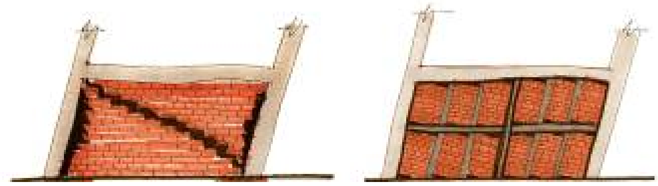
ARMATURE CROSSWALL PROJECT

PROJECT DESCRIPTION



RC frame without armature crosswalls with armature crosswalls

Introduction:

After recent devastating earthquakes in Turkey, India, Morocco, Iran, Haiti, Chile, New Zealand and Japan, as well as other places, we have repeatedly seen images of people crushed under collapsed multi-story reinforced concrete (RC) infill buildings. At the 13th World Conference on Earthquake Engineering in August, 2004, Fouad Bendimerad, Director of the Earthquakes and Megacities Initiative said that roughly 80% of the people at risk of losing their lives in earthquakes in the world today are subjected to risk from collapse of reinforced concrete (RC) frame with masonry infill buildings. This is a remarkable statistic because such buildings are entirely of recent origin. There is a discrepancy between the current state of earthquake engineering knowledge and the actual performance of many contemporary buildings. Even though most building codes have been updated, many RC buildings continue to be constructed that fail to conform to codes or good practices. In fact, as a class, RC infill-frame buildings have proved to be particularly vulnerable in many different countries, yet they continue to proliferate throughout the world, particularly in Turkey, India, Pakistan, Mexico, the Middle East and North Africa, Central and South America, and parts of Asia.

a) View of reinforced concrete (RC) Juarez Hospital in Mexico City after it was collapsed by the 1985 earthquake.

b) Whole row of multi-story RC apartment blocks in Gölcük, Turkey collapsed by the 1999 Kocaeli earthquake. *(UNISDR)*

Figure 1: Examples of multi-story reinforced concrete frame with infill masonry buildings collapsed by earthquake

In the United States, modern frame with infill-wall construction dates from the invention of the "Chicago Frame" in the 1880s, which was common in the United States through the first third of the 20th Century. By mid-century lighter materials were substituted for the heavy masonry, and wall systems were separated from the frames. A large number of the early Chicago Frame Buildings in San Francisco in 1906 continue to exist today, despite the fact that all were ravaged by fire in addition to the 1906 earthquake itself. While these buildings proved to be exceedingly robust in 1906, the 1989 Loma Prieta earthquake caused cracks in the infill in other similar buildings, causing much concern in Oakland and San Francisco. In addition, RC buildings of the 1950's, 60's and 70's have proven to be particularly vulnerable because their frames often proved to be inadequate on their own after the use of infill masonry was discontinued. In some countries, the situation was improved by the introduction of more robust ductile detailing, improvements in construction practices, and strengthening of the codes, but reliance on the RC frame alone for seismic resistance together with continued use of brittle and heavy unreinforced masonry infill has continued to have disastrous results in earthquakes.

a) Masonry with timber armature *hımış* wall in Düzce, Turkey after 1999 Düzce earthquake.

b) Typical collapsed masonry infill wall in RC multi-story residence in Gölcük, Turkey after 1999 Kocaeli earthquake.

c) Infills blown out by 1999 earthquake in Gölcük, Turkey

Figure 2: Example (left) of traditional construction and (right) typical modern infill frame RC construction in Turkey.

<u>The Armature Crosswall (ACW) Concept:</u>

The **<u>Armature Crosswall Project</u>** is founded upon the assumption that (1) vulnerable RC frame structures will continue to be constructed in great numbers, and (2) weak existing buildings will continue to be occupied. RC infill construction has become the default form of construction in many countries even though it has proved to be particularly deadly in earthquakes except where engineering design and construction quality control is rigorous. Rapid urbanization and development continues to lead to severe compromises in engineering and construction quality. The technical knowledge and the equipment necessary for construction of acceptable quality simply does not exist in many regions, and proper enforcement and inspection in many locations is simply not possible. The problem with most RC Infill construction in many parts of the world thus is not an <u>engineering</u> problem; it is a problem in <u>building delivery</u>. (Langenbach, 2003, 2006)

The Armature Crosswall Project is focused on the infill walls themselves, rather than the frame. It is based on the idea that the masonry infill walls may hold the key to the prevention of such wide-spread collapses of RC buildings, just as they did for the Chicago Frame buildings in San Francisco in the 1906 earthquake. Previous efforts to reduce the negative effect of the infill walls have included separating them from the frame or reinforcing them, but these approaches do not help to protect against collapse when the RC frames prove to be deficient – especially when supporting the weight imposed when masonry is used for all exterior walls and partitions.

An Armature Crosswall (ACW), is a masonry infill wall that has been constructed or retrofitted with studs and horizontal members (the "armature") that subdivide the masonry infill, and surround all openings.[1] The purpose of the armature is to change the behavior of the wall when subjected to earthquake shaking so that the infill masonry will: (1) remain in place without falling out of the frame from either in-plane or out-of-plane forces, (2) add substantially to the lateral capacity of the building, (3) avoid development of an "equivalent diagonal strut" that can impose excessive loads onto the beam/column joint, (4) avoid propagation of diagonal tension cracks that can cause the infill wall to fall out of the frame, (5) allow increased flexibility within narrowly defined limits compared to standard infill walls, while resisting extreme excursions that place the stability of the frame at risk, and (6) dissipate substantial amounts of energy over many cycles of severe shaking, and by so doing, reduce the resonance of the structure with the earthquake vibrations. The ACW concept is based on the goal of making the infill walls serve both as a secondary means of support and as economical energy dissipaters. The energy dissipation results from the friction from the controlled cracking and sliding of the masonry within the armature. The goal is to develop a design for the ACW that is capable of sustaining inelastic deformation with consequential friction over many cycles. To do this, the concept is to make the walls *more flexible* – that is to reduce their elastic stiffness compared to non ACW walls, while making them more stable and robust in their inelastic behavior.

The ACW system proposed here has been inspired by a type of traditional construction found in Turkey and other counties such as India (Gujarat and Kashmir), Pakistan, Afghanistan, the former Yugoslavia, and Greece, Italy, Portugal, with variants in Central and South America. This construction, known in Kashmir as *dhajji-dewari* and in Turkey as *hımış* construction, (refer to Figure 1 in Summary) consists of thin-wall (one wythe) masonry contained within a timber frame (Aytun, 1981) (Langenbach, 2003)[2]. In both Italy and Portugal, similar forms of construction were actually designed, published, patented, and in the case of Portugal, required to be used by law as earthquake resistant construction following earthquakes in the 18th Century. In Italy, this was called "*Casa Barracatta,"* and in Portugal, the "*Pombalino wall"* or *"Gaiola"* (Mateus, 2002). Although it has evolved over centuries in answer to many environmental forces, one of the consistent characteristics of this form of construction is that it has shown comparatively high resistance to collapse in earthquakes even though its materials and

[1] The term "crosswall" has been drawn from the terminology used in the Uniform Code for Building Construction (UCBC) Chapter 1 as applied to unreinforced masonry construction. In that code, a *"crosswall decreases the displacement ... and will provide damping of the response of the diaphragm to earthquake shaking."* For the purposes of this proposal, a "*crosswall*" is an infill wall inserted into the building's structural frame, rather than only connecting floor diaphragms, and thus it is not limited to interior partitions. The word is chosen because of the similar emphasis on its reduction of deflections of the structure and its provision of damping through hysteretic behavior of the crosswalls themselves.

[2] Part of the research on the Turkish *hımış* construction has been accomplished with a 2003 EERI Lessons Learned over Time grant. The research and publication of the papers referenced on the last page was supported by this grant.)

connections are weak in comparison to modern materials and the buildings have a low threshold for the onset of earthquake damage. (Langenbach, 2003, 2005, 2006)

a) Late 18th century building in central Lisbon showing 'Pombalino 'gaiola' construction during remodeling in 2003..

b) Gaiola wall sections removed to a Portugal government testing lab.

c) Hysteresis diagram from one of the wall tests of the walls in figure 17. *(Santos)*

Figure 3: The *Gaiola,* an example of timber and masonry 'Armature Crosswall' precursor which was developed and promulgated by law in Lisbon, Portugal after the 1755 Lisbon earthquake by the Marquis de Pombal

The "armature" in an ACW consists of a series of studs and cross-beams that divide the infill-wall masonry into a series of panels. Although traditionally of timber, the materials to be used for armatures are not critical. Research will include the use of timber, steel, precast concrete, or combinations thereof. The ACW is intended to be tightly fitted within the building frame so as to provide sustained friction and energy dissipation over repeated cycles. ACWs will be designed to accommodate doors and windows, and also allow for partitions that are not confined within the frame together with those that are. Research under this proposal will focus on mortar strength as a significant variable, with attention focused on the efficacy of using weaker lime mortar, rather than stronger, but brittle, cement-based mortar, so that the masonry units are stronger than the mortar. Research will determine what thresholds may exist in terms of gaining the most benefit from the ACW technology by the configuration and location of the walls, including those not confined by the frame, and also how best to accommodate the negative effects of existing cement mortar and hollow tile units in infill walls to be retrofitted.

The ACW technology can avoid the initial stiffness in earthquakes, with the resulting higher forces, by allowing the building frame to deflect uniformly across its entire height. This also will serve to reduce the effect of "soft stories" at the shop front level, which is now one of the most prevalent reasons for building collapse. The energy dissipation reduces the building's resonance with the earthquake. As an ACW building's story drift increases over the course of an earthquake, the individual crosswalls, held up and reinforced by the armature, are squeezed within the deflecting frame of the building, thus serving to brace the frame from collapse.

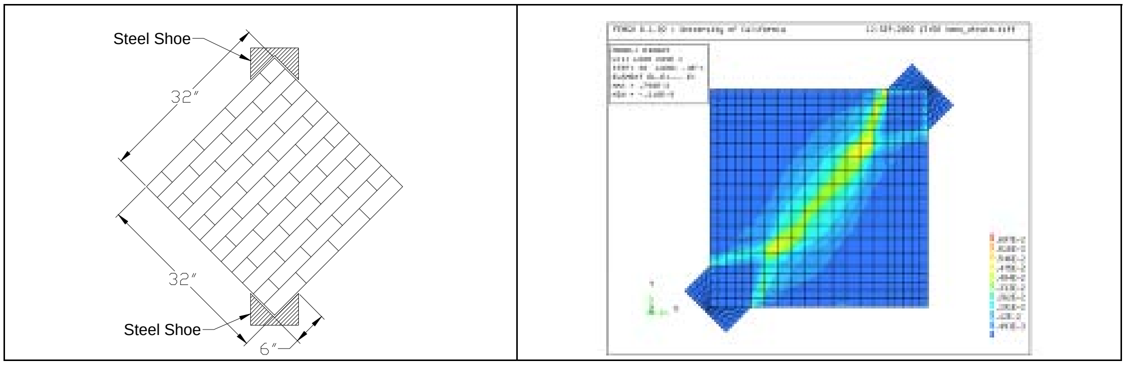
The Research Proposal: The proposal is to bring together a select international research team to establish a research program and to fund the initial research in the USA, Italy, and Turkey, and India. This research project will focus on both the retrofit of existing buildings and on the construction of new buildings. This project will establish the basis for the further work by establishing the feasibility of the concept and identifying the variables involved (brick and block size and capacities, mortar strength and characteristics, armature configuration, etc) for future larger scale testing and implementation. It will also allow for a thorough survey of the scientific literature related to the project, and an initial study of the economics of its implementation in new and existing buildings in different local environments.

The United States provides an excellent base for a portion of this initial research because its history in the use of infill-wall high-rise construction dates from the late 19th Century through the first third of the 20th Century. During this period, engineering and construction methodology research was done on the subject of masonry and hollow clay tile infill construction. More recently, when the 1989 Loma Prieta earthquake damaged early 20th century steel and concrete mid-rise buildings, there has been renewed interest in this subject, and a number of building upgrades were carried out. Sigmund Freeman, of Wiss Janney, Elstner Associates, wrote in 1994 that "*Not much is known on how these [infill wall] buildings will perform in a major earthquake. They are difficult to evaluate by conventional analytical procedures because of the uncertainty of how the brick walls interact with the structural steel frames."* (Freeman, 1994) As a result of the many unknowns surrounding the frame and masonry interaction, and thus the difficulty that engineers have had in dealing with them, many of the seismic upgrades done on such structures have not considered the contribution of the walls, and, in many cases, the walls have been removed. In Oakland, California, a previously retrofitted steel infill-frame building was heavily damaged in the 1989 earthquake, damage which was a product of its flexibility after the removal of the infill walls. (Langenbach, 1992a&b)

Armature Crosswalls can be installed in situations where the lack of wall continuity from floor-to-floor make shear walls infeasible. They may also provide an alternative strengthening method for soft stories with the advantage that they can be installed without the expense of new or expanded footings and they can be tuned to reduce the transfer of forces into the superstructure above. The ACW may be able to provide an economical alternative even to the installation of superstructure mechanical dampers because the ACW walls double as fireproof and sound resistant walls, and, because of their comparative stiffness to alternatives, they can be engineered to provide high levels of damping within a sufficiently constrained story drift capable of protecting buildings vulnerable to frame or façade damage if drifts exceed a narrow range.

In summary, research will include the following: **(1)** Meeting of international participants to agree on best practices and individual parts of the research program, **(2)** Survey of relevant scientific literature, **(3)** Development of finite element computer models of ACW behavior with variations in the configuration of the armature (Mosalam, et al, 1997), **(4)** Initial testing of reduced-scale prisms with and without installed armatures in order to secure the initial findings under the grant and provide a sound basis for the further testing. **(5)** Research of comparative costs of installation of ACW compared to conventional construction in new buildings, and retrofit of existing infill walls in typical existing construction by converting them into Armature Crosswalls without having to remove and reconstruct them.

The objective of the physical testing will be to analyze the effect of variations in masonry and mortar strength, and the configuration of the studs and cross-members of the armature on the behavior (strength, ductility, and controlled degradation) of the Armature Crosswall. The test setup and modeling in this pilot study will utilize the standard ASTM diagonal tension configuration as depicted in Figure 1 with elements of the "armature" added. This pilot testing program will provide the basis for development of a detailed testing program to be carried out in other countries, most likely including Turkey, Italy and India as resources allow.



a) ASTM diagonal tension test setup. *(Mosalam)* b) Computational modeling using FEM *(Mosalam)*

Figure 4: Proposed test setup and accompanied computational modeling

Research on existing building retrofit will include studies of the feasibility of installing armatures into existing walls of low-fired brick (as are common in India and other parts of Asia), and hollow clay tile (as are common in Turkey and other parts of Europe and the Middle East), and methods for gaining the best performance from the retrofitted walls. This research idea is derived from a practical concept that is intended to be developed in a way that it will be comparatively easy to learn and apply. Cost estimates will be based on analysis of the most efficient means of construction using as many commonly understood locally existing practices as possible that can meet the goal of rapid installation with as little disruption to occupants as possible. Elaborate and complicated methods, or the use of costly materials, equipment or multiple trades, will be avoided where possible. The objective is to develop an installation methodology for retrofit projects that will avoid having to vacate the occupants of the buildings, which often has to be done if shear walls are installed.

Conclusion: Broader Impacts: While the efficacy of flexibility rather than strength has become accepted in earthquake hazard mitigation design, the application of a sub-frame “armature” concept to RC frames of inadequate ductility, and particularly to existing brittle masonry infill walls, has rarely been the subject of prior research. In the many countries located in the seismically active belt that rings the globe, this research may lead to the widespread adoption of construction techniques that could potentially save hundreds-of-thousands of lives in future earthquakes by substantially reducing the likelihood of pancake collapse of RC buildings where construction quality of the RC frame is likely to continue to be low, and where shearwalls are rarely used.

In the United States, this research is also of potential value for three reasons: (1) there is a large number of steel and concrete infill-frame buildings still extant from the early 20th century in West Coast cities, (2) the ACW technology is of potential value for hazard mitigation in mid-20th century non-ductile RC frame buildings, and (3) the ACW technology is also applicable to the many buildings owned and occupied by the United States in foreign countries for embassies, consulates, and residences in earthquake areas of the world. RC buildings constructed in the US during the 1940s until the 1970s have proven to be particularly vulnerable because of the non-ductile detailing, soft stories, and a lack of bracing or shearwalls. San Francisco Chief Building

Inspector Laurence Kornfield has observed that the prohibitive cost and disruption of installing shear walls makes the need for a more economical and less disruptive alternative, such as the ACW, particularly acute for the many apartment buildings of this construction in San Francisco. (Kornfield, 2005).

a) Apartment building after soft story collapse of ground floor during the 1987 El Salvador earthquake.

b) Upper story wall in building in (a) showing reinforced concrete sub-frame "armature" that may have prevented the collapse of upper the building's upper stories.

c) Building next to the collapsed Juarez Hospital (see Fig 1a) that survived undamaged. Concrete 'armature' subframes exist between the floor levels.

Figure 5: Examples of infill masonry walls with sub-frames similar in concept to Armature Crosswalls that have demonstrated resilience in past earthquakes.

This research also will be of benefit for historic preservation. Many historical buildings from the first half of the 20th century have brick and hollow tile infill walls, and in countries such as Greece, Turkey, Pakistan, Afghanistan, Nepal and India, as well as areas in Central and South America, the timber and masonry vernacular construction which has inspired the concept has been at increasing risk of destruction. In Turkey, many significant historic vernacular buildings have been condemned because earthquake damage was interpreted by engineers and inspectors as irreparable and dangerous to life because of a serious misunderstanding of how such buildings perform. Research under this grant will include the testing of materials and calibration of the computational models based on the construction found in historical buildings so that more can be understood about their performance in earthquakes. The concept for this proposal came from the successful performance of historical construction, so by seeing these historical vernacular buildings in a new light, an ancient culture can be reclaimed in the present by coming to understand it in a new way.

The Armature Crosswall concept was the subject of peer reviewed papers presented at (1) the Fifth Turkish National Conference on Earthquake Engineering, Istanbul, May, 2003 (*"Crosswalls Instead of Shearwalls"* by Randolph Langenbach), (2) an invited paper at the (NSF-supported) Joint US-India Symposium on Urban Housing and Infrastructure in New Delhi, October, 2005, and the 8th US National Conference on Earthquake Engineering, San Francisco, April 18 to 22, 2006 ("*Armature Crosswalls: A Proposed Methodology to improve the seismic performance of non-ductile RC infill frame structures,*" by Randolph Langenbach (USA), Khalid Mosalam (USA), Alberto Dusi (Italy), Sinan Akarsu (Turkey)). This concept was also the subject of an article by Randolph Langenbach: *Learning from the Past to Protect the Future: Armature Crosswalls,* published in the August 2008 issue of Elsevier's Engineering Structures. These papers are available on the web at www.conservationtech.com.