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"CROSSWALLS" INSTEAD OF SHEARWALLS
A Proposed Research Project for the Retrofit of Vulnerable Reinforced Concrete Buildings in Earthquake Areas based on Traditional *Hımış* Construction

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ABSTRACT

This paper will describe the parameters for a proposed research project to develop a design for the structural retrofit of particularly vulnerable reinforced concrete (RC) structures. This design is inspired by the characteristics of the traditional construction practice in timber and masonry infill-frame known in Turkey as *hımış*. The purpose of this proposal is to apply some of the basic philosophical ideas derived from an examination of earthquake damaged *hımış* infill-frame buildings that resisted collapse in the same earthquakes that leveled so many of their modern counterparts, and apply these ideas to the design of an economical retrofit scheme for the vulnerable reinforced concrete (RC) infill buildings. The basic objectives of this proposed retrofit design are that it should (1) be economical to install, (2) cause minimum disruption to the existing occupants of the buildings (installation without vacating the building or the individual residential units), (3) provide as much damage control as possible together with collapse prevention. To achieve this goal, this paper proposes that existing and new infill walls in vulnerable RC residential buildings be subdivided with studs and cross-pieces, and that new walls be constructed with lime-based mortar of lower strength than Portland cement mortar so that the elastoplastic behaviour of the infill will have a lower initial stiffness combined with higher "ductility" and stability.

Figure 1: "Pancake" collapse in Mexico City, 1985.

Figure 2: Partial collapse of RC Building, Gölcük , Turkey, 1999.

INTRODUCTION

The tragic earthquakes that struck the Marmara Region of Turkey in 1999 heightened concern that another disaster will soon strike the densely populated city of Istanbul. This concern is not focused primarily on the city's rich historical resources, all of which have been through many earthquakes. It is the thousands of modern buildings constructed in reinforced concrete in which most of the population lives that are now known to be exceedingly vulnerable. Large numbers of these moment-frame, hollow clay block[1] infill-wall structures (RC buildings) have been designed with minimal engineering input, and constructed by contractors having little knowledge and respect for the sensitivity of reinforced concrete to the need for proper detailing and correct construction procedures to ensure the full strength of the material. While the 1999 İzmit Earthquake made clear their particular vulnerability to lethal "pancake" collapse, it only served to highlight a problem that had been known to earthquake specialists for years.

The question now is whether anything can be done to improve on this situation. What are the possible parameters of a retrofit of existing structures that are now known to be vulnerable to collapse by the searing evidence of those that already have collapsed, and also for new construction? As Nuray Aydinoglu, Professor of Earthquake Engineering at Boğaziçi University has recently observed in a conversation, the efforts to retrofit the tens of thousands of vulnerable buildings in Istanbul are stymied by two things – the lack of resources to cover the costs of properly engineered retrofits, and the inability to gain consensus among owners, as most are divided into condominiums. In Istanbul alone, it is almost an insurmountable challenge – but it is one that must be tackled. It is a problem that is expanding exponentially, as more such buildings are constructed every year. And, as it is largely a socio-economic problem, even the most sophisticated engineering alone will not solve it.

Thus the parameters of this project is to develop a design for the structural retrofit of these particularly vulnerable structures inspired by the characteristics of the traditional construction practice in timber and masonry infill-frame known in Turkey as *hımış*. The purpose is not to replicate the materials and methods of pre-modern timber and masonry construction, but rather, to apply some of the basic philosophical ideas derived from an examination of earthquake damaged *hımış* infill-frame buildings that resisted collapse in the same earthquakes that leveled so many of their modern counterparts, and apply these ideas to the design of an economical retrofit scheme for the vulnerable RC infill buildings.

Figure 3: Large 3 story house in *hımış* construction, Safranbolu, Turkey, 2000.

Figure 4: *Hımış* construction on 3 story house in Safranbolu, Turkey, 2000.

The most important philosophical underpinning of the research is that the initial stiffness of reinforced concrete frame with infill wall buildings be deliberately reduced from the current conditions so that the overall structure can remain flexible within the limits of the integrity of the surrounding RC frame. To accomplish this, it is the infill walls that must be made to behave in a less stiff manner. Since masonry is inherently stiff, it is a plastic, rather than elastic, behavior that must occur at the outset of earthquake shaking that must be designed into the system to accomplish this objective. Thus, the second objective is a corollary of the first. It is that the "ductile behavior" of the walls must be increased, and their rapid degradation in multiple cycles be avoided. By "ductile behavior," what is meant is the dissipation of energy through the controlled cracking of the constituent brittle materials that make up the walls – particularly the mortar. Thus, the objective is to modify the existing infill walls to avoid their common early shear failure and falling out of the frame, so as to provide continuous additional support to the

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[1] In the United States, this is called "hollow clay tile," but this term may be confusing to those unfamiliar with its use in English because such masonry units are not "tiles" as commonly understood, but blocks. They are larger than bricks and slightly smaller than standard concrete blocks. They are heavily perforated in one direction to make them light. In light of the confusion, throughout this paper, they are called "hollow clay blocks."

building during the course of the earthquake shaking by "working" through many cycles of without loss of their integrity.

For this proposed retrofit to be practical and economically feasible it is important that, wherever feasible, it entail a minimum of demolition work, and be installed rapidly enough to cause minimum disruption and added costs for the occupants. To meet this objective, it must include the use of the existing infill walls to the greatest extent possible (for economy and avoidance of disruption in occupied buildings). The addition of new walls of the tested design will be needed only where excessive open spaces (such as at the ground level) exist.

The author's training is in the field of architecture and building conservation, rather than structural engineering. This paper is meant to be reflective of a perspective on this subject from these allied fields, rather than based within the discipline of structural engineering itself, and so the discussion deliberately explores the subject through the historical background of the construction methodology. The following paper is primarily focused on a *proposal* for a structural testing program, rather than being a report on a completed testing project. The reason why a proposal for a physical testing program is the subject of a paper will emerge from the background materials presented here, which are both an unusual and an inevitable "second step" from the field observations that the author has reported on in a series of papers beginning one year after the 1999 İzmit and Düzce Earthquakes.[2]

THE PRECEDENT IN TRADITIONAL CONSTRUCTION

After having researched and documented various types of timber-laced, masonry construction, the 1999 Turkey earthquakes provided an opportunity to witness how at least one type of timber-laced system performed in large earthquakes.[3] Although located for the most part in areas of relatively modern industrial development, the damage district does contain many clusters of buildings constructed in what in Turkish is referred to as *hımış* construction.

Figure 5: Row of collapsed RC buildings showing typical hollow clay block infill on end wall left exposed by the collapse of another building.

Figure 6: 3 story *hımış* house in the heart of the damage district in Gölcük , photographed one month after the 1999 earthquake. There was no evidence of damage visible on the exterior, yet many RC buildings had collapsed within the surrounding area.

Hımış construction is simply described as a timber frame with masonry infill. The masonry is usually a single "wythe" or layer, often with the bricks laid at angles to fit between the studs, or alternatively, if stone is used, random rubble set into thick layers of mortar. Depending on the local, the mortar commonly a lime mortar, but in some more rural areas, a mud mortar may be used.

Hımış was a characteristic form of construction in many parts of Turkey during the Ottoman period, and has continued in common use up until it was rapidly displaced by reinforced concrete

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[2] These are available at www.conservationtech.com.

[3] The term "timber-laced" masonry is herein meant defined as masonry constructed with timber elements (beams, columns, and/or braces) placed within the plane of the wall such that they form potential tension-bearing elements acting within the plane of the wall. Simple timber lintels, or short joist setting blocks are not meant to be included in the definition, but, as will be described, timber lacing can either consist solely of horizontal timber elements, or vertical and horizontal elements. It may or may not, taken together, form a complete timber frame.

frame with hollow clay block infill construction beginning in the middle of the Twentieth Century. The middle of the Twentieth Century is a relatively late date for a construction method that is little different from what was common throughout Europe in the Middle Ages. *Hımış* construction is variation on a shared construction tradition that has existed through history in many parts of the world, from Elizabethan England, to Nineteenth Century Central and South America. In Britain, for example, it would be referred to as "*half-timbered*," in Germany as "*fachwerk*," in France as "*colombage,*" in Kashmir, India as "*Dhajji-Dewari*," in El Salvador as "*bahareque*." (Correia, 2003) Ancient Roman examples have been unearthed in Herculaneum, several involving interior partitions, but one involving the construction of an entire two story row house. (Langenbach, 2003) The palaces at Knossos have been identified as having possessed timber lacing of both the horizontal and the infill frame variety. This takes the date of what can be reasonably described as timber-laced masonry construction back to as early as 1500 to 2000 BC. (Kienzle, 1998)

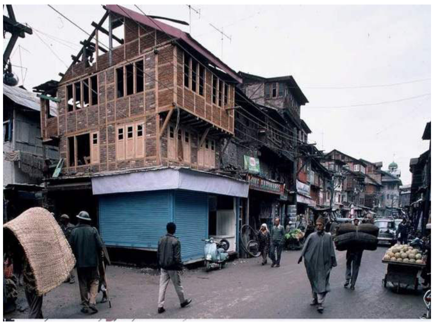

Figure 7: *Dhajji-Dewari* construction used for a new house in Srinagar, Kashmir in 1989.

Figure 8: *Bahareque* construction in San Salvador showing effects of 1986 earthquake. The loss of the stucco shows that the wall underwent deformations without loss of its underlying structural integrity.

The Marmara and Düzce Earthquakes

The Marmara earthquake (also called the Kocaeli earthquake) of August 17, 1999 killed approximately thirty thousand people. (Kandilli, 2000) The epicenter was just 200 kilometers east of Istanbul. In some areas of Gölcük and Adapazari, the earthquake destroyed more than a third of all housing units, almost all of them in reinforced concrete buildings. (Kandilli, 2000) There were clusters of *hımış* buildings in the heart of these districts. These houses, mostly dating from the early part of the twentieth century, pre-dated the ruined reinforced-concrete apartment blocks nearby. Many of the older *hımış* houses remained intact, but a few were heavily damaged. This finding was confirmed by two Turkish professors who conducted a detailed statistical study in several areas of the damage district who found a wide difference in the percentage of modern reinforced concrete buildings that collapsed, compared to those of traditional construction (Gülhan and Güney 2000).[4]

Figure 9: Three story RC building next to a 2½ story *hımış* house near Düzce showing the repair of severe damage to the RC building (notice the size of the ground floor columns). The *hımış* structure has lost only stucco on the side. Almost all of the hollow clay block on the RC building has been reconstructed after the earthquake. This shows that even low rise RC buildings sometimes suffered more damage than nearby traditional buildings.

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[4] Gülhan and Güney documented that in one district in the hills above Gölcük of the 814 reinforced-concrete, four-to-seven-story structures, 60 collapsed or were heavily damaged, while only 4 of the 789 two-to-three-story traditional structures collapsed or were heavily damaged. The reinforced-concrete buildings accounted for 287 deaths against only 3 in the traditional structures. In the heart of the damage district in Adapazari, where the soil was poorer, this research shows that of the 930 reinforced concrete structures, 257 collapsed or were heavily damaged and 558 were moderately damaged, while none of the 400 traditional structures collapsed or were heavily damaged and 95 were moderately damaged.

Inspecting the interiors of some of the *hımış* houses provided a more complete understanding of the behavior of *hımış* as a structural system. It was evident that the infill masonry walls responded to the stress of the earthquake by "working" along the joints between the infilling and the timber frame; that is, the straining and sliding of the masonry and timbers dissipated a significant amount of the energy of the earthquake. The only visible manifestation of this internal movement was the presence of cracks in the interior plaster along the walls and at the corners of the rooms, revealing the pattern of the timbers imbedded in the masonry underneath. This level of damage was evident in every house. On the exterior, unless the house was plastered on the exterior, damage was mostly impossible to see. The bricks themselves only infrequently were displaced sufficiently for a crack to be visible. The movement was primarily along the interface between the timbers and the brick panels rather than forming a crack within the panels themselves.

Figure 10: Exterior of 1955 *hımış* house in Gocuk damage district one month after 1999 earthquake. Do damage is visible.

Figure 11: Same wall as Fig.10 showing earthquake caused cracks in interior mud plaster.

The typical *hımış* construction does not have mechanical ties between the timber and masonry to hold the infill masonry in place. As a result, in some cases, small sections of the infill were shaken out from between the studs near the top of the upper-story walls. Because of the existence of the timber studs, which subdivided the infill walls into small panels, the loss of portions or all of several panels did not lead progressively to the destruction of the rest of the wall. Many walls were missing some of their infill, but evidence of 'X' shear cracks, so common in the infill in the modern reinforced concrete buildings, was non-existent in the *hımış* structures. The closely spaced studs reduced the likelihood of the propagation of 'X' cracks within any single panel. In addition, the subdivision of each structural bay with a tight network of vertical, horizontal, and diagonal timbers, rather than vertical studs alone, appeared to have been successful in reducing the possibility of the masonry falling out of the frames.[5]

An important additional factor in the performance of the walls was the use of weak, rather than strong mortar together with bricks that are stronger than the mortar. The mud or weak lime mortar tended to encourage sliding along the masonry bedding planes instead of cracking through the masonry units when the masonry panels deformed, reducing the contrast between rigid masonry panels and the flexible surrounding frames.

Strength vs. Capacity

This pattern of damage helped explain why these buildings were capable of surviving a major earthquake that had felled modern reinforced-concrete buildings. The basic principle in this weak,

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[5] A smaller earthquake (6.1 magnitude) that struck the rural town of Orta on June 6, 2000 provided an interesting comparison with the damage caused by the İzmit and Düzce earthquakes the previous year. In this smaller earthquake, the damage to the *hımış* structures was similar to the pattern of damage to those affected in the larger earthquakes, whereas the damage to RC structures was much less. This provided an example of why there is the false but widespread perception that RC buildings are safer. The comparison shows that the RC buildings have very little reserved capacity, as this example shows that they can go from exhibiting little damage to collapse very quickly, whereas the traditional structures can withstand many cycles of shaking by dissipating energy through the friction of their component parts – which means they show about the same level of damage at both low and high levels of shaking. (For more information on the Orta earthquake, see Langenbach, 2003)

flexible-frame-with-masonry-infill construction is that there are no strong and stiff elements to attract the full lateral force of the earthquake. The buildings thus survive the earthquake by not fully engaging with it. This "working" during an earthquake can continue for a long period before the degradation advances to a destructive level.

While these structures do not have much lateral *strength*, what they possess is lateral *capacity*. These buildings respond to seismic forces by swaying with them, rather than by attempting to resist them with rigid materials and connections. This is not an elastic response, but a plastic one. The swaying and deformation of these structures is different from that of a tree, the suppleness of which allows it to bend elastically. When these structures lean in an earthquake, they do so with incremental low-level cracking which is distributed throughout the wall by the interaction of the timber structural elements with its confined masonry infill. This controlled damage is what the "working" of the structure means. It is how a building made with a disparate assembly of brittle materials is able to survive seismic forces that are far larger than could be resisted by it in a fully elastic undamaged state. In other words, although the masonry and mortar is brittle, the *system* — rather than the materials that make up that system — behaves as if it were "ductile."[6]

Figure 12: House in Orta, Turkey one day after the 2000 Orta earthquake – showing plaster cracking that reveals the timber frame.

Figure 13: *Hımış* interior wall in house in Düzce earthquake damage district showing "working" of wall that caused loss of plaster.

In addition, by dissipating energy, the "working" also affects the natural frequency or "period" of the vibration of the structure. Resonance with earthquake vibrations is a principal factor in the cause of earthquake damage to buildings in general. The controlled sliding and cracking of the infill masonry reduces the infill-frame structure's ability to resonate with the earthquake by providing damping, just as a shock absorber does for a car. In contrast to this, there are many examples of modern structures that were strong enough to resonate elastically at ever increasing amplitude until the catastrophic failure of a critical structural member caused their sudden collapse. Simply stated, all of this is the difference between *strength* and *capacity*.

Figure 14: Soft-story collapse of a RC infill wall building in Adapazzari where the infill walls resisted the pancake collapse of the upper floors.

Figure 15: Collapse of a brittle interior hollow clay block wall illustrating typical failure pattern for such walls lacking subdivisions.

After witnessing the survival of the *hımış* buildings in the İzmit earthquake, one may ask: *Did they build this way because of earthquakes?* This is a difficult question to answer in Turkey where it is the continuance of a widespread construction tradition until a relatively recent date that may have been in part stimulated by earthquake risk, but was not so identified as such when the decisions

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[6] *Ductility* refers to a material's capacity for being bent beyond its elastic range without breaking. In the case of this traditional construction, where most of its lateral resistance is provided by the brittle masonry, the term applies to the behavior of the system, not the materials which make up that system. In the 1981 published paper "*Earthen Buildings in Seismic Areas of Turkey*," Alkut Aytun credited the bond beams in Turkey with *"incorporating ductility to the adobe walls, substantially increasing their earthquake resistant qualities."* (Aytun, 1981)

were made to use it. For clearer records on this questions, we must migrate to examples in both Portugal and Italy where a similar form of construction was specifically selected as a preferred system for seismic hazard mitigation.

The Timber Frame and Infill Walls of Baixa Pombalina, Portugal, and Calabria, Italy

Following the 1755 earthquake in Lisbon, which destroyed the center of the city, an area known for its lower geographic location as Baixa, 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, a single wall of which is referred to as a "parede Pombolina" or Pombolino wall. In its complete form, it is referred to as "Gaiola" or "cage,"construction – an interesting play on the Marquis' own name, which translates into English as "Pigeon House." Most, if not all, of the buildings reconstructed in the reconfigured planned Baixa area were constructed with Pombalino walls, and sometimes (but not always) with complete "gaiola" timber frames.

Figure 16: Pombalino "Gaiola" walls in Baixa, Lisbon, Portugal.

Figure 17: Typical hidden timber frame in central Madrid, Spain, 5 story building.

The Pombolino system used on the interior of buildings consisted of timber frames with vertical and horizontal timbers of approximately 10cm to 12cm square, with internal braces, forming an "X" or, as it is referred to in both Italy and Portugal, the "Cross of St. Andrew." (Figure 16) The timbers for the cross are 9cm by 11cm in section. The frame was then "nogged"[7] in the triangular spaces formed by the crosses with a mixture of stone rubble, broken brick, and square pieces of Roman brick in different patterns in each panel. The interior walls were then covered with plaster, hiding the timber frame. The infill masonry usually extended beyond the surface of the wood slightly, allowing for a thick coating of plaster to hide the wood, thus keeping plaster cracks to a minimum.

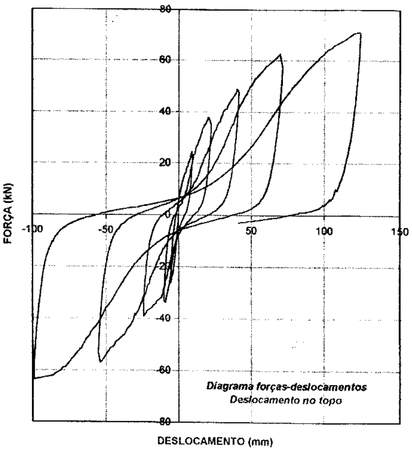

Figure 18 & 19: One story frame section removed from "gaiola" building tested for strength and stiffness in Portugauese National Lab by Cóias e Silva recently. Fig.18 shows one of three walls after cyclical tests to a point just short of collapse, and Fig.19 shows hysteretic behavior of one of the walls. The loss of the plaster and the wide hysteresis loops show that the walls were able to dissipate energy over many cycles without losing their structural integrity. (Cóias e Silva, 2002)

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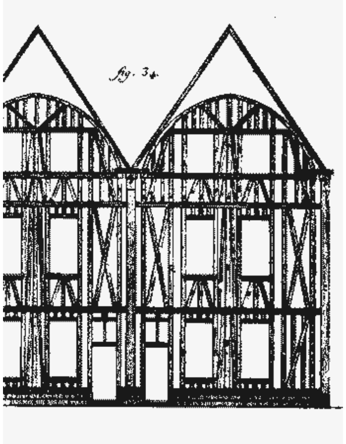
[7] filled in with brick

The exterior facades of the Baixa buildings were reconstructed with load-bearing masonry walls of about 60cm in thickness. Some, but not all, of these exterior walls were constructed with a timber frame on the inside face. This frame was also nogged with brick, but may not always have contained the timber diagonals. The incidence of the use of the complete "gaiola" frame is not entirely known, but there is evidence that in later buildings the system was reduced to the use of the Pombalino walls for the interior partitions. (Cóias e Silva, 2002; Correia, 2003]

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. In Baixa, the buildings are five and six stories, making them taller and more substantial than most of the Turkish *hımış* structures. What may be more important than the Pombalino System itself, is the answer to the question: *How did they know that it would work?* There must have been buildings in Lisbon constructed with timber frames and infill masonry that were seen to have survived the earthquake. Next to the Baixa area is Alfama, which dates back to Medieval Lisbon, and reportedly was not destroyed during the 1755 earthquake. Were there infilled timber frame buildings there? Since this form of construction was common throughout Medieval Europe, including the Iberian Peninsula, quite likely it existed in parts of Lisbon, including Alfama, at the time of the earthquake. For example, in Madrid, which has not historically been subject to earthquakes, most of the historical buildings within the formerly walled city area around the Plaza Major, which from the front look like standard masonry buildings, are in fact almost completely timber frame structures. Only the street façades are bearing wall masonry, and the internal structure of the buildings is resting completely on timber columns with rubble masonry infill. Some of these buildings are six or seven stories in height, with most no less than five stories (Figure 17). (Langenbach, 2003; Gonzales Redondo, 2003) Thus, the adoption of the Pombalino system serves to systematize specifically for earthquake resistance a building tradition that, as was pointed out above, extends back over 1500 to 3000 years to Roman and pre-Roman precedents.



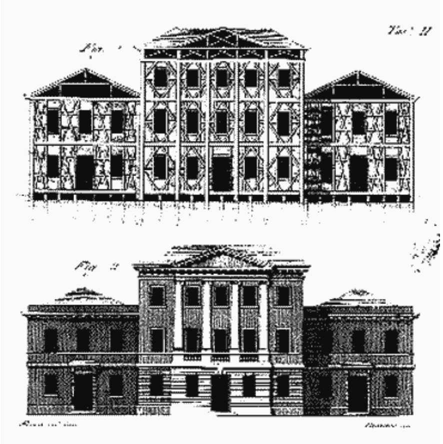


Figure 20: Illustration of timber frame for infill-wall construction done *"in the modern way."* from 1751 *Encyclopédie. (Diderot, et al, 1751-72).*

Figure 21: Illustration of Giovanni Vivenzio's Italian "anti-seismic house" showing *casa Baraccata"* dated 1783. (Vivenzio, 1783, from Barucci, 1990)

The fact that the favorable performance of infill masonry had not only been noticed, but was, at the time of the Lisbon earthquake, in the process of being broadly accepted as a principle means of achieving earthquake resistance can be seen from the publication of what was described in French as a "modern method of wood framed walls" (Figure 20) in *Encyclopédie* by Diderot and D'Alembert in Paris in 1751-72. (Diderot & D' Alembert, 1751-72; Barucci, 1990; Mateus, 2002). The illustrations in this work are remarkably close to the timber framing used in Pombalino system.

In fact, as documented by Clementina Barucci (Barucci, 1990), the development of the Italian *"Casa Baraccata"* system in Calabria, and Sicily, where devastating earthquakes had occurred with astonishing frequency, was contemporaneous with the Gaiola in Portugal, and each may have been influenced by the other. In Italy, the *Casa Baraccata* (Figure 21) became the underlying basis for a whole series of manuals of practice, and even of patent applications for seismic resistive construction techniques, through the Nineteenth Century and the first two decades of the Twentieth Century. (Barucci, 1990).

Looked at simply, this is an example of what is essentially an ancient and medieval form of construction, common throughout Europe and other parts of the globe, that was identified in the 18th and 19th Centuries as being earthquake resistant. It was not until the middle of the 20th Century that the bare frames with hollow clay block infill became so universal as the default form of construction. The fact that masonry and timber infill frame construction was considered in both Italy and Portugal as earthquake resistant for a century and a half is now largely forgotten. Reinforced concrete was initially thought to offer greater strength and more seismic protection, all with an open flexible floor plan. However, between LeCorbusier's ethereal prototype of the *Maison Dom-Ino* and the generic RC buildings that crumbled in Turkey in 1999, there is yet another, very different, historical prototype – the American steel frame skyscraper.

A Revolution in the History of Building Construction – the "Chicago Frame"

The watershed event that is often cited as having defined the introduction of modern construction practice for mid and high-rise buildings is the "invention" of the steel frame skyscraper in Chicago in the 1880's with the construction of the world's first high-rise steel frame building, the Home Insurance Company building, in 1885, designed by William LeBaron Jenney.

In some sense, there was a more profound, but more subtle revolution that followed it – the "invention" of the curtain wall. It was only with the invention of the curtain wall that the structural frame became free to work as a frame laterally and vertically. While in the simplest sense, this was thought to be the case with Chicago Frame buildings, in practice, it was not. In many ways, the masonry infill dominated the performance of the frame, stiffening and strengthening it. For example, a 1938 report on the tallest, and one of the last, examples of this type, the 1931 Empire State Building in New York City, reveals that the infill masonry at the 29th and 41st floors cracked during a storm with wind speeds of 90MPH. Strain 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)

Figure 22: New York City's Woolworth Building, by Cass Gilbert, was constructed in 1913 using the Chicago Frame system. At the time of its construction in 1913, it was the world's tallest building.

With the collapse of the 110 story twin towers of the World Trade Center in 2001, visible in the foreground, it resumed its place as the tallest structure in Lower Manhattan, and its 1931 successor for the title of World's Tallest Building, the Empire State Building, also a Chicago Frame type structure, resumed its place as the tallest building in New York City.

From the standpoint of the applied technology of their enclosure systems, the first "Chicago Frame" buildings were transitional. While they had steel skeletons, the masonry exterior and some interior walls enveloped that frame, tightly filling the space from shelf angle to shelf angle.

These facades were not curtain walls suspended and separated from the frame. In spite of this, unlike their distant reinforced concrete cousins in Turkey, the earliest Chicago Frame buildings both in Chicago and New York City have proven to be exceedingly durable. The solid walls of masonry in the early American sky scrapers belie their internal structures of steel. Very much like the SRC buildings that are the focus of this paper, the Chicago Frame buildings are of infill wall masonry construction – but the masonry is stronger (and also heavier) than that in the standard reinforced concrete frame buildings. However, conservation issues that have emerged reveal the underlying ambiguity of their nature – cracking and spalling of the masonry skin has been caused by the inevitable slight expansion of the masonry working against the creep and shrinkage of the frames. (Searls & Bronski, (2002)).

There may also be another factor in play that has contributed to these problems. A subtle but significant historical transition that followed the steel frame was the transition in the early part of the 20th Century from the use of lime mortar to Portland cement-rich mortar. At the time of the first Chicago Frame buildings, masonry mortar was composed of lime and sand, but beginning in about 1920, the principal constituent used for masonry mortar began to shift from lime to Portland cement. It is possible – even likely – that frame/wall compatibility problems have been aggravated by the substitution of Portland cement mortar for the lime mortar, despite its greater strength and resistance to erosion from the weather.

This brings us back to the infill-frame RC buildings that are the subject of this article. Instead of tightly packed strong walls with a certain amount of give in them imparted by the lime mortar, we now have walls, which are treated as if they are modern curtain walls, that are as rigid and brittle as they possibly could be. In Turkey, the hollow clay block is as fragile and brittle as a dinner plate, and the mortar is equally inelastic. In a residential building with its many internal walls, during an earthquake, the combination provides immense initial stiffness with strength enough to force all of the initial deformations into the weakest parts of the structure at the base, which can collapse the building. If that does not occur, then the weak walls soon crack and fall out of their frames, which can also cause the building to collapse. In other words, the ideal of frame action occurring unencumbered by stiffening elements is a goal only realized when a structure can be left open, as in the tropics, or clad with light weight curtain walls and the interior partitions are light weight. For the housing blocks in Turkey, that is not the case.

REINFORCED CONCRETE INFILL-FRAME CONSTRUCTION

In many, if not most countries along the seismic regions of the world, RC construction has now almost entirely displaced traditional forms of construction in urban and urbanizing areas. Thus, the great preponderance of building construction is of reinforced concrete, and most of these buildings are residential. One cannot underestimate the scale of the revolution in building practice that this represents, and from Mexico City to Delhi and on to Guadalajara, RC multi-story frame technology has left its indelible stamp on the urban world – unfortunately, most often for the worse aesthetically. While artistic giants like Le Corbusier have sometimes done their greatest work in this medium, what most commonly passes for building design in reinforced concrete is usually far more pedestrian.

From a structural standpoint, the codification of the RC frame technology into a cookie-cutter standardized production of routinely produced poured-in-place structural frames has contributed greatly to the deadening monotony of urban developments around the world. The large standard bay width, combined with the need for regularity in the vertical placement of the columns lends itself to repetition of forms with only cosmetic variation. Worse, however, is that, as RC has become the default construction technology, in earthquake areas, the great promise of the material has failed to be realized. The shift from traditional low strength materials to reinforced concrete is a radical transformation of the entire building construction process that has affected many regions of the world. Reinforced concrete is an industrialized high-tech material that is safe and strong *only* when it is used in a way that shows knowledge and respect for its properties. And indeed, therein lies the problem. In many countries where this method of construction now predominates, it is subjected to a low-tech building process not unlike that used for the vernacular masonry buildings it has now displaced. When misused, it is dangerous – as the recent earthquakes have so tragically shown. Unlike timber and masonry infill systems, reinforced concrete is unforgiving of both poor design and poor execution. In addition, such faults are often completely hidden once the structure is completed.

Figure 23: Typical Turkish RC building under construction showing the hollow block infill being installed.

Figure 24: Typical hollow clay block infill as used in reinforced concrete residential construction in Turkey.

Earthquakes are in fact only the leading edge of a more universal problem. While examples of Roman construction in concrete have survived for two millennia, modern reinforced concrete is proving to be an ephemeral medium. The combination of Portland cement and aggregate with steel reinforcement means that the longevity of the system is only as long as the longevity of one or the other of its constituent materials. Eventually, through the inevitable loss of alkalinity of the cement matrix, the natural protection of the imbedded steel reinforcing is lost, and thus vulnerability to corrosion increases dramatically.

Unlike wood construction, where rotted beams can be replaced, with concrete the repair can often require the complete demolition of the deteriorated floor, wall, or even the whole building. In addition, imperfections in the selection of the aggregate, mixture of the concrete, placement and compaction around the steel, and inadequate curing can lead eventually to catastrophe – sometimes without warning or evidence of distress. Earthquakes are not the only cause of such problems. One or more RC buildings in Bombay, for example, have collapsed during almost every monsoon season. Earthquakes do, however, provide a view into the larger problem of building stability and longevity, by bringing together into a single terrible moment problems that would otherwise emerge only over generations.

With a recent history of so many earthquakes in places such as Mexico City, Morocco, Yugoslavia, India, and of course, Turkey, where hundreds, even thousands, died under tons of reinforced concrete, few would argue that there is not a problem with reinforced concrete construction. But, is it an *engineering* problem? After each earthquake, teams of engineers have descended onto the devastated areas, rendering opinions as to the causes of the collapses. A common verdict is that engineering knowledge is not the problem, but that the quality of construction (and sometimes the design) of the collapsed buildings is. True enough, in most of these places, well designed and well constructed buildings in reinforced concrete survived.

However, identifying the fact that collapses were caused by failings of builders to meet even locally acceptable standards of practice obscures one fundamental point about the building process – that most likely there will *always* be a preponderance of poor construction, despite the best efforts of educated engineers.[8] The human consequences of this reality raises an important

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[8] This is true in all places, including the United States, but in North America, the predominant construction is timber, not concrete. Unlike in Turkey and most other parts of the world, concrete buildings are at a cost premium above

question – could we establish a standard system of construction that – even if poorly executed – does not lead to collapse in earthquakes? For examples of such systems, one must turn back the pages of history before the advent of the "strong" materials of reinforced concrete and steel, to look at what succeeded and what failed in earthquakes when people had to do more with less. While drawing parallels between two, three and four story traditional structures with eight, ten and twelve story reinforced concrete buildings may be risky, it is none-the-less important. It is these examples from the past that could inspire a new philosophical approach to the production of buildings in the modern age.

The Standard Reinforced Concrete Frame (SRC)

The basic RC frame that is now so common was first promulgated as the basis for a new architectural form by Le Corbusier in his "*Maison Dom-Ino*" in 1915 (Figure 25). (Frampton, 1994) What was idealized as a liberating form of construction with flexible space because of its absence of structural walls, has now become the standard "default" form of construction over much of the globe.

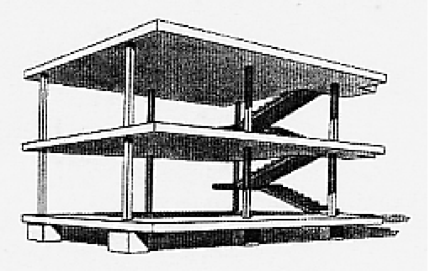

Figure 25: Le Corbusier, Maison Dom-Ino reinforced concrete structural frame, 1915. (Frampton, 1980)

Figure 26: Eight-story reinforced concrete frame structure in Gölcük under construction at the time of the İzmit, Turkey earthquake in 1999, which collapsed many occupied buildings around it. From a street-level inspection, this building did not appear to be damaged. Undoubtedly, the absense of the masonry infill allowed the frame to deflect evenly, rather than causing a soft story at the base of the structure where it is most vulnerable. Had the building been finished at the time of the earthquake, the results may have been quite different.

It is interesting, and not entirely clear why the RC moment frame has become almost exclusively this default form of RC construction, especially in earthquake areas, where it has repeatedly proven to be vulnerable to *pancake collapse*, (Figure 1) a modern term coined after so many of these structures collapsed into tight and impenetrable piles of floors. RC frame with shearwalls would have been a safer choice, as even poorly constructed buildings with shearwalls have a greater reserve capacity than a poorly constructed moment frame. In contrast to shearwall buildings, the moment frame relies on the strength of the beam/column intersections to resist deformation and collapse in earthquakes.

The most significant problem with moment frame construction is that a failure to provide for sufficient strength or ductility in the frame joints can lead rapidly to collapse in an earthquake. Perhaps the influence of Le Corbusier and his contemporaries may have had something to do with this choice because there is a great deal of magic in the potential of a structural system that does not impose itself onto the special layout of a building, apart from accommodating the columns. More likely than that, however, is the cost. Shearwall buildings are more expensive than those with bare frames.

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those in timber, which encourages a greater quality control in their production. When it comes to earthquakes and construction shortcomings, timber construction is much more forgiving than is reinforced concrete.

Figure 27 & 28: Five story building damaged in the 1999 Düzce earthquake in Turkey, being retrofitted with reinforced concrete shearwalls. No.28 shows the existing hollow clay block walls removed and steel being inserted for the construction of a reinforced concrete shearwall. These images illustrate the extent of the work, and disruption needed for earthquake strengthening using shearwalls. The occupants had to move out for the duration of this work as many existing walls were removed.

The Masonry Infill in Reinforced Concrete Construction

In most regions of the world, some form of masonry is used for walls and partitions in reinforced concrete frames. It is the masonry infill that turns a raw structural frame into a building by enclosing and partitioning the interior. The masonry used in infill frame construction is either of fired solid brick, or of fired hollow clay block. In Turkey, where block is used, the most common block is extremely light and brittle – an asset in terms of avoiding excessive weight in the upper stories of a multi-story structure, but a drawback when such a wall becomes a *de facto* secondary structural element in an earthquake.

Figure 29: Infill wall RC building in Mexico City damaged in 1985 earthquake. The infill masonry in this structure almost caused the collapse of the building. The damage to the corner column that left the building teetering on the edge of collapse can be seen on the right.

Figure 30: Typical hollow block infill wall partially fallen out of the frame of a building under construction at the time of the İzmit earthquake in Turkey in 1999. The typical infill construction has no mechanical ties other than loosly packed mortar to hold the infill masonry from falling out of the frame. The subdivisions in *himiş* construction help hold the masonry together in the frame because the panels are much smaller.

Even though these walls have usually been ignored (except as dead weight) in the engineering design of reinforced concrete frames, for many years, they have been the focus of concern in engineering research and code development. Research has shown that the infill masonry walls behave as a “diagonal strut” resisting the deflection of the frame when lateral forces are applied. If the masonry infill is strong enough, the diagonal strut that is formed when the frame is forced to sway in an earthquake can cause the shear failure of the column, precipitating collapse (Figure 29). In addition, the stiffness of the walls cause the buildings to be subject to greater forces than the walls or the frame are capable of resisting. As a result, designers and buildings have frequently sought ways to isolate the infill from the frame, but this solution has never found wide acceptance because of the problems trying to stabilize these now free-floating masonry walls out-of-plane.

In Turkey, the hollow clay block that is commonly used is weaker, and thus less likely to damage the RC frames, but the infill unquestionably has had a role in the performance of the SRC buildings during an earthquake. Observations after the 1999 İzmit earthquake have ricocheted between condemnation of the walls as having contributed to the collapses, and acknowledgement that the walls may have helped to save some buildings that otherwise would have collapsed. The one thing that cannot be argued, however, is that the walls in earthquakes are suddenly brought into action as structural elements.

The problem that happened repeatedly in both the recent Turkey and India earthquakes is that the exceedingly stiff walls on the upper floors of a building over the open shop fronts or parking below contributed to the collapse of the structure because the frame deformations were concentrated in the soft story at the base (Figure 14). Even though the RC frame was of uniform design for the full height of the structure, the installation of the rigid "non-structural" infill walls on the upper floors is responsible for the creation of a soft story at the ground level where they are mosty absent. When the upper story infill is of solid brick, sometimes only the weak bottom story will collapse, allowing people in the upper stories time to escape, whereas when the walls are constructed in hollow clay block, as in Turkey, the kinetic energy overwhelms them, bringing all floors to the ground (Figure 1&2). Over 20,000 people died in such buildings in Turkey in 1999.

CROSSWALLS FOR VULNERABLE REINFORCED CONCRETE FRAME BUILDINGS

The transition to reinforced concrete frames represents more than a change in materials – it is a change from the reliance on the plastic behavior of masonry walls to that of a reinforced concrete frame. The problem, as recent earthquakes have shown, is that once reinforced concrete frames are pushed beyond their elastic range, those that are deficient in steel or construction quality do not have the kind of reserve capacity needed to survive many earthquake cycles.

By comparison, as shown in recent earthquakes, the timber and masonry infill walls exhibit extensive capacity. This capacity may be hard to calculate, but it is demonstably there. It is the fact that the infill walls can sustain repeated cycles, dissipating energy and thus damping the motions of the structure, that make the walls a successful seismic mitigation element. This is undoubtedly what Pombal and his engineers saw in Lisbon in 1755, and what the Italians witnessed in Calabria in the 18th Century as well.

Figure 31: Infill RC building in Mexico City after the 1986 earthquake collapsed many buildings nearby. Each panel is subdivided vertically and horizontally.

Figure 32: A subdivided internal brick infill wall in San Salvador after the 1986 earthquake.

It is this kind of capacity that, if introduced into vulnerable reinforced concrete structures, could improve their performance. Thıs is accomplished by retrofitting the infill walls (or constructing new ones) to increase their "ductility." In fact, if successful, this approach can serve a protective function because the eleastoplastic behavior of the retrofitted walls and partitions is called into play at the very outset of an earthquake, while the frame is still within its elastic range. If they function properly, the walls will continue to work compatibly with the frame by extending the natural period of the structure and reducing its destructive resonance to the earthquake vibrations. This may keep the underlying reinforced concrete frame within its elastic range, or at least keep damage to it to a level that can be repaired.

In both the Mexico City Earthquake in 1985 and the El Salvador earthquake in 1986, there were examples of walls that had been constructed with one vertical and one horizontal subdivision that exhibited good behavior in those events (Figures 31&32). In both cases, the walls were constructed of solid fired brick, rather than hollow clay block. . In the Mexic City case (Figure 31), the building remained undamaged while many other structures near it collapsed (Figure 1), and in the El Salavador example (Figure 32) , the walls prevented a pancake collapse when the building collapsed on its weak bottom story. The photograph shows that the stresses in the wall from the ground floor collapse of the building caused only the plaster to shed, but did not cause the masonry to fall out.

The previous sections may seem like a circuitous path to arrive at a proposal for the stabilization of building of recent vintage that are totally different structural systems and also often considerably larger. The purpose here, however, is not to propose a technology transfer from the past to the present in a literal sense, but to use the past examples to help define a series of physical performance objectives – and to ground these objectives in an historical context. In otherwords, the proposal is not necessarily to use timber, or to reproduce the kind of masonry used in the past, but to explore how to gain similar performance characteristics while using modern materials, such as steel, or even pre-cast concrete elements, together with modern brick or hollow block masonry units that are commonly available.

The performance objectives for these redesigned infill walls in standard reinforced concrete buildings are the following:

1. Make the interior and exterior infill masonry walls (infill walls) have *low*, rather than high elastic strength so that controlled elastoplastic or plastic behavior will begin at the onset of an earthquake at relatively low levels of shaking (but well above normal wind vibrations and other non-earthquake in servic loading.)
2. Support the infill walls so that internal cracking will not cause them to collapse or fall out of their frames, and to avoid as much as possible, localized crushing of the infill masonry. To the greatest extent possible, the objective is to encourage plastic deformations to be primarily in the mortar joints and in the joints between dissimilar materials (the interfaces between the masonry and the vertical and horizontal lacing), and spread to the greatest extent over the entire wall area.
3. Maintain as much friction and energy dissipation within the wall as possible over repeated cycles of earthquake vibrations.
4. Design window and door frames and other boundary features in perforated infill walls, or walls with only three sides contained within the structural frame, such that these walls also perform as in 1-3 above at the same time as do the non-perforated walls. In otherwords, the "tuning" of the individual walls, and the building as a whole should, to the extent possible, be designed to have all walls "in play" at the same time, rather than "breaking" in sequence, shedding loads sequentially to unbroken walls.

The proposed approach to achieving these objectives is where the concept of the "*crosswall*" comes under discussion. The term "crosswall" is borrowed from the "Special Procedures" in Appendix, Chapter 1 of the *Uniform Code for Building Conservation* (UCBC) published in the United States where it refers to walls that are not shear walls, but which nonetheless participate in the lateral resisting system. The UCBC code was developed for existing unreinforced masonry buildings, and in it, a "crosswall" is an interior partition that extends from floor diaphgram to floor diaphgram that will help to control the deformations in the structure by limiting the differential movement between the floors, and dissipating energy in the process through the inelastic behavior of its materials (usually timber studs covered with lath and plaster.)

As applied to the infill walls in reinforced concrete construction proposed here, the purpose of using this term is to (1) emphasize the fact that they are deliberately *not* intended to behave as shearwalls, and (2) that, instead, they are intended to control deformations and provide energy dissipation. Based on extensive research, the UCBC was written with the recognition that this was applicable to the behavior of floor-to-floor interior partitions in unreinforced masonry buildings. The intention here is to research how this can be applicable to standard RC buildings as well.

Converting Infill walls to "Crosswalls"

Much of the research into the performance of masonry infill walls in modern frame structures of steel and reinforced concrete has been focused on how to enhance the strength of the masonry, and then, once it cracks, how to keep it from collapsing. Over the years, more and more researchers have credited the walls for providing much needed ductility to reinforced concrete structures,[9] but this ductility was short lived, as the walls tend to degrade very quickly. The research proved that such walls increase the initial stiffness over that of bare concrete frames "*from four to twenty times.*" (Eldakhakhni, 2002). For most earthquakes at close range, this added stiffness can bring about a considerable increase in the total base shear on the structures, negating any increase in strength that the walls provide. The subsequent rapid degradation of the walls can then lead to the collapse of the structure through a number of failure mechanisms that the degraded walls can cause, such as short column failure or the collapse across a weak story resulting from the loss of the walls localized across a single floor near the base of the structure.

Increasing the strength of the infill walls (by adding ferro-cement jacketing, steel braces, or reconstructing them in stronger masonry) only addresses part of the problem and can add additional weight to the structure. The problem of the initial stiffness followed by its rapid degradation still exists, even if the initial strength is increased.

Thus, the objective of this research concept is to utilize the infill-walls of the RC infill buildings as "crosswalls" rather than replace them with shearwalls. While a "shearwall" is defined as a structural wall intended to take forces from the frame of a structure to the ground, thus requiring its own foundation and strong structural continuity through all floors of the structure, "crosswalls" need not line up vertically nor be as strong because they are only intended to connect one floor level to another, and to dissipate energy as they are distorted by the deflection of the surrounding frame. To accomplish this, it is proposed that the infill walls be modified in the following ways:

(1) Subdivision of the walls: In light of this concern, the first key concept presented is to subdivide the walls, much as they are in the historical infill-frame buildings, with a series of studs and cross pieces. In this modern re-adaptation of the infill wall system, the intention is to reduce the initial stiffness of the infill walls, allowing the reinforced concrete frames to bend within their elastic range over their full height, rather than force the deformation into the single weakest story.[10]

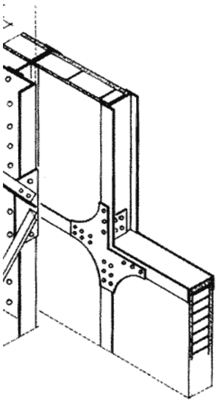

Figure 33: Detail of masonry wall in Istanbul's Silahtarağa Powerplant showing brick infill with horizontal and vertical light-frame steel "I" sections. (Kiraç et al, 2003) This construction is similar to that shown in Figure 34 below.

Figure 34: Detail of exterior wall of Mexico City power plant in the heart of the damaged district photographed after the earthquake in 1985 showing light steel frame and infill wall construction. The building had no visible damage, yet was next to reinforced concrete buildings that collapsed. It had a floorless open interior space that was approximately 20 meters high. This photograph provides an idea of how steel channels or angles could be inserted into existing hollow clay block infill walls to subdivide them.

For existing buildings, the challenge is to come up with procedures for accomplishing this objective without having to demolish and rebuild a significant number of walls. In Turkey, this is

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[9] A research engineer, A.J. Kappos, in an analytical study published in 2000, showed that approximately 95% of the energy dissipation in an RC infill building during an earthquake is in the infill walls until the walls degrade. Only then does it shift to the frame. In the frame, such energy dissipation is a corollary of damage to the buildings primary load carrying structure, whereas in the walls, it is not. This supports efforts to design walls that continue to dissipate energy over many cycles from the outset, without the usual excessive stiffness at the beginning. (Kappos, 2000 reported in Eldakhakhni, 2002)

[10] After the 1999 İzmit earthquake, it was interesting to notice a number of examples of buildings that were under construction at the time of the earthquake, but which did not yet have the infill walls installed, that survived with little or no evidence of damage. By contrast, in the completed and occupied buildings, it was common to leave most of the walls out at the ground floor for commercial spaces. Many of these collapsed because the stiffness of the infills forced the earthquake deformations into a single story.

an even more difficult problem because of the prevalence of the weak and brittle hollow clay block. Nevertheless, it may be possible to accomplish the objective by cutting the walls, and installing an armature of steel channels or “t” sections into the cut joints. This armature will serve both to subdivide the wall into sections, as well as tie it together against early collapse when it is degraded by earthquake shaking.

(2) Weaker mortar, stronger block: The second key concept is to provide for as much energy dissipation capacity in the infill walls as is possible. For those walls constructed anew under this program, this means (1) the use of an effective energy dissipating interface between the studs and cross pieces and the masonry infilling, (2) the use of a lime-based mortar[11] that is weaker than the masonry units, avoiding a strong but brittle Portland cement-rich mix, and (3) the use of masonry units (bricks or blocks) that are comparatively strong in relationship to the mortar. In Turkey, for those walls expected to function as newly constructed “crosswalls,” particularly in the lower stories of a multi-story building, this means avoiding the use of the thin shell hollow clay block now in common use. The lighter blocks may work more satisfactorily in the upper stories.

For the retrofit of existing walls, where the choice of the masonry units is not possible, this objective may be possible to achieve in part on existing walls through the design of the interface between the existing blocks and the installed armature of studs and cross pieces. The objective would be to force the initial cracking of the wall to occur in this interface, rather than through the blocks themselves, through the careful selection and installation of the materials for the studs and crosspieces and particularly the mortar used in the retrofit work.

For both new and existing walls, the subdivision of the wall is intended to cause the wall to “work” in an earthquake as a series of smaller blocks – as is demonstrated in traditional *hımış* structures which resist earthquakes with a degree of flexibility and ductility imparted by the stud frame which subdivides the masonry walls into panels. Testing of the retrofit procedure will be aimed towards development of a viable detail to accomplish this.

Figure 35: Interior of *hımış* house after the Orta earthquake showing the “working” of the masonry panels.

Figure 36: Orta area farm family in a tent the day after the earthquake.

CONCLUSION

The details of a lab testing program will be developed and described in a separate paper, but the broad outline is that such testing focus on both (1) developing details for the retrofit of existing infill walls into “crosswalls,” and (2) the development of the ideal design for newly constructed crosswalls in existing buildings. Another objective is to work both with solid brick and hollow clay block, so as to be applicable in countries where either one is in common use. The choice of materials for the internal boundary elements (studs and cross pieces) is not predefined. Research and testing can include steel, polymers, an even precast concrete elements, and it may be premature to eliminate wood entirely, as it is so easy to work, and, when it is imbedded under plaster, the risk from fire is reduced to minimum.

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[11] Lime mortar has other potentially beneficial attributes as well that are well known and accepted in heritage conservation work, but not often considered in new construction. Principally, it lacks the brittleness of concrete, and can undergo some deformation and microcracking without loosing its serviceability as quickly as Portland cement mortar.

The first phases of testing will be static tests on parts of the crosswalls in order to determine the effects of varying the mortar constituants and mortar thickness, and other aspects of the design that can be tested at small scale. Ultimately, the plan is that the most refined aspects of the design for both new and retrofit be tested at full scale on a shaking table and with computer models, so that the behavior of a building with the crosswalls installed will be understood. The final step is to refine the procedure with careful study to achieve the most economical installation process.

If the "crosswall" concept can be proven to work, and if the installation detailing can also be worked out, it can stand as an example of an idea that is born directly from the pre-industrial construction heritage found in Turkey, Italy, Portugal and other countries. This program is based on the belief that the principal lesson embodied in comparing the performance of the timber-laced vernacular construction with that of the modern buildings that collapsed in the earthquakes is thus: strength and rigidity are less effective in than flexibility, ductile behavior, and cumulative nondestructive damping.

To improve the performance of reinforced concrete infill-wall construction, the lesson from the traditional construction is to make the infill walls act, not as "shear walls," which they cannot be, but as "cross walls," which they are eminently capable of being. People in the modern world are now used to seeing pre-industrial construction as "primitive" and not "modern," but perhaps, this is one instance where the text of that French *Encyclopédie* published in 1751, describing the timber with infill construction as *"à la moderne"* may still turn out to be true – two hundred and fifty years after it was written.

Figure 37: Interior of house of family in tent in Fig.36 the day after the earthquake in 2000.

Figure 38: Same room six months later after they had repaired the house and moved back in. *Hımış* construction can be easily repaired, and, in contrast to damaged RC, when repaired, it retains its capacity.

REFERENCES

Aytun, Alkut. "*Earthen Buildings in Seismic Areas of Turkey*," Proceedings of the International Workshop on Earthen Buildings, Vol 2, Albuquerque, p352.1.

Barucci, Clementina, (1990). La Casa Antisismica, Prototipi e Prevetti, Gangemi Editore, Reggio Calabria.

Cóias e Silva, Vítor, (2002). *"Using advanced composits to retrofit Lisbon's old "seismic resistant" timber framed buildings,"* European Timber Buildings as an Expression of Technological and Technical Cultures, Editions scientificques and médicales Elsevier SAS, p109-124.

Correia, Mariana, (2002). *"Preliminary Report of the Local Seismic Culture in Portugal*", Unione Europea.

Correia, Mariana, (2003). Escola Superior Gallaecia, Portugal, oral discussion and unpublished paper.

Diderot, D., D'Alembert, J.B., (1751-72). Encyclopédie, Paris.

Eldakhakhni, (2002). Experimental and Analytical Seismic Evaluation of Concrete Masonry-Infilled Steel Frames Retrofitted using GFRP Laminates, Dphil Thesis, Drexel University.

Frampton, Kenneth, (1980). Modern Architecture, Thames and Hudson, London, p 153.

Gonzales Redondo, E., Aroca Hernándes-Ros, R., (2003). "*Wooden framed structures in Madrid domestic Architecture of the 17th to 19th Centuries*," Proceedings of the First International Congress on Construction History, Instituto Juan de Herra, Escuela Técnica Superior de Arquitectura, Madrid, Vol. 2, p1077-1091.

Gülhan, Demet, and Güney, İnci Özyörük (2000). "*The Behaviour of Traditional Building Systems against Earthquake and Its Comparison to Reinforced Concrete Frame Systems; Experiences of Marmara Earthquake Damage Assessment Studies in Kocaeli and Sakarya,"* Proceedings for Earthquake-Safe: Lessons to Be Learned from Traditional Construction, Istanbul, Turkey. (available at: http://www.icomos.org/iiwc/seismic/Gulhan.pdf)

Kandilli Earthquake Research Institute (2000). Web Site, Boğaziçi Üniversitesi, Istanbul, Turkey.

Kienzle, Peter, (1998). Conservation and Reconstruction of the Palace of Minos at Knossos, DPhil Thesis, IAAS, York (UK), pp122-134.

Kıraç, Binnur; Kaptı, Mevlüde; Ökten, Sadettin, (2003). "*The Old Power Plant at Silahtarağa in Istanbul,"* Proceedings of the First International Congress on Construction History, Instituto Juan de Herra, Escuela Técnica Superior de Arquitectura, Madrid, Vol. 2, p1239-48.

Langenbach, Randolph, (1989). "*Brick, Mortar, and Earthquakes*." APT Bulletin 31:3-4. (available at: www.conservationtech.com)

Langenbach, Randolph, (2003), "*Survivors Amongst the Rubble: Traditional Timber-laced Masonry Buildings that Survived the Great 1999 Earthquakes in Turkey and the 2001 Earthquake in India, While Modern Buildings Fell*," Proceedings of the First International Congress on Construction History, Instituto Juan de Herra, Escuela Técnica Superior de Arquitectura, Madrid, Vol. 2, p1257-1268. (available at: www.conservationtech.com)

Mateus, João, (2002). Técnicas Traditionais De Construção de Alvenarias, Livros Horizonte, Lisboa.

Rathbun, J.C., (1938). "*Wind Forces on a Tall Building*," Proceedings, American Society of Civil Engineers, Vol 64. pp 1335-1375.

Searls, C.L., & Bronski, M.B., (2002). "*Early Twentieth Century Transitional Facades in the United States: Common Maladies,*" Proceedings of ARCHI2000, UNESCO-ICOMOS & Bethlehem 2000 Project, (available at: www.UNESCO.org/archi2000)

UCBC. Uniform Code for Building Conservation, International Conference of Building Officials (ICBO), Whittier, California.

Vivenzio, Giovanni, (1783). Istoria e teoria de' tremuoti in generale ed in particulare di quelli della Calabria e di Messina,, Napoli, (from excerpts in Barucci, 1990)

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