ARMATURE CROSSWALLS

How pre-modern construction practices may hold the key to avoiding the collapse of vulnerable urban housing blocks.

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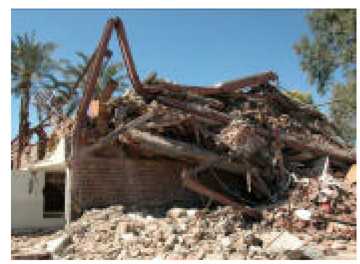
ABSTRACT: This paper describes a proposal for 'Armature Crosswalls,' to be used as earthquake hazard mitigation for reinforced concrete and masonry infill-wall buildings vulnerable to collapse. RC frame and infill construction is common throughout the world and often has proved lethal in earthquakes. The paper traces the history of masonry infill construction from pre-modern forms that have shown earthquake resistance in the past, to the early modern steel skeleton frame buildings that survived the 1906 San Francisco earthquake. Armature Crosswalls are based on the flexibility and energy dissipation properties found to have existed in the non-bearing infill walls in these earlier forms of construction.

Keywords: Reinforced Concrete, Infill-frame, masonry infill, seismic hazard mitigation



1) Male and female demolition workers on collapsed RC infill building in Bhuj, 2001 one month after the Gujarat Earthquake. Women work alongside men in heavy construction tasks in India.

2) Bare Frame of incomplete building next to partial collapse in Bhuj, 2001. Bare frames, even if weak and poorly constructed, often do better than expected in earthquakes that happen before the infill is installed because the buildings are lighter than when finished, and frame action can take place.

3) Collapsed steel frame infill wall building in Bam, Iran, after the 2004 earthquake. Many light frame buildings with infill masonry collapsed in the Bam earthquake largely because of defective welding and poor layout that resulted in torsion.

Introduction: At the 13th World Conference on Earthquake Engineering in August, 2004, Fouad Bendimerad Director of the Earthquakes and Megacities Initiative, reported that "*approximately 80% of the people at risk of death or injury in earthquakes in the world today are the occupants of reinforced concrete frame infill-masonry buildings.*" Concrete frame buildings with masonry infill-walls (RC infill) are commonly constructed with brick or hollow block masonry partitions and exterior walls. Thousands have died in this type of building in earthquakes in different countries around the world, including recently in Turkey and Taiwan in 1999, India in 2001 **(Fig.1&2)**, and Morocco in 2003. In Iran, where light steel frames are used instead of concrete, these infill wall buildings also fell down in Bam in 2004 **(Fig.3)**. How can it be that a technology of building construction based on these promising new strong materials of steel and reinforced concrete could ultimately be connected to such deadly catastrophes? Is it sufficient to explain such pervasive and repeated calamities by pointing a finger only at bad quality construction practices? Instead, it may be possible to find the precursors leading to this problem in history.

Steel Skeleton Frames: Modern skeleton frame construction evolved from iron frame construction of factories and exhibition buildings that originated in the late 18th century and developed through the 19th century, but it was not until the first efforts to construct tall office buildings in Chicago and New York City that the iron frame was extended into the masonry exterior walls of multistory buildings. The early skyscrapers were infill-frame buildings with the exterior and interior masonry walls enclosing and infilling the steel frames **(Fig.4)**. Carl Condit (1968) states: "*A puzzling feature* [of the first skeleton frame "skyscraper," the Home Insurance Company Building in Chicago,] *was the total absence of wind-bracing, an omission that the designers may have defended on the ground that the masonry bearing members and the heavy masonry cladding on exterior columns and girders proved sufficient rigidity for the whole structure. As a matter of fact, the view persisted for nearly a decade that buildings with relatively extensive horizontal dimensions needed no internal bracing.*"

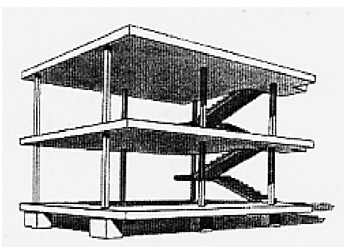
This was a practice that would later meet with criticism, and steel braces quickly became common, but the masonry infill and cladding also remained, even though it was not included in the engineers' calculations. The first earthquake test of the capacity of the early steel skeleton frame buildings was the 1906 San Francisco earthquake and fire. A significant cluster of Chicago skeleton frame buildings had been constructed in San Francisco in the decade before 1906, and post-earthquake reports prove that their performance ranged from good to extraordinary. None collapsed from the earthquake, and damage in many was minimal. The masonry of the partitions and façades, as would be expected, showed the most disruption, but the steel frames were rarely found to be damaged **(Fig.5)**.

4) Flatiron Building in NYC under construction showing masonry started at 7th floor level and at base at same time. (1901).
(NY Historical Soc.)

5a&b) Chicago Frame Bldgs in San Francisco after 1906 earthquake. All standing buildings shown are still extant today.
(Museum of City of SF)

To understand why this history is significant, it is important to take note that the design effort for wind forces was then, as it is now, aimed to provide enough resistance to avoid damage. For large earthquakes, however, the forces are too large to have any reasonable expectation to be resisted without damage. Even today, code conformance is based on an expectation that damage will occur, and so the damage that was found in the infill-masonry from the 1906 earthquake means that the masonry must have helped protect the underlying steel frame from damage that it otherwise would have sustained had the masonry only been dead weight. Even in the case of high winds, this was later proven to be true. A 1938 report on the brick and stone clad 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 gages 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) reported in Eldakhakhni, 2002)

In many histories of the modern skyscraper from the Home Insurance Co. Building to the glass curtain wall towers today, one reads a story of seemingly marvelous progression until, in all its glory, the skeleton frame emerges out of its antiquated masonry jacket. As Sigfried Giedion, the principal historian of the Modern Movement, said: *"the ornamentally accentuated play of load and support* [in the] *nonsupporting exterior walls [of early]…American Skyscrapers…is an embarrassing farce."* (Giedion, 1928) Here Giedion is focused on the establishment of a new architectural style for low and mid-rise building that is to be based on the open skeleton frame. Again, Giedion in 1941: "*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"* (Giedion, 1941)



6) "Domino" frame as ideal structural form by Le Corbusier, 1915. **(Giedion, 1928)**

7) A massive RC frame in Golcuk, Turkey under construction at time of 1999 earthquake before installation of infill masonry walls. Much greater damage or collapse would have been likely had the infill walls been installed by the time of the earthquake.

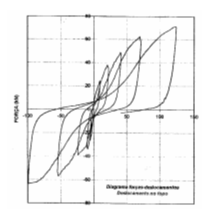
Thus "Modern Architecture," embraces skeleton frame construction as the basis for radical changes in architectural expression **(Fig.6)**. What Giedion did not recognize, and few engineers of his time and since have given credit for, is that it may have been the "*nonsupporting*" masonry walls that may be the reason why most of the pre-1906 steel frame buildings in San Francisco are still there today, despite being hit by the earthquake and then totally burnt out. To fully understand this conceptual shift, it is worth placing the early skyscraper infill frame construction into its true historical context. Rather than seeing it only as a transition to a new form of honesty in architecture, it is more accurate to place it into the context of more than 2000 years of construction history, where timber frame with masonry infill has been used from well before the Roman Empire right through history until the present. Regional manifestations of the timber and infill masonry construction have been called "*colombage*" in France, "*fachwerk*" in Germany, and, of course, "*half-timber*" in Britain. In Turkey, it has been called "*himis*" **(Fig.9)**. But how does this form of construction relate to the Chicago Frame buildings in San Francisco in 1906?

The answer is best found in considering the example of Lisbon after the great earthquake, fire, and tsunami of 1755. In planning for the rebuilding of Baixia, the completely destroyed area of central Lisbon, the Marquis of Pombal gathered a group of engineers to determine the best manner of earthquake-resistant construction to use for the rebuilding. The type of structural wall construction selected has become known as the Pombalino system. It is essentially a well-braced form of half-timber construction, the use of which was probably inspired by what Pombal's engineers could see had survived the earthquake. 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 **(Fig.8)**.

8) Pombalino walls in Baixia, Lisbon, 2003

9) House in Golcuk showing *himis* construction. This house was abandoned and in ruins at the time of the Kocaeli earthquake in 1999, but remained standing with little additional damage from the earthquake.

In recent Portuguese Government sponsored lab tests on actual wall sections removed from a Pombalino wall, the wide hysteresis loops show that the walls were able to dissipate large amounts of energy over many cycles, without losing their structural integrity. The sample remained largely intact despite having been cyclically pushed beyond what would be expected from an earthquake **(Fig.10&11)**. (Cóias e Silva, 2002)



10a&b) Sections from a Pombalino wall that was cut out and tested in the Portuguese Govt. lab.

11) The hysteresis loop from the test of the Pombalino walls showing extensive ductility and reserve strength. **(Cóias e Silva, 2002)**

In Turkey, 20th Century examples of *himis*, another regional form of half-timber construction, survived on average much better than the modern reinforced concrete buildings around them **(Fig.9)**. (Langenbach, 2000) In other earthquake areas, variations on this construction system can be found with a history of resilience in past earthquakes. The way these pre-modern infill wall buildings responded to the earthquake vibrations is not unlike the way that the Chicago Frame structures must have behaved in the 1906 earthquake – with the masonry confined by the steel frame, working together with the frame and also protecting it by cracking and dissipating energy without falling out.

While steel frame construction emerged in the 1890's for highrise construction, reinforced concrete construction made its debut for low to mid-rise construction. It was reinforced concrete of which Giedion speaks when he describes how Le Corbusier: *"develops the new housing function from the ferroconcrete skeleton frame with a thrusting boldness that has enriched all of architecture…The shells fall away between interior and exterior…Air becomes a constituent factor! There is only a single, indivisible space."* (Giedion 1928) Freestanding columns supporting slabs of concrete became the basic structural system for housing that spread, first through Europe, and then over the rest of the world. As long as the placement of the infill walls was to be left up to the architect, then the engineer thought they could be ignored in his calculations.

The problem is that masonry walls did not actually disappear. In reality, even the most open residential floor plan required many walls, and the most practical fire resistant material for them is masonry. From the robust walls of the early skyscrapers, the walls evolved into weak and loose single-wythe membranes of brick or hollow clay tile. One is forced to wonder why the RC moment frames, rather than shearwall design, became the default system for residential buildings in most places because, in earthquake areas, they are so unsuitable for buildings that are permanently divided into small rooms anyway. The added cost of shearwalls is only part of the explanation. A more compelling reason may be the force of the Modern movement that began in the 1920's and '30's that led first to its firm establishment in areas where earthquakes are not a risk, such as France and Germany, and then its dispersion to areas that have suffered from pervasive problems in construction quality together with great earthquake risk.

This story brings us back to the present, with the vast problem referenced by Fouad Bendimerad at the beginning of this article. This problem is expanding daily, as more vulnerable buildings continue to be constructed in cities around the world. The proposal outlined below for "Armature Crosswalls" is founded upon a simple practical premise: that it is necessary to recognize and accept the fact that defective RC infill buildings will continue to be constructed, despite the best efforts by both engineers and public officials to improve RC design and construction practices, so additional safety measures are required.

Armature Crosswalls: Instead of the existing method of constructing the infill walls totally out of hollow clay tile or brick, the Armature Crosswall proposal is that they be constructed with studs and cross-pieces of timber, steel or concrete. These studs and cross-pieces (the 'armature') would be securely attached to the primary frame of concrete, and the bricks would be tightly packed into the 'armature.' The mortar to be used for this construction would be a high-lime mix intended to be less strong, stiff, and brittle than ordinary cement mortar. When finished, the wall would be plastered as it would normally. The intention is that these walls would have less initial stiffness than standard infill masonry walls, and the studs would also serve to reduce the development of the equivalent diagonal strut.

This system is based on an approach where all parts of a building's fabric are to be regarded as "structure," so that the ductile behaviour that cannot be assumed to exist in the underlying concrete frame can be achieved through the energy dissipation provided by the controlled degradation of the infill walls. The danger of a soft story can be reduced or avoided using the Armature Crosswall system because (1) the crosswalls can be extended to the ground more conveniently than shearwalls because they do not have to follow such a rigid system of lining up with the walls above, and (2) the reduction in the initial stiffness of the walls at all floor levels allows frame action to occur in the superstructure frame because it can sway within its elastic range before the crosswalls begin to bind. This sway is then restrained when the crosswalls begin to shift and crack along the interface with the 'armature,' which dampens the building's response and dissipates energy. Then, as they yield and degrade, they shed load to other crosswalls so that all parts of the building function to support and supplement the frame. This can be termed a "*sequential degradation*" approach to earthquake resistance design. (Langenbach, 2003)

Thus, 'Armature Crosswalls' are intended to address the initial stiffness, diagonal strut formation, out of plane collapse, and energy dissipation issues that exist for RC infill buildings. The purpose is to make the infill walls into a productive part of the overall structural system, in a way that turns what is now a problem into an advantage. This approach to mitigation is based on the assumption that low to mid-rise buildings will continue to be constructed with the same palate of materials as are currently used, and that the RC frames themselves are most likely to continue to be unreliable.

Conclusion: The continued creation of bad buildings is not so much an engineering problem as it is a socio-economic problem in the "building delivery" process. As long as this is the case, efforts to solve the problem only with the dissemination of technical reports for engineers may best be described as a "Marie Antoinette approach to Earthquake Hazard Mitigation" from the quote "*Then, let them eat cake*" attributed to her when there was a bread shortage in Paris. If money, materials, or trained engineers necessary for proper detailing, good quality steel and concrete, or tools for mixing and vibration of the wet concrete, or water for hydration, are simply unavailable, then the chances for safe reinforced concrete frame construction will continue to be remote.

Armature Crosswalls are not intended to displace good design, but rather add to it – and to be there when nothing else works. They are based on an empirical wisdom that has been passed down through the ages and will probably defy most attempts to turn them into a system that can be fully calculated. One architect said to me recently: *For many engineers, if it cannot be calculated, it does not exist."* Here is one example where the time has come, after years of collapsing buildings, to borrow an idea from the past that was not meant to be calculated, and to have the humility to accept the fact that nevertheless it may work now and in the future.

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