buildings in France, the UK, and even India.

2.5 *Mixed frame and solid wall construction*

The balance of my presentation focuses on mixed frame and solid wall construction, because in recent earthquakes such as those described above it has become impossible to ignore the risks of not paying attention to the structural dynamics that affect buildings in this category. This proposed taxonomy is thus instructive because it isolates the seismic performance attributes of this

‘mixed’ category of buildings from all of the diverse body of historic and present day building construction data – where, to use a particularly apt metaphor, “*the bodies are buried.*” While it is easier in the “solid wall” category to classify differences between round-rock rubble stone in mud mortar construction from buildings constructed of shaped ashlar with lime mortar, or, in the “frame” category to distinguish between frames with or without sufficient member and connection strength or flexibility, or with or without sufficient bracing or ductile design, this mixed category is where one finds most of what I have identified as pertaining to the “*great counterintuitive*”.



Figure 13. This was a 5 story RC frame building after the 1986 San Salvador earthquake caused a soft-story collapse. Figure 14 was taken in one of these remaining floors.



Figure 14. View of an infill wall in the building in Fig. 13. The fallen plaster has revealed that the wall was reinforced with an RC sub-frame that kept the masonry from falling out of the frame, and thus helped prevent a pancake collapse of the upper floors, saving the lives of the occupants. (See Section 2.10 below)

Frame construction is both a general term and one with very specific meaning as an engineering term of art – as for example in “*frame action.*” The question of whether a frame is a braced frame or a moment resisting frame is important on its own, but with buildings, almost all of which necessarily have enclosure walls and interior partitions, it is also important to recognize how these walls interact with the structural frame. For example, infill masonry is almost always left out of the engineering calculations except as dead weight, but it has often been cited as a significant contributor to soft/weak story collapse of RC frames. In addition, it has also served on occasion to arrest the soft story collapses it helped to precipitate through the strength of the upper floor infills which in residential structures are plentiful. This can allow almost all of the residential occupants to be able to survive and escape from the ruins as for example with the building seen in Figures 13 & 14.

By contrast, “confined masonry” is a term of art for reinforced concrete construction where the infill walls are constructed first with gaps left for the columns to be poured in between the sections of the walls, which then infill the resulting frame (Figure 17). Then, as a separate pour, these walls and columns are overlaid with the floors and roof, each of which includes a bond beam bearing on the walls.

Confined Masonry has shown more resilience on average than has conventional moment frame with infill construction in a number of recent earthquakes around the globe. This is particularly noteworthy because this system is more often used in poorer socio-economic environments for buildings with little or no engineering input (Figure 18). This phenomenon proved to be particularly profound in Haiti, where, contrary to the news reports with photographs showing devastation in the hillside slum settlements, extensive areas of these settlements on less steep areas came through the earthquake with far fewer collapses, even though the buildings were constructed of concrete frames, slabs and blocks (Figure 16 & 17). In fact, except for the steepest hillsides, these illegal owner-built poor slum dwellings overall performed on average much better than did the contractor-built, sometimes even engineered, downtown commercial reinforced concrete buildings, as counter-intuitive as that would seem. (Langenbach 2012)

One simple explanation is that for buildings constructed entirely of confined masonry, the walls rest on the foundations and extend up through the full height of the structures. Thus, the earthquake-vulnerable weak first story common in the moment frame structures is avoided. This is particularly true for residential structures which by necessity are divided into many rooms, and thus have a redundancy of infill walls. However, this is not the only reason for this greater durability in earthquakes. A fundamental part of their resilience comes from the fact that the infill walls are fully bonded and engaged with the building's structural frame such that they effectively work in concert with the frame. They are not shear walls, but in some cases they can work as well or better than shearwalls, and because they include most or all of the walls of the building, the seismic performance benefits from redundancy.



Figure 15. Aerial view of downtown Port-au-Prince after the 2010 Haiti earthquake showing the widespread numbers of collapsed buildings. *Oblique aerial photographs done by Pictometry International Corporation.*



Figure 16. Aerial view of informal slum settlement near central Port-au-Prince showing slum housing that is almost entirely still standing after the earthquake. This was typical for most of these settlements except for those areas on steep slopes. *Photo: Pictometry International Corp.*

Confined masonry buildings are, in effect, solid wall buildings, despite the fact that when completed they have reinforced concrete frames. In other words, these buildings are of mixed construction, but the walls are dominant. Frame action does not and cannot be expected to occur. Unlike moment frames where such frame action is dependent on the capacity, integrity, and high quality of the construction of the frame, particularly of its beam/column joints, confined masonry is reliant on a much simpler engineering concept – one that is harder to do badly and thus much more suitable for untrained builders without oversight.



Figure 17. Typical detail of 'confined masonry' when under construction before the walls are topped out and the columns are poured. This example was photographed in Beijing, China.



Figure 18. Typical view of informal slum houses of low quality concrete block confined masonry that survived largely undamaged, photographed in Port-au-Prince, Haiti after the 2010 earthquake. *Photo, Carlos Barria, Reuters.*

By confining the masonry, the frame keeps in-plane and out-of-plane cracks in the masonry from rapidly expanding to the point of collapse of the walls. This allows the walls to help support the frame even while they crack and shift – that is to “work” and thus to dissipate energy. All of this contributes to preventing collapse of the building. (See www.confinedmasonry.org for more information.)

2.6 *‘Frame Dominant’ and ‘Wall Dominant’ Mixed Construction*

Taking the divergence in earthquake performance between these examples with closely related RC structural systems demonstrates that the ‘mixed frame and wall’ category should be divided into two categories: (1) mixed-wall dominant and (2) mixed-frame dominant. In my opinion, this has singular importance in a vulnerability analysis because a proper engineering assessment of the two different types must look first to the frame or the wall elements, depending on which is expected to play the primary role in keeping the building standing in an earthquake, or, in contrast, which may be a contributor to its collapse.

For example, in the case of a ‘wall dominant’ building, the resilience depends on the capacity and integrity of the walls to respond to the earthquakes beyond the elastic range, without localized collapse or diagonal strut action that can cause the frame to come apart. Rather than frame action, this resilience is a product of load shedding from one wall to another, resulting in hysteretic damping across many of the infill walls, which, in multi-story structures, must extend up the height of the building.

By contrast, one may appraise the collapse risk of a ‘frame dominant’ building by evaluating the potential effectiveness of the frame to undergo frame action without excessive interference from the walls or from an early brittle failure of the frames members, particularly at their intersections.

In both systems, load paths are important. In the ‘frame dominant,’ the frame is the primary load path, and the wall materials must be evaluated for their lack of interference with that, while in the ‘wall dominant,’ the wall and the frame must be evaluated together as a unified system, with the wall elements, such as infill masonry, treated as an integral part of the load path even when the columns may be the primary elements carrying the weight of the upper story walls to the ground.

2.7 *Organization of Present-day Building Codes*

The ‘solid wall’, ‘mixed-wall-dominant’, ‘mixed-frame-dominant’, ‘frame’ subdivision I have described here is not perfect. It does not encompass certain construction types like shell structures, but it illustrates how the concepts of traditional construction in earthquake areas fit into a larger context. By focusing on this continuum for this paper, I wish to explore a way of thinking about earthquake resilience and vulnerability in buildings across time and into the present, in ways that begin to explain some of the counterintuitive examples described above. Focusing on the building codes and conventional wisdom of our own time can isolate us from the knowledge and even the accepted wisdom of the past. Many people can cite more than one instance when they have heard words to the effect that an historic structure “*is a fine old building, but it does not meet modern earthquake codes ...*” as a justification for tearing it down or radically restructuring it.

This does not mean that following the trajectory of the evolution of the building codes in the USA and other countries is not a reasonable way to explore the evolution of knowledge about earthquake resistant construction. With each earthquake, observations of the damage have led to revisions of the building codes here and elsewhere, such as when brittle failures were discovered in steel framed structures in Los Angeles County after the Northridge earthquake. In fact, the final version of the GEM Taxonomy is more along the lines of how the building codes are organized than what I have described here.

However, focusing on the organizational structure of the North American or European Building Codes as a basis for organizing data on existing buildings across all ages is more like finding a present-day snapshot when what is needed is a feature-length moving picture. We are so used

to the conventional wisdom expressed in the GEM quote in the second paragraph of 2.1 above, that it is easy to fail to fully grasp that some of the buildings constructed during the centuries prior to the existence of modern codes – even some of those constructed mainly of stone masonry – have actually shown a level of resilience in earthquakes that meets or exceeds the objectives of the codes for new buildings despite the fact that their archaic construction does not come close to conforming to that allowed by modern codes. (India and some other countries in South Asia have developed some codes which recognize traditional construction, but usually under very restrictive conditions (Figures 19 & 20). For more information, see Langenbach 2009.)

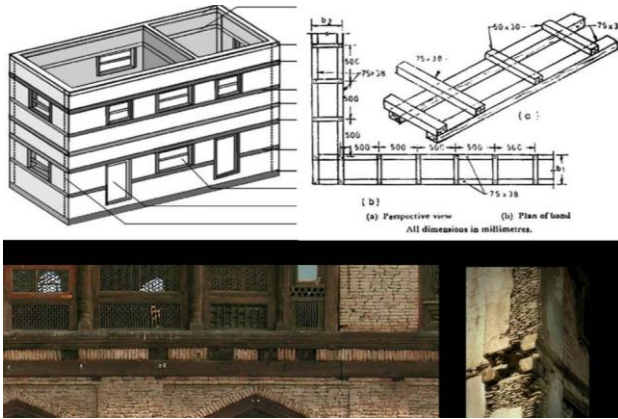


Figure 19. Illustration from Indian Standard Code IS 13828-1993-Low strength Masonry, together with view of traditional *Taq* construction in Srinagar Kashmir, which the principle author of the code explained was a source for this code concept. It is also included in IS 13827: Earthen Buildings.

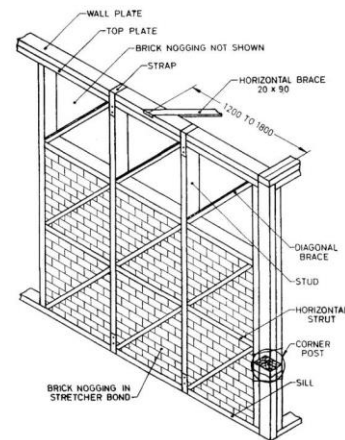


Figure 20. Illus. from Ministry of Home Affairs, *Guidelines for Earthquake Resistant Reconstruction and New Construction of Masonry Buildings in Jammu & Kashmir State* by A.S. Arya.

More importantly, this approach can lead us to solutions to problems such as those revealed by the 2011 earthquake in Christchurch NZ, where certain seismically upgraded load-bearing masonry buildings failed while others did quite well (Figure 21 & 22). It appears from the available reports that those retrofits that did well embraced and augmented the existing masonry walls, whereas those that did worse had new structural framework that was structurally separate from the masonry.



Figure 21. Chemistry block of the former Canterbury University Campus (now “Arts Complex”) in Christchurch viewed before the earthquake. Only the top of the central tower was significantly damaged in the earthquake while other unretrofitted buildings around it were collapsed.

Photo Panoramio.com



Figure 22. Detail showing the exterior steel rods and clamps that are part of the retrofit done during the 1980's. This retrofit was comparatively less expensive than other methods where new structural frames were added.

Photo Panoramio.com

2.8 First Generation Steel Skeleton Frame Skyscrapers

This situation can be quite profound with the ‘mixed’ category of buildings. As mentioned above, a 1980’s engineering study of the 1914 Oakland City Hall (Figure 5) concluded that the steel frame was of inadequate strength to keep the building from collapsing in even a minor earthquake when considering the masonry infill and exterior masonry only as weight. The building was damaged in the 1989 Loma Prieta earthquake, but came nowhere near to the collapse that had been predicted. The building has very thick masonry walls surrounding the steel frame in the same way that the early skeleton steel frame highrise buildings had been constructed first in Chicago and in San Francisco prior to the 1906 earthquake and fire. The City Hall survived the 1989 earthquake in the same way that the earlier buildings had survived the 1906 earthquake – many of which remain standing today despite having been totally burnt out in the fire that followed. (Langenbach 2006)

This example only throws into relief one of the critical issues of our time in earthquake areas – the difference between the effective resilience of the masonry walls in structures like the pre-1906 highrise buildings in San Francisco, and the Oakland City Hall vs. those buildings that are also built with masonry infill that have collapsed by the hundreds in recent earthquakes around the world, including Turkey, Pakistan, India, China and Haiti. Although fewer in number, there were devastating collapses as well in Chile and New Zealand. In Christchurch, the loss of life in one such building, the CTV Building, was 119 out of the 158 in the building when it collapsed, with 16 of 38 dead in another pancaked RC building, the Pyne-Gould building. What is revealing is to compare this outcome with the fact that only a total of 35 people died from all other causes in the central city – including falling masonry, despite the widespread damage and partial collapses of many masonry buildings. (New Zealand Police & Pomonis, 2011)

Research on the reasons for this apparent discrepancy turns out to have some interesting parallels to what appears to be some of the reasons for the resilience of timber-framed masonry construction in earthquakes. Looking back at the era of what came to be called “skyscrapers” of skeleton frame construction in American cities, particularly Chicago after the fire that had swept the city in 1871, one finds that historians focus on the replacement of solid wall masonry construction with frame construction – as symbolized by the construction in 1884 of the 10-story Iron and steel framed Home Insurance Company building, designed by William LeBaron Jenney, to be followed in 1889 nearby by the last of its breed, the 17-story load bearing brick masonry walled Monadnock Building designed by the now famous architects Burnham and Root.

Over the century and a quarter since these buildings were constructed historians, engineers and architects have focused on the revolution in design and construction presaged by the shorter and older building by Jenney as the first “skyscraper,” despite the more remarkable height – particularly for a masonry bearing wall building – of the Monadnock.

Interestingly, masonry remained an important part of the structure of the first generation of skeleton frame steel buildings – in particular for its role in resisting lateral forces. This is made clear by the author of one of the first textbooks on the subject of skeleton frame construction, Joseph Freitag when 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” (Freitag 1901)

He goes on to say that such a building “*should be safe...if the exterior of the iron framework is covered with well-built masonry walls of sufficient thickness...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....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)*

2.9 Contraflexure Portal Frame Analysis Methodology

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 not so broadly known – it is, within the field of structural engineering, the “invention” of a way of doing a portal frame analysis using the contraflexure methodology for isolating moments. In lay language, 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 then allows for the forces to be calculated using the three equations of equilibrium. Prior to that, the forces inherent in “frame action” could not be accurately calculated. As long as, in effect, columns were pin connected at the floor levels, this was not a problem (Figure 23), but as structures grew taller, this was structurally inefficient. Modern skyscrapers in every practical sense date their origin to this change in engineering analysis methodology (Figure 24). (Robison 1989)



Figure 23. Portal frame arch in 1891 steel frame addition to Monadnock Building showing an element of design prior to use of contraflexure methodology.

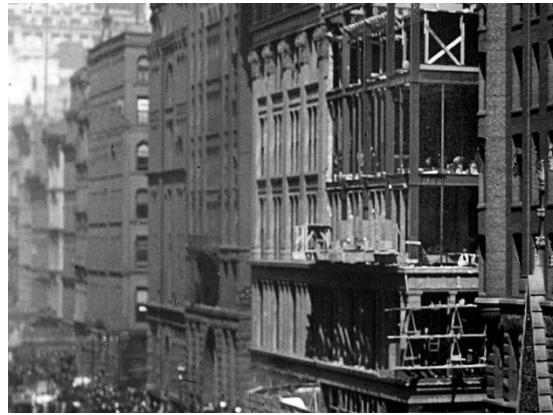


Figure 24. View of new skeleton frame buildings being constructed in Chicago after ca. 1900 adoption of contraflexure methodology allowed for thinner members with moment connections. Masonry provided most of the wind bracing. *Photo courtesy owners of Monadnock Bldg.*

It was only about 10 years after the invention of the contraflexure methodology 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. This is succinctly described in 1906 by Himmelwright, an engineer for the Roebling Construction Company of New York City who observed: *“The successful manner in which the tall, steel skeleton frame buildings withstood the effects of the earthquake and the fire is most reassuring... 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)

However, it was after the ‘invention’ of the 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, so over the years to follow, the masonry walls were made thinner and weaker until they increased, rather than decreased the risk of collapse in earthquakes. As mentioned above, even the weaker masonry walls prevented the “frame action,” on which the engineer’s calculations were based. For wind, this was not considered a problem as the system together with the masonry was designed to remain elastic, so the addition of the masonry simply made it stiffer and thus likely to be more resistant. Earthquakes though were another matter.

Thus one must ask why did these first generation steel skeleton skyscrapers in San Francisco remain standing with undamaged frames and repairable damage to the masonry walls when so many frame with infill masonry buildings have been collapsed by earthquakes a century later? As clearly stated by Freitag, it was not the frame alone, but it was the masonry in effective partnership with the frame that is responsible. On the continuum, these are ‘mixed-wall dominant’ structural systems. 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 (See Figures 25 & 26 for one of many examples).



Figure 25. The Flood Building in San Francisco after the 1906 earthquake and fire. *Photo from A.L.A. Himmelwright. The San Francisco Earthquake and Fire, New York City, The Roebling Construction Company, 1906.*



Figure 26. The Flood Building today. As of 2013, this building, constructed in 1904 and restored after the earthquake, is 109 years old. *Photo by © Randolph Langenbach.*

Notice that Mr. Himmelwright says that the construction on which he reports was “*executed with skill and workmanship of only fair quality...*” It is in comparison with this that the present day earthquake collapses of modern RC building must be compared. It is one thing for those that are of good quality construction to survive – as indeed they have, even in Haiti, but what about with construction of *fair quality*? It is indeed only reasonable and responsible to consider “fair quality” to fall in the middle of the bell curve of the quality of all buildings constructed.

Unfortunately, the widespread collapses of RC frame and infill buildings in many recent earthquakes has demonstrated that, despite advances in engineering and construction over the past 100 years, vulnerability has increased, rather than decreased. Himmelwright made a prescient observation for 1906: *Enthusiastic persons...have [been]...advocating buildings constructed entirely of reinforced concrete as a type well adapted to resist earthquake shocks. ...It would therefore seem appropriate and necessary to sound a note of warning...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)

This would describe many of the failures seen repeatedly over the 100 years since his report was published. While thousands of such buildings have collapsed, countless millions have been and continue to be constructed. How can this be addressed? Is it to move the buildings completely into the ‘frame’ end of the continuum by eliminating the use of masonry as an infill material – replaced with plaster board or lath and plaster on steel studs, as is now common in the USA or Canada? This works fine for frames of good quality – but perhaps not for frames of fair to poor quality, which has to be a large percentage of the buildings almost everywhere, particu-

larly where there is an absence of building codes and/or weak governmental regulatory and inspection programs – a situation common in many parts of the world.

Adding shear walls would help, but is often too costly to be practical. What about more masonry – like returning to the turn of the 20th century? This would be unwise too because, again, the examples cited here were the premium buildings of their time – with high quality materials and with steel rather than concrete frames, even if Himmelwright considered the craftsmanship to be only of fair quality. Is it then possible to achieve the good performance shown with ‘confined masonry’ by retrofitting buildings with masonry infills that are securely bonded to the confining frame, and added where missing at ground floor level? It is possible that this could resolve the most conspicuous problems, but would be costly, and may not resolve the issues such as the jacking apart of the frame from the diagonal strut effect of the masonry infill. The design guidelines published on www.confinedmasonry.com have been developed for low rise buildings, and recommend the use of cement mortar. Many of the pancake collapses involve RC frame structures taller than that, and stiff but brittle walls have contributed to their collapses.



Figure 27. This house of *colombage* construction was in the heart of the 2010 Haiti earthquake damage district in Port-au-Prince. It suffered only minor damage while many RC buildings less than a quarter of its age collapsed on nearby lots around it.



Figure 28. The concrete infilling of this former window opening was forced out of the wall during the 1994 Northridge earthquake in Los Angeles, Ca. USA.

How did the pre-modern and casually constructed timber and masonry infill *colombage* buildings survive so well – even in Haiti in the heart of the damage district (Figure 27), despite the fact that (1) they were of fair quality in terms of their original construction, (2) they were over 100 years old with little maintenance, and (3) some had advanced fungal decay and insect damage to their timbers? It is not because of their strength, but their flexibility. It is not only the framework that is flexible, but also the masonry itself. In the resilient examples seen in India, Pakistan, Turkey and Haiti, the masonry is laid with a soft mud or lime mortar, rather than a strong but rigid and brittle cement mortar.

One example that demonstrates this phenomenon of differential in the give and flexibility of masonry is from the other side of the world from traditional construction in South Asia. It was taken after the Northridge Earthquake of 1994 in Los Angeles, showing a window opening in a retrofitted multistory URM building that was infilled with reinforced concrete as part of the retrofit measures. This rigid concrete infill essentially “walked” out of the surrounding wall in the earthquake when the surrounding masonry set in traditional lime mortar allowed the building to sway in the earthquake (Figure 28).

2.10 “Armature Crosswalls”

The confined masonry example may indeed hold a key – but a counterintuitive modification of it may be to use softer and weaker mortar for the masonry, and also to introduce ‘sub-frames’ into the infill masonry walls. By sub-frames, I mean a system of studs and horizontal members designed to hold the infill panel together while at the same time holding the now multiple sub-panels of masonry apart. This allows the masonry sub-panels to move within tight tolerances

without developing the destructive X cracks leading to collapse. The difference in performance can be seen by comparing figures 29 and 30.

This modern variation of an ancient technology could even be economically applied to existing and future RC moment frame and infill masonry buildings to radically reduce their likelihood of collapse. I have given this concept the name “Armature Crosswalls” so as to distinguish the concept clearly from that of shearwalls. The term, ‘crosswalls’ is already used to describe interior partitions that contribute to seismic resistance in a North American code for upgrading of masonry buildings. To witness how well de facto examples of this has already worked in RC frame buildings, see figures 13 and 14 above, and Figure 31 and 32 below.



Figure 29. View of a collapsed infill masonry wall in a partially collapsed multistory building in Gölcük, Turkey after the 1999 Kocaeli earthquake. This kind of damage is typical when the infill walls are single layers of brittle masonry set in cement mortar without any sub-frame or other reinforcement.



Figure 30. View of the typical timber frame with masonry infill of Turkish *hıms* construction. This photo was taken in a two and a half story dwelling in Düzce, after the 1999 Düzce earthquake. It was surrounded by collapsed RC multistory buildings. It is this kind of construction that forms the inspiration for the “Armature Crosswalls” concept.

The intention is that the infill walls, with their weaker mortar and multiple panels, would have less initial stiffness and more frictional damping than standard infill masonry walls. This reduced initial stiffness can avoid the potentially destructive “equivalent diagonal strut,” thus, allowing the frame-action on which the portal frame analysis relies to occur. In addition, the energy dissipation from the working of the combination of timber, bricks and mortar against each other serves to dampen the excitation of the building by the earthquake. (Langenbach 2008)



Figure 31. View of the Juarez Hospital after the 1985 Mexico City earthquake collapsed it trapping approximately 950 people, of which 561 were killed.

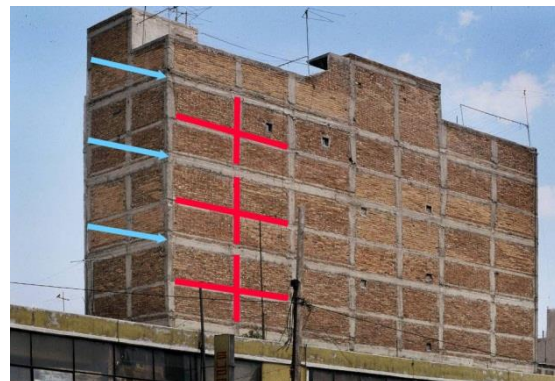


Figure 32. View of a RC building next to the Juarez Hospital with no visible earthquake damage. The floor levels are marked with blue arrows, and the infill walls have sub-frames marked in red. (See Sect 2.10 “Armature Crosswalls.”)

3 CONCLUSION

One of the problems that plague the assessment of existing buildings and the archaic structural systems used for non-engineered buildings is the basic difficulty of establishing a norm for earthquake safety and performance when avoidance of damage is not a viable objective. With wind, for example, one uses real expected maximum wind speeds with an added safety factor. With earthquakes, as mentioned in 2.2 above, it has been determined that to require all buildings to remain within their elastic range for design-level earthquakes is economically infeasible for such a large but infrequent event, so the codes have been drafted with reduced forces to be used for linear elastic analyses with ductility factors to account for the expected non-linear response. Thus, in this context, it is difficult to properly recognize the post-elastic performance of archaic non-engineered structural systems constructed of materials that do not appear in the codes, and for which there are little or no codified test results. This is particularly true for systems which incorporate masonry, whether it is historic timber-laced masonry, or the solid-wall masonry in late 19th and early 20th century skyscrapers.

This problem is not just academic; it is integrally connected to the longer-term issues of post-disaster recovery and regional development. Old ways of building that are based on an empirical wisdom passed down through the ages will probably defy most attempts to be rationalized into systems that can be fully calculated, but the evidence remains that some of these systems nevertheless have worked well even in large earthquakes—in fact sometimes so well that it is important to learn why. Because of this lack of set rules and methodologies for quantification, the evaluation of older structures after earthquakes can lead to broadly divergent views on the significance of particular damage and on the reparability of the structures. This inevitably has led to the unnecessary destruction of many historic buildings and even whole city districts.

One of the most prolific and brilliant earthquake engineers of the 20th century, John A. Blume, who was based in California, USA, described when interviewed in 1994 how in a paper written in 1958 he had expressed concerns about the ignorance of the important role that the masonry had in keeping the early skeleton frame buildings from collapsing in San Francisco in 1906. In 1994, he reflected on this by saying: *“The traditional buildings, such as were present in San Francisco in 1906, were of totally different character than the contemporary buildings that were being erected in the ’50 and ’60s. The difference lay mainly in the fact that the 1906 buildings had heavy masonry or other walls, in addition to the fairly light steel frame, as compared to the modern buildings with a heavier steel frame but no walls, only architectural cladding...When the [1906] earthquake came along, the buildings cracked their walls. Everybody said, “The steel frame buildings stood up fine,” not giving adequate credit – in my opinion- to the fact that those brick walls were not present in modern buildings, so something has to be done to make up the difference. I think it has been done to a certain extent [by improvements to the building code and construction practices.], but perhaps not enough.”* (EERI 1994)

One can say that this quote by John Blume in 1994 is perhaps as prescient as that by A.L.A. Himmelwright in 1906 when he identified weaknesses in reinforced concrete frame construction which was new at the time, and warned about its adoption in earthquake areas. In the two decades since John Blume’s interview and a century after Himmelwright’s, earthquake after earthquake have proven that indeed *“perhaps not enough...has been done...to make up the difference”* in modern buildings. Perhaps instead of eliminating ‘solid walls’ from frame structures, it is time that they become better understood – and embraced.

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