

## **ARMATURE CROSSWALLS: A PROPOSED METHODOLOGY TO IMPROVE THE SEISMIC PERFORMANCE OF NON-DUCTILE REINFORCED CONCRETE INFILL FRAME STRUCTURES**

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### **ABSTRACT**

This paper describes a proposal for ‘Armature Crosswalls,’ to be used as earthquake hazard mitigation for buildings with reinforced concrete (RC) framing and masonry infill-walls 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.

### **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, similar types of infill wall buildings also collapsed in Bam in 2004 (Fig.3). These disasters raise an important question: How can a technology of building construction based on these modern materials of steel and reinforced concrete (RC) be connected to such deadly catastrophes? Is it sufficient to dismiss these pervasive and repeated calamities by laying the blame on poor quality construction?



**Fig.1** Demolition of collapsed RC infill building in 2001 Bhuj, India Gujarat earthquake.



**Fig.2** Bare Frame of incomplete building next to partial collapse in 2001 Gujarat earthquake.



**Fig.3** Collapsed steel frame infill wall building in 2004 Bam, Iran earthquake.

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Over the course of the last few decades, the history of RC infill buildings has been marked by a debate over the positive or the negative attributes of the infill masonry. Elimination of the infill masonry forces total reliance on the concrete frames, and these are not always constructed well enough to be reliable. While this infill masonry has never been embraced as an essential and integrated part of the structure of these buildings that can supplement the frames. It is time to resolve that issue – not by eliminating the infill, but embracing it. First, it is worth looking more broadly at the history of infill-frame construction – beginning with the 1906 San Francisco earthquake and fire.

### **Steel Skeleton Frames**

If one were to survey the ruins of San Francisco after the 1906 earthquake and fire, the scene would have been a field of rubble, had the first steel and masonry “Chicago” skeleton frame buildings not yet been built. Almost all of these structures had been burned out, but all were still standing, and, as a testament to their resilience, most of these are still standing today. These include the Monadnock Building, Mills Building, Call Building, Chronicle Building, St. Francis Hotel, and Fairmont Hotel, to name only a few. (This history has been repeated after 9/11 in New York City, when the 28 story high 90 West Street Building by Cass Gilbert, constructed in 1908, was completely burned out from the collapse of the World Trade towers. In its burned-out state, it replicated in the present day what many of these San Francisco buildings looked like after the 1906 fire. Of the many buildings that burned in the fires that ensued from the collapsed towers, it is the only building that can be repaired.)

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 provided 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 1906 San Francisco earthquake and fire was the first earthquake test of the capacity of the early steel skeleton frame buildings and of the reliance on the infill masonry to resist the earthquake forces. Because these buildings represented a new and up-to-date building technology, there was much interest in their earthquake behavior, and the 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).



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

**Fig.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 note that, while the design for wind was then, as it is now, based on avoiding structural damage, for large earthquakes, damage is assumed, while collapse is to be avoided. 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 been only dead weight. Even in the case of high winds, this was also 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 Eldakhkhni, 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] non-supporting 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)

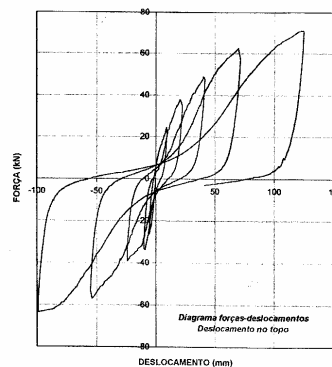
Thus “Modern Architecture,” embraces skeleton frame construction as the basis for radical changes in architectural expression. What Giedion did not recognize, and few engineers of his time and since have given credit for, is that it may have been the “non-supporting” masonry walls that may be the reason why most of the pre-1906 steel frame buildings in San Francisco are still in existence, despite being hit both by the earthquake and the fire. 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. Examples from ancient Rome were even unearthed in Herculaneum and Pompeii. In Turkey, it has been called “*hımsı*” (Fig.9). Variations that used earthen plaster and sticks or reeds (wattle and daub) include Turkish *Bağdadi* and Peruvian “*quincha*.” Recent archeology has even discovered that *quincha* existed as much as 5,000 years ago at Caral. 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 the destroyed area of central Lisbon, the Marquis of Pombal, then Chief Minister Sabastiao Jose de Carvalho e Melo, 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”) and, after testing a prototype, made its incorporation into the reconstructed buildings a requirement (Penn, et al, 1996). 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, as it is known that timber framed houses survived near Castle Hill (Penn, et al, 1996). This record is consistent with the eyewitness report by Reverend Charles Davy: “*With regard to the buildings, it was observed that the solidest in general fell the first.*” (Tappan 1914) The significance of the *gaiola* lies in the fact that it was deliberately developed and selected as earthquake-resistant construction for a major multi-story urban area (Fig.8). In recent Portuguese Government sponsored laboratory tests on actual wall sections removed from a Pombalino wall, the recorded 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.6&7). (Cóias e Silva, 2002)



**Fig.6a&b** Sections from a Pombalino wall that was cut out and tested in the Portuguese Govt. lab.



**Fig.7** The hysteresis loop from the test of the Pombalino walls showing extensive ductility and reserve strength. (Cóias e Silva, 2002)

For a major earthquake test of timber infill-frame construction, one must turn to Turkey, where the 1999 earthquakes were severe enough to collapse hundreds of RC infill frame buildings, but left most of the *hımsı* houses intact. Also, the 2001 Gujarat, India earthquake caused the collapse of many modern RC infill apartment blocks while multi-story timber infill buildings in the historic center survived almost completely intact. For a full description of these observations in Turkey and India, see (Langenbach, 2000 & 2003). In other earthquake areas

including Kashmir, the former Yugoslavia, Greece, and Central America, 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 collapse.



**Fig.8** Pombalino walls in Lisbon, 2003.



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

At the same time as steel frame construction emerged in the 1890's for high-rise construction, RC construction made its debut for low to mid-rise construction. It was RC 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 across 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 the 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 in most places the RC moment frame, rather than shearwall design, became the default system for residential buildings because, in earthquake areas, it is unnecessary 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 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.

There has also been a more subtle, but equally significant change in the field of engineering. As the field has advanced and become more analytical, it has also become more abstract. Practitioners have consequently become less conversant with traditional methods of construction that do not lend themselves to mathematical modeling as a frame – namely masonry infill. Many engineers have tackled the problem by treating the masonry separately from the frame, but if treated as dead weight alone, the computations quickly show the frame to be overwhelmed in a design level earthquake. There is a wide leap between infill masonry

calculated as dead weight and actually using its inelastic response as an integral part of the seismic design. Accepting this principle as a defining feature of a building's response to a design level earthquake is a leap that most engineers and public policy officials are unwilling to make. Who can imagine today that an entire city could be reconstructed with a seismic hazard protection scheme based on the construction of a prototype masonry infill structure and the physical testing of it? This is exactly what Manuel da Maia and his architects and engineers did in 18th Century Lisbon, and the buildings they produced are still there today, 250 years later.

This story brings us back to the present, with the vast problem referenced by Fouad Bendimerad above. 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 or the surrounding masonry. When finished, the wall would be plastered as it would normally. The intention is that these walls will have less initial stiffness than standard infill masonry walls because of their subdivision by the armature. The armature also serves to hold the masonry securely within the frame not only to prevent falling hazards, but also to allow it to "work" in plane, dissipating energy. The studs also serve to reduce the development of a single equivalent diagonal strut that can damage the RC.

This "Armature Crosswall System (ACS) is based on an approach where all parts of a building's fabric are to be regarded as "structure," so that the ductile behavior 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 ACS 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 because it can sway within its elastic range before the crosswalls begin to bind. When the crosswalls begin to shift and crack along the interface with the 'armature,' energy is dissipated, which dampens the building's response. Then, as crosswalls 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 (Fig.10). This approach to mitigation is based on the assumption that low to mid-rise RC frame buildings are most likely to continue to

be unreliable, even while all efforts to improve this situation around the world should continue. The October 8, 2005 Kashmir earthquake is a demonstration of this (Fig.11).



**Fig.10** House in Baramulla, Kashmir, Oct.8,2005. The roof and 3<sup>rd</sup> floor walls were left in place with no support from below. The intact walls of the top floor are of timber with masonry infill (Dhajji Dewari) construction, while the destroyed lower floors are unreinforced masonry without the timber armature. (Reuters) See (Langenbach, 1989) for more on Dhajji Dewari.



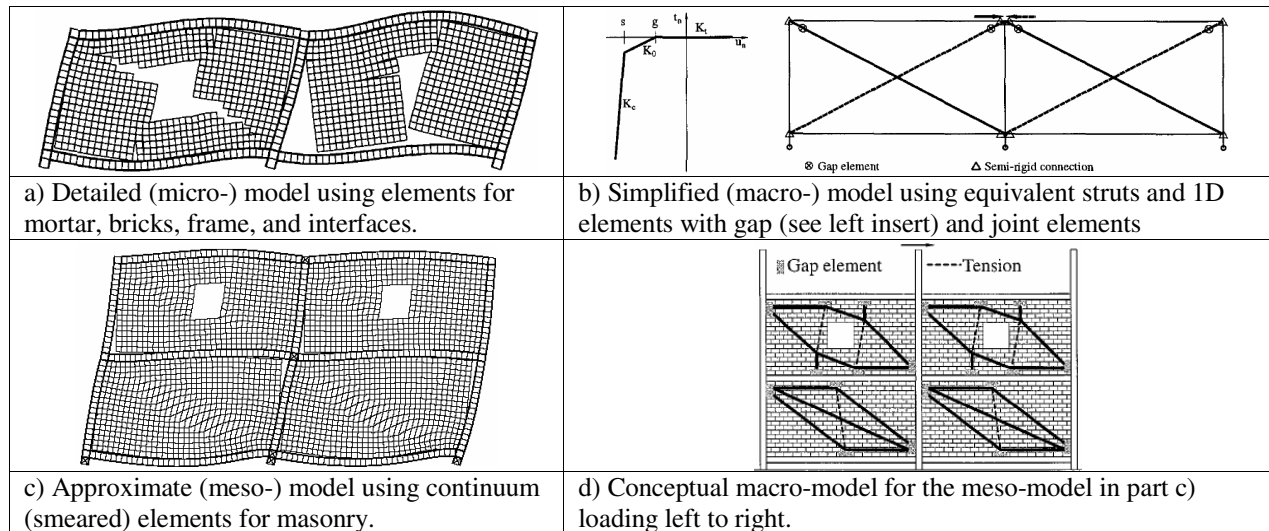
**Fig.11** The Apartment tower in Islamabad that collapsed in Oct 8, 2005 was a premium project. Its failure along side other wings of the complex that survived demonstrate how hidden shortcomings in RC structures can lead to catastrophic collapse in earthquakes. Armature Crosswalls may reduce the risk of this type of collapse in such structures. (AP)

### **The Art of Modeling Masonry Infill Walls**

Practicing engineers as well as researchers constantly face the problem of evaluating the seismic behavior of new and existing frames with infills. Evaluating and, if necessary, retrofitting seismically-deficient infilled frames requires accurate analytical models. Experimental and analytical investigations conducted on gravity-load designed frames infilled with unreinforced masonry walls can be found in a plethora of publications. Refer to (Moghadam and Dowling, 1987, Mosalam et al., 1997a, b, c, and d) for details. Most available analysis methods are based on linear behavior which contradicts the fact that under current seismic design regulations structures non-linear behavior is expected and accepted. 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. Accordingly, it is necessary that the computational tools available to the designer be capable of predicting the nonlinear performance of structures with infills when subjected to severe earthquake excitations. Computational models ranging from very crude to detailed can be envisioned (Fig.12).

Some efforts have been directed towards the definition of mechanical models representing the seismic behavior of infill walls. However, inappropriate considerations of material nonlinearities, e.g. treating material as homogeneous, or failing to accurately account for masonry dilation, and frame/wall interface conditions led to only a partial success of these efforts. Four issues contribute to this difficulty: (1) Uncertainties inherent in the material and geometrical properties of constituents of infilled structural systems, namely, bounding frame and its components and infill wall and its material phases of mortar and bricks or blocks; (2) Complexity of frame-wall interaction for general loading conditions under seismic loads involving in-plane as well as out-of-plane forces; (3) The necessary accommodation of openings

such as windows and doors; and (4) The asymmetrical and unorganized arrangement of walls and partitions due to the common perception that masonry infills are “non-structural” elements that need not be considered in the engineering design of the building, apart from their imposed load. These difficulties of the current practice of the infill-frame system will be eliminated or mitigated to a safe level if the proposed ACS is adopted. The effectiveness of the ACS is attributed to the added redundancy of the armature and the less sensitivity of the response to the geometrical and material properties of individual constituents of the system. Moreover, resilience of the ACS to out-of-plane loading is obvious because of the enhancement of effectiveness of the arching action of the masonry, due to the introduction of the sub-frame of the armature elements in both vertical and horizontal directions.



**Fig.12** Computational modeling techniques (of conventional infill without ACS) with different levels of complexity of infilled systems. (Mosalam et al., 1997c and d)

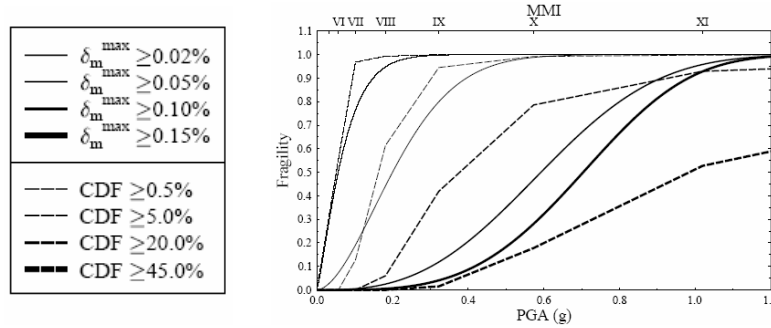
### Preliminary Evaluation of ACS

In a previous investigation by Mosalam et al. (1997a and d), the seismic fragility or vulnerability of non-seismically designed (i.e., mainly gravity-load designed) low-rise RC frames with masonry infills was assessed (Fig.13). The main observation is the very limited ductility defining the system limit state of the standard unmodified infill-wall system characterized by the maximum interstory drift, which, as shown in this figure, closely coincides with the ATC-13 curves for different levels of damage. With the goal of improving this limit state and gaining more ductility of such commonly constructed system worldwide, preliminary analyses are conducted.

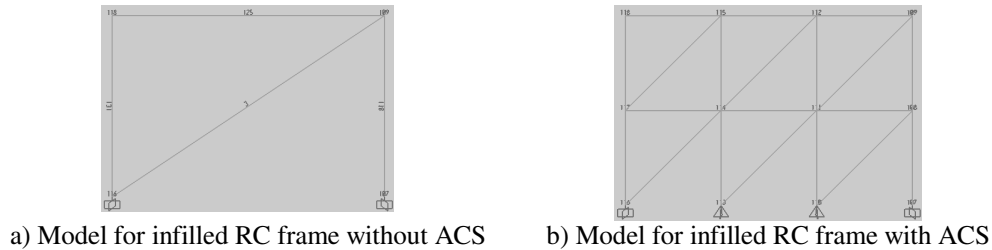
This analysis is based on simplified models using equivalent struts of the infill panels with and without ACS. The computer program SAP2000 is used for this purpose and the models are schematically illustrated in Fig.14 with results indicated in Table1. The SAP2000 models are based on commonly used geometrical and material properties in the Turkish *hmuş* construction. The models utilize conventional techniques of 1D frame elements of the RC frame with plastic hinging based on the conventional section moment-curvature analysis. As for the equivalent struts representing the infill panels with and without the ACS, FEMA-356 recommendations for stiffness are adopted. The axial strength of the equivalent strut is estimated using the recommendation for plastered brick infills found in (Ozcebe and Ersoy, 2003). Finally, the timber armatures are accounted for using experimental data from testing timber elements



commonly used in *humus* construction, namely Scotch Pine (*Pinus Sylvestris*). These armature elements in the vertical (studs) and horizontal (beams) directions are modeled with real hinges at their ends. ACS decreases initial stiffness of the structural system by 39% while increasing the strength by 23% compared to the case without ACS, as shown in Table1. Evaluation of the ductility capacity of the two systems is in progress as it requires more sophisticated modeling approach.



**Fig.13** Fragility curves for masonry infilled non-seismically designed RC low-rise frame in terms of Peak Ground Acceleration (PGA) and Modified Mercalli Intensity (MMI) for limit states in terms of maximum interstorey drift ( $\delta_m^{max}$ ) and central damage factor (CDF) defined by ATC-13. (Mosalam et al., 1997a and d)



**Fig.14** SAP2000 models for the preliminary analyses.

**Table1** Preliminary results of SAP2000 models.

Frame type	Initial stiffness [kN/mm]	Strength [kN]
Infilled RC frame without ACS	585.9	1393.0
Infilled RC frame with ACS	358.8	1715.0

The ultimate goal of the Armature Crosswall project is to develop workable design guidelines for its use in the field. While the modelling of ACS is complex and time consuming, the research work aims to undertake both experimental activities (from simple panels, aimed at quantifying the benefit of the system in the in plane and out-of-plane collapse mechanisms, considering different materials and studs locations), and complex detailed FE modeling that incorporates the non elastic behaviour of the constituents and the interfaces. From the analysis of these models and the experimental evidence, simplified guidelines and calculation rules will be derived.

### Conclusion

The present continuation of the creation of seismically-deficient 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, tools, or trained engineers necessary for proper detailing, good quality steel and concrete, or mixing and vibration of wet concrete, are simply unavailable, then the chances for safe RC 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 stated 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, both now and in the future.

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