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Bricks, Mortar, and Earthquakes,
Historic Preservation vs. Earthquake Safety

by

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Traditional mud, stone, brick and timber houses in Srinagar, Kashmir, 1989
photo © Randolph Langenbach, 1989

There was a great earthquake, and the tenth part of the city fell, and in the earthquake were slain of men seven thousand; and the remnant were affrighted.

Revelation, 11:13

More than any other natural catastrophe, an earthquake represents the undoing of our most basic preconceptions of the earth as the source of stability for our buildings. Steel and reinforced concrete have made it possible to design buildings which can be expected to resist major tremors without threatening the lives of those within. But, in terms of historic preservation, these developments present us with a real dilemma - can the preservation of unreinforced masonry buildings be justified when modern building systems can afford a greater degree of life safety?

The answer lies in our ability to use new materials to strengthen historic buildings. For such structures, however, a conflict arises when the chosen strengthening technique involves the destruction of the historic fabric or the disruption of the building's visual appearance. Moreover, many historic structures have been abandoned or demolished because of the belief that there is no alternative to the costly and destructive replacement of the primary structural system.

As much as Le Corbusier and other widely influential design theorists might have wished otherwise, buildings do not have the industrialized perfection of ships or airplanes, The limitations of the local socioeconomic system will ultimately prevail in determining not only the design, but also the structural strength of most ordinary buildings. Indeed, the lack of industrial-level perfection often contributes to the individuality and charm found in certain buildings, new or old.

What this means is that the use of steel or concrete for new buildings does not and, indeed, cannot guarantee that they will always survive an earthquake. Yet, if this is so, then historic preservation techniques should also respect these same limitations by not always requiring the more complex and expensive solutions to every strengthening problem even though, in theory, the results might be stronger.

Earthquake safety concerns did not emerge only in modern times with industrialized building materials. In the past people had more limited means of dealing with seismic threat. Although we cannot always separate the influence of earthquake danger from other historical forces which have shaped building construction, by attempting to do so we can learn something useful from how people have dealt with earthquake hazards in the past.

This article first explores how our current preconceptions tend to shape our response to the hazards presented by older buildings. It then examines some examples of indigenous masonry load-bearing vernacular building systems which exhibit a greater degree of resistance to collapse than conventional unreinforced masonry. The principle of this aseismic masonry construction is that the masonry is expected to crack and shift slightly during a tremor, allowing energy to be dissipated within the walls in a ductile manner.

The article then ventures beyond the historical chronicle of these archaic systems by drawing linkages with contemporary construction and seismic strengthening practice. Although further research remains to be done, it is possible that the early technology of these vernacular buildings might provide insight into unreinforced masonry building behavior, thus improving construction and conservation practice, particularly in developing countries.

Collapsed building, Juarez Hospital, Mexico City, 1995

The Power of Perceptions

On December 7, 1988 an earthquake struck the central part of Armenia. Measuring 6.9 on the Richter Scale, it did not fall into the strongest category. Nonetheless, this earthquake caused major destruction and unspeakable human tragedy. The sight of the devastated buildings with thousands of victims crushed or trapped beneath the mountains of debris touched people around the world.

Just after the Armenian earthquake a San Francisco Examiner headline read: *"Unreinforced stone, cement collapses."* The article followed with: *"Most of the buildings that collapsed were unreinforced concrete structures or older brick, and stone buildings built before the modern earthquake-resistant codes."* In the same article, an official from the California Office of Emergency Services was quoted as saying, *"Many of the buildings constructed before 1940 in California are unreinforced brick and concrete like those reduced to rubble in Wednesday's quake ... some 30,000 buildings in the State would be unsafe if a similar earthquake shook California."* [1]

Contrary to these early pronouncements, however, when the American scientists and engineers arrived in Armenia two weeks later they found the truth to be quite different. Indeed, many masonry buildings in the rural villages closest to the fault were damaged or destroyed, but in Leninakan, where the death toll was highest, the *modern* buildings were subject to the most catastrophic failures. Ironically, many of the survivors are now living in the older unreinforced masonry buildings in the city, many of which emerged with little damage.[2] One member of the American team, Fred Krimgold, reported: "It was amazing to see that masonry buildings, while not unscathed, did not cause the major part of the fatalities."[3]

This situation illustrates that earthquake safety is often as much a problem of perception as it is of engineering knowledge. The profound effects of an earthquake on the collective consciousness of a people are particularly powerful in connection with masonry buildings. The image of heavy blocks of stone upset by the powerful motion of the ground is almost biblical. Every child has watched toy block models of buildings brought down in an instant by a sharp shake of the table. As shown by the headlines following the Armenian earthquake, most people view unreinforced masonry as dangerous regardless of the actual potential for earthquake damage. However, there are many different types of masonry construction.[4] In addition the characteristics of each earthquake and its impact on different types of buildings can vary dramatically from site to site.[5]

Preservation and Seismic Strengthening

When issues of life safety exist, it may be hard to focus on the problems of preservation, without running into a great deal of confusion over what is needed and what can safely be left alone. Once a property is identified as a seismic hazard, the way is left open for proposal of the most extensive and extreme mitigation measures. Often what is proposed might be termed the "Vietnam" approach to preservation, that is, destroying the original fabric of the historic structure in order to "save" the building. Since masonry constitutes the primary structural and architectural material in a vast number of historic structures in seismically active areas around the globe, to destroy or rebuild these structures in the interests of the perceived risk would lead to a substantial loss of the cultural heritage of these regions.

Once it is decided that strengthening is feasible, does one (1) insert new steel or concrete structures, or (2) rebuild them completely with stronger materials hidden behind the carefully "restored" walls so that the change can scarcely be detected? Indeed, if these are the only choices, what future is there for many historic structures? The seismic system adopted can be of critical importance to the future of the landmark. At some point we are in danger of turning our historic landmarks into Disneyland recreations. One must ask whether there are less destructive (and costly) alternatives which can meet life safety objectives with equal effectiveness.

The California Capitol: Gutting for Strengthening

One example in the United States, the California Capitol building, was completely gutted in 1976, leaving only the exterior walls and the central drum and dome.[6] All of the interior floors and walls were removed. The remaining masonry was covered with an internal skin of shotcrete and the floors were replaced in reinforced concrete. As a result, while the interior of this building is now genuinely spectacular, with impressive museum rooms, excellent craftsmanship, rich materials, stunning colors and textures, none of it is authentic.

The California Capitol is located in seismic zone #3, rather than the most severe category #4 which applies to San Francisco and most of the southern California coast. In spite of this, on the basis of a 1971 seismic study, the building was condemned. A "heart transplant" was authorized when an "ace bandage" may have been all that was needed. The Capitol most probably needed to be strengthened and repaired, but one must ask whether the risk identified in 1971 could not have been satisfactorily alleviated by less drastic, destructive, and expensive measures.

Gutting structures for seismic strengthening is not limited to the United States. For example after the 1979 earthquake in Montenegro, Yugoslavia, many structures in the historic cities of Kotor and Budva have been reconstructed with reinforced concrete floors, replacing the original heavy timber. In some of these structures reinforced concrete columns have been cut into the masonry forming completely new reinforced concrete structures, with the historic masonry attached. In addition to the destruction of all of the historic interiors, another tragic consequence of this costly and time-consuming reconstruction is that all of the local residents have had to be resettled. Now, a decade after the earthquake, many buildings are still unprotected and rotting, awaiting reconstruction, and massive government investment is needed. In the end, these historic towns will never again he genuinely alive or real. Now they serve only as tourist attractions, with the shuffle of countless visitors replacing the evidence of generations of life and use.

After the 1979 earthquake in Kotor Yugoslavia many buildings were completely gutted. Although the historic masonry was reattached the historic interiors have been completely destroyed

The Salt Lake City and County Building, USA

In Salt Lake City, rather than being gutted, the building was the subject of an interesting and provocative debate over the choice between two alternative schemes, both of which promised to preserve most of the interior. These two schemes, however, came from diametrically opposed philosophies on how unreinforced masonry buildings should he reinforced for earthquakes.

The Salt Lake City and County Building project is the first historic preservation project incorporating base isolation. Because base isolation dampens the frequency of the shaking as felt by the building, thereby lowering the forces experienced by the structure, it has the advantage of allowing the preservation of far more of the existing interior surfaces. Therefore, instead of what was originally proposed by engineers following the Uniform Building Code (UBC)[7] as *a "complete gutting and replacement of the interior,"* the base isolation enabled most of the interior surfaces of the Salt Lake City building to be retained.

However, a simpler and less expensive scheme had also been proposed by a second engineer hired as a consultant, John Kariotis, co-author of the "ABK Methodology."[8] Kariotis also proposed a system requiring little destruction of the interior fabric, but with a cost substantially below that of base isolation. What was most radical about his approach was that Kariotis said that the seismic forces computed to exist using conventional methods of analysis would not occur in reality, even in an earthquake of the same magnitude as that for which the base isolation scheme was designed.

Kariotis' research asserts that masonry buildings actually respond differently than the way traditional codes and engineering approaches have assumed. Rather than amplifying the forces of the earthquake, he states, the heavy masonry walls have the effect of dampening the shaking by acting as a *"rigid rocking block on a soft soil base."* As a result of the ABK analysis and strengthening methods, the computed force levels in the strengthened building are lower than found under conventional analysis. To explain this, Karotis reports that the amplified force level of 55 percent of gravity which was reported that the City and County Building might be subjected to was computed based on the model of a "single degree of freedom, 5 percent damped elastic oscillator with a fixed base."[9][10] In Kariotis opinion, the expected force levels from the predicted .17G earthquake would be much lower, and the base isolation unnecessary.[11]

In deciding between the two proposals, the Mayor's Assistant Phil Erickson recently said, *"The City Council wanted to satisfy their moral obligation to the public safety, and this [base isolation] was a way to do it."* Politically ,this was important. As Erickson added,

> *We might have been able to find a way around full compliance, but everybody in town comes here for a building permit, and we had to set a good example. You know, I got a sense that the engineers got a real charge out of scaring each other .... I don't know, maybe the building is perfectly fine, but, when I came in 1984, the City was at the point of nearly vacating it. The engineers, they are credible people, so we just moved ahead and that's what we did [base isolation]*.[12]

To the City Council it seemed less risky to accept a system which was shown to lower dramatically the earthquake forces on the building than it was to embrace one based on the observation that those computed forces could not possibly occur.[13] This building, like the California Capitol, is located in an area which is only seismic zone #3. The prediction of extreme shaking, and thus of serious building damage, is more remote than for the California coast where many unstrengthened buildings continue to be used.

The problem is that the cost of this project, and the extraordinary amount of engineering work it required militates against the more general application of this technique.[14] The restoration of the building with the base isolation scheme has been completed at a total project cost of over $30 million.[15] Undeniably, it did achieve its intended results: the resulting restoration is spectacular. People are proud of the building now and comfortable inside it.

Engineers may argue over whether a less expensive solution, based on a simpler technology, would be less safe, but the real question is what is applicable to the widest range of historic buildings, and will thus do the most to mitigate the earthquake hazard for the greatest number of people.[16] While the high-technology, expensive solution is within reach for monumental buildings in the United States, it is not accessible as a solution for most of the world's historic buildings. In justifying the base isolation, it was explained that the building was found to have a weak lime mortar in a deteriorated condition. If every building with soft mortar must either be isolated or rebuilt, many of the most interesting and culturally meaningful landmarks in the world would be lost.

There is, however, another direction which also can be found in vernacular masonry buildings, a direction which deals with the core problem of what happens when masonry walls crack in an earthquake. All of the American retrofit work, including that following the ABK methodology, has focused on preventing masonry walls from yielding in earthquakes. With the current use of strong cement-based mortars, combined with steel and concrete, - this is at least conceivable.

In historic times, however, it was impossible. In spite of this fact, not every masonry building collapsed in every major earthquake. Apart from making the masonry walls excessively thick, the only solution was to introduce timbers or iron cramps to help restrain the masonry from breaking apart when it moves. Of interest here are the indigenous buildings with timber, not just because of the timber, but because of the weakness of the mortar, and the expectation that cracking of the masonry wall will take place.

The buildings found in Kashmir, India, provide an opportunity to examine this approach to masonry construction. They are of particular interest because their height, often three or four stories, is more in line with modern urban construction than the more usual one or two story adobe or brick vernacular buildings found in other areas.

SRINAGAR, KASHMIR

Wood and masonry houses line the Rainawari Canal in Srinagar. Many of these buildings date back to the eighteenth and nineteenth centuries, demonstrating the ability of native construction methods to withstand earthquakes.

The Aseismic Attributes of Traditional Construction in Kashmir

Entering Srinagar, in Kashmir, is like going back in time. The houses appear to be ancient and timeless, with the evidence of the wear-and-tear of years very much present. It is a "medieval" city transported to the present. Even 75 years ago, the city appeared "tumbledown and dilapidated" to the European traveler, "with many of the houses out of the perpendicular, and others semi-ruinous."[17]

Multi-story timber and masonry houses along the River Jelum, Srinagar, Kashmir, 1981

Although the picturesqueness of the place belies some very severe economic and political problems, such an extensive example of an urban environment still used in a traditional and unselfconscious way forces one to ask if there is any way it can be preserved.

Earthquakes in Kashmir have occurred with a degree of regularity over the centuries, and the Kashmiri people have had to learn to live with them.[18] Kashmir is poor and largely removed from the mainstream of industrialized society, with construction methods remaining virtually unchanged for generations.

Pre-industrial building methods are still used in India. This ancient method of cutting timber into planks is not uncommon in this village in Kashmir.

Most of the traditional buildings in Srinagar can be divided into two basic systems of construction. The first system, sometimes referred to as Taq, consists of load-bearing masonry piers and infill walls, with wood *"runners"* at each floor level used to tie the walls together with the floors.[19] The second system, known as *Dhajji-Dewari* construction, consists of a braced timber frame with masonry infill.[20]

Taq System

An eighteenth or early nineteenth-century canal warehouse in Srinagar illustrates the TAQ system of construction. The alternating timber "runners" and brick infill create a "woven " appearance.

The timber beams used in buildings in the Taq system do not constitute complete frames. Instead, large timber "runners" rest along the load-bearing masonry walls, with the floor beams and the "runners" for the cross walls lapping over them. The wood serves to tie the walls of the structure together with the floors. The weight of the masonry serves to "prestress" the wall, contributing to its resistance to lateral forces.[21]

The construction practices used for these Kashmiri buildings, which stand in contrast to today's codes and commonly-accepted practices, include (1) the use of mortar of negligible strength, (2) the lack of any bonding between the infill walls and the piers, (3) the weakness of the bond between the wythes of the masonry in the walls, and (4) the frequent (historical) use of heavy sod roofs.[22] Just such buildings were observed almost a century earlier by Arthur Neve, a British visitor to Kashmir, when he witnessed the 1885 Kashmir earthquake:

> *Part of the Palace and some other massive old buildings collapsed ... [but] it was remarkable how few houses fell.... The general construction in the city of Srinagar is suitable for an earthquake country; wood is freely used, and well jointed; clay is employed instead of mortar, and gives a somewhat elastic bonding to the bricks, which are often arranged in thick square pillars, with thinner filling in. If well built in this style the whole house, even if three or four stories high, sways together, whereas more heavy rigid buildings would split and fall.*[23]

More recently, two Indian engineers, N. Gosain and A.S. Arya ascribed the damage from a 1967 earthquake to the different types of traditional and modern construction in Kashmir:

> *The timber runners ... tie the short wall to the long wall and also bind the pier and the infill to some extent. Perhaps the greatest advantage gained from such runners is that they impart ductility to an otherwise very brittle structure. An increase in ductility augments the energy absorbing capacity of the structure, thereby increasing its chances of survival during the course of an earthquake shock. This was substantiated by the observation that dhajji-dewaris in which a larger volume of timber was used were comparatively safer.*[24]

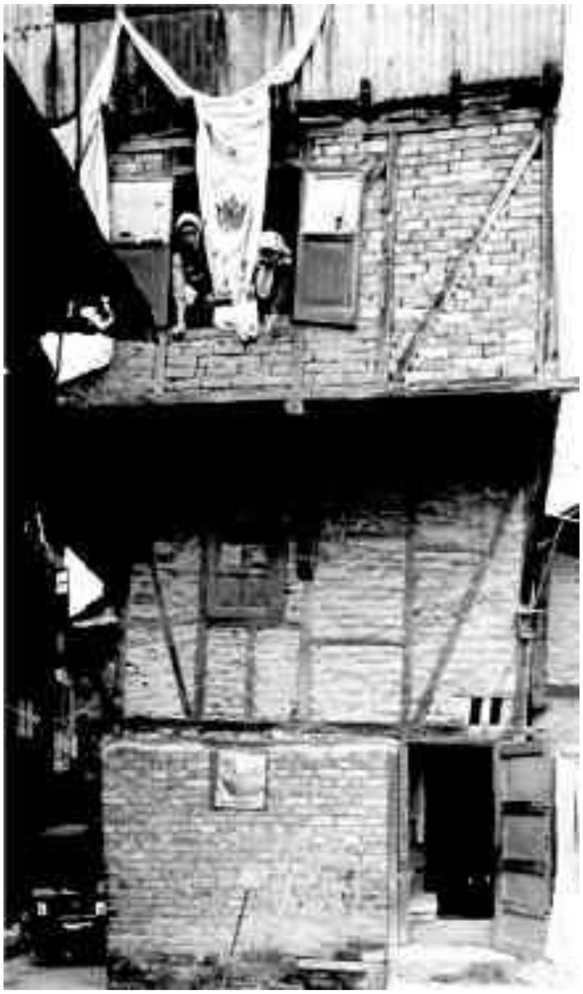
Gosain and Arya note that during the 1967 Kashmir earthquake buildings of three to five stories survived relatively undamaged. Arya confirmed that his research shows that one of the most important reasons for this is the damping from the friction induced in the masonry of the Taq and Dhajji-Dewari walls. Internal damping *"may be in the order of twenty percent, compared to four percent in uncracked modern masonry (brick with Portland cement mortar) and six to seven percent after the masonry has cracked."* His explanation for this is *that "there are many more planes of cracking in the Dhajji-Dewari compared to the modern masonry."*

Srinagar House being demolished showing the *Taq* timber and masonry construction with timbers imbedded into the wall lengthwise and cross-wise.

This distribution of the forces throughout a larger area of the wall, preventing destructive cracking in one area, leads to a much greater level of energy dissipation than would otherwise be possible. As a result, even though the mortar is extremely weak, causing the wall to yield under a much smaller load, the masonry continues to have a good chance of holding together. The timber runner beams and floor diaphragms keep the individual piers from separating, which would cause the house to break apart.[25] In Kashmir, rigidity carries the potential for destruction. The more rigid a building is, the stronger it must be in order to avoid fracture. Because of the primitive materials and means of construction in Kashmir, strength was not possible, so flexibility was necessary.

Also in Srinagar, this wood and brick house under repair shows the timber "runners" supporting the masonry. The masonry walls are light enough to be supported temporarily by the thin wooden piers.

Dhajji-Dewari



DHAJJI-DEWARI construction, shown here, differs from the TAQ system in that the beams form a complete braced timber frame.

The half-timber, brick-nogged type known locally as *Dhajji-Dewari* exists side by side with the Taq system in Kashmir. *Dhajji-Dewari* construction continues to provide an efficient and economical use of materials. The use of wood was kept to a minimum, but it still enabled the 1/2-brick-thick walls to resist out-of-plane collapse, while it restrained the in-plane movement of the masonry. This type has also shown a marked resistance to earthquakes when compared to conventional fired masonry or adobe structures.

Variations of the brick-nogged type were historically common in many areas not affected by earthquakes, such as medieval England and Europe, and it extended even into North America. However, it has proved especially suitable in seismically active regions such as Yugoslavia, Greece, Turkey, and Kashmir. In some of these areas, earthen or brick building continues to be built in this method and is allowed by the local building codes.[26] Arya reports that it has formed the basis for the current Indian Standard Building Code #4326.[27]

EL SALVADOR AND NICARAGUA

An example of BAHAREQUE construction, a native method in El Salvador, this building withstood the quake with little damage apart from plaster falling off the walls.

Taquezal Construction in Nicaragua and Bahareque Construction in El Salvador

A different variation on the infilled timber-frame system is common in several countries in Central America. This system, which reportedly was introduced from Spain during the colonial period, is known in Nicaragua as *Taquezal*, or "pocket" system, and in neighboring El Salvador as *Bahareque.*

In *Taquezal* construction, the timber frame consists of a row of studs, approximately 2 feet on center. These studs, which are approximately 2x4 inches, are set within a heavy timber frame. The timber frame consists of hardwood posts, often made of unsawn logs, placed at the comers and at points in the walls about every 7 feet. Wood lath or bamboo is then nailed across the studs to form a kind of basket, and the resulting pockets are filled with layers of small stones (*Taquezal con piedra*), or adobe (*Taquezal con barro terra*). The wall is then usually plastered with a final layer of mud or lime plaster.[28]

Buildings of this type at one time filled Managua, the capital of Nicaragua. In 1932 about 85 percent of the buildings in the city were of this type.[29] Records show that in the 1931 earthquake they survived well enough to be compared by J.R. Freemen, a well known earthquake researcher of that time, with the *Baraccata* type of historic reinforced aseismic masonry construction developed in Italy in the eighteenth and nineteenth centuries.[30]

In 1971, the results, however, were quite different. In a report by the Earthquake Engineering Research Institute, Richmond, California, engineers observed that *"approximately 70 percent of the Taquezal buildings in the central area of the city collapsed or were seriously damaged. This mode of construction was the major cause of the high death toll."* This same report recommends that *Taquezal* should be banned in earthquake-prone areas such as Managua.[31]

Learning from the El Salvador Earthquake of 1986.

In contrast, witness the dramatic partial collapse of a reinforced concrete structure nearby in central San Salvador.

The October 10, 1986 earthquake in El Salvador provided the chance to study all of this in detail. The damage to the *Bahareque* buildings was extensive, and ranged from a minimum of a loss of some of the exterior stucco to total collapse. Examination of this damage was revealing. It was possible to document structures in every stage of disintegration. In almost every case, if structural failure had occurred, the failure originated at a point where the wood armature was rotted or damaged by bug attack. Those structures with a greater level of damage were invariably those which were more rotted. In addition, with the less substantial squatters' housing, the structures tended to come apart at the seams, as no provision had been made to hold the walls and roof together.

Returning to the historical case of Managua, it is interesting to note that Freeman anticipated the problem of wood decay in 1932: *"In the Managua climate this type of structure in course of time may become weakened by decay of the wood posts and by the eating out of the interior of the posts by termites or white ants."* This comment turned out to be a correct forecast.

In 1972, the average age of the existing *Taquezal* buildings in Managua was substantially older than it was in 1931, and therefore, their condition was probably more deteriorated.[32] In addition, the rot resistance of the available wood was reduced as the quality of wood supplies had declined. The evidence, therefore, is that the primary cause of failure of this class of buildings was not the result of a defect in the system itself, but rather a problem in the long term stability of the structures affected by environmental factors other than the earthquake.

If we can explain the failures of this system by rotten wood, what can we learn from those buildings which did not suffer heavy damage? Looking more closely at the exterior plastered walls of those standing after the earthquake is revealing. In the 1931 earthquake in Managua, Freeman notes that practically all of the plaster was shaken off. in San Salvador in October 1986, there were many *Bahareque* buildings where the plaster had fallen off, but there was little or no evidence of damage in the structure of the walls themselves.

The dislodging of the plaster from practically the entire surface of the walls is evidence of the distribution of the earthquake stress throughout the wall, rather than its concentration in one localized area. The shedding of the plaster, therefore, draws attention to the fact that the earthquake stress is dissipated throughout the wall with small movement of the masonry and wood, so that no one major destructive crack occurs. The buildings which did survive showed that the walls were able to dissipate a significant amount of energy through the working of the material, rather than by rigid strength.

Traditional and Modern Masonry: "Ductility" versus Brittle Failure

Surveying the damage caused by the 1963 Skopje, Yugoslavia, earthquake, a London engineer N.N. Ambraseys reported that the *"old adobe construction, particularly those with timber bracing, resisted the shock with some damage, but behaved far better than the [modern] brick or the hybrid [reinforced concrete with brick infill] construction."* Many of the modern reinforced concrete buildings, which ranged from three to six stories in height, were seriously damaged or destroyed, while the less substantial adobe buildings survived.

Although it is difficult to make meaningful comparisons between the performance of the adobe and brick houses and the much larger reinforced concrete buildings in Skopje or other cities, the brick-nogged type does form a historical precursor to the reinforced concrete frame with unreinforced masonry infill wall construction, now common in many countries. It is striking to note how many buildings affected by the earthquake in Skopje, as well as more recently in Mexico City and San Salvador, which had appeared to be solid concrete shear wall structures, were revealed by the earthquake damage to include a generous amount of unreinforced brick masonry in their construction. The problem is that many of these modern infill wall buildings have performed poorly in earthquakes. If these modern buildings do poorly, how is it possible that the much weaker historic buildings would do well?

The brick-nogged construction shown here survived the great earthquake of 1963 in Skopje, Yugoslavia.

The infill walls in modern buildings are not designed to be shear walls: they are meant only for enclosure. When masonry is used, it is either brick or hollow tile laid in a cement-based mortar, and these walls are inherently very stiff and brittle. If the lateral loads are great, the deflection of the more flexible frame throws all of the lateral force onto these infill walls which were never intended to carry large loads. As a result, these walls can be shattered. The failure of the walls across one floor of a building can lead to the creation of an unintended "soft story," resulting in the collapse of the structure in subsequent cycles.

Victims of the 1985 Mexico City earthquake, the reinforced concrete columns on the right of this building have been damaged almost to the point of collapse by the "equivalent diagonal strut" effect of the infill masonry.

In engineering terms, research has shown that the behavior of these infill walls is often equivalent to that of a "diagonal compression strut."[33] When the frame deflects, it bears upon the infill wall on its upper corner. The stresses in the wall become concentrated along a narrow zone diagonally across the face of the panel. As a result, until the wall collapses, all of the resisting pressure is delivered to the top of the column just below the intersection with the beam. This can be sufficient to cause the reinforced concrete column to fail in shear, again leading to the progressive collapse of the structure.[34]

If the masonry infill with its equivalent diagonal strut is a danger to the modern reinforced concrete frame, why is it not more hazardous to the weak timber frames found in Kashmir, and Yugoslavia? The most plausible explanation is that the precompression stress provided by the load bearing weight of the wall, combined with the weak and non-brittle behavior of the mortar, enables the stresses to be spread throughout the wall rather than being concentrated along the diagonal. Instead of one large tension crack, with crushing failure at the comers, the softness and give of the mortar encourages a more wide-spread, small-scale cracking across the mortar joints of the whole panel. This also allows the building to dissipate energy, and thus perform in a ductile rather than a brittle manner.

While stronger cement-based mortar can provide for a wall with greater strength within its elastic range, the problem in earthquakes is that failure of the masonry units themselves can lead to the collapse of the wall. Strength can be important in preventing damage in mild earthquakes, but in severe tremors, even massive strength, especially if it is associated with greater stiffness, can be overwhelmed.[35]

Conservation Technology versus the Building Codes

Mortar strength and composition have been a chief concern in building conservation technology. Few subjects have received more attention in recent years than mortar and repointing. The discovery of the importance of reducing or eliminating Portland cement from masonry mortars in restoration is one of the cornerstones of recent conservation practice:

> *The use of lime-sand mortar ... furnishes a plastic cushion that allows bricks or stones some movement relative to each other. The entire structural system depends upon some flexibility in the masonry components of a building. A cushion of soft mortar furnishes sufficient flexibility to compensate for uneven settlement of foundations, walls, piers and arches: gradual adjustment over a period of months or years is possible. In a structure that lacks flexibility, stones and bricks break, mortar joints open and serious damage results.*[36]

This was not meant to refer to masonry in earthquakes, but in light of the Kashmiri experience it is intriguing to ask whether the notion of a *"plastic cushion"* is an appropriate concept for walls subjected to earthquake forces. In terms of modern construction, it is not possible to do any more than open this subject up to analysis, but it is worth noting the conflict between historic preservation documents which recommend using the weakest and most lime rich ASTM formula K-1 unit cement to 21/4 to 4 units lime for restoration work, and the Uniform Building Code, which prohibits the use of mortar weaker than the three strongest categories, known as ASTM types M, S and N (1 unit cement to ¼ to 1¼ units lime) for any mortar used in structural masonry (which includes most historic masonry walls).

A typical masonry-wood connection in Kashmiri construction. These wood brackets are ubiquitous in both TAQ and DHAJJI-DEWARI structures. The masonry simply rests on top of the wood beams.

One reason for this conflict is that while the Code is founded upon the performance of the wall under load at its design strength at the time of construction, the preservation documents are aimed towards maximizing the long-term durability of relatively weak walls in response to all environmental conditions. This does not, however, resolve the question of what is best in earthquake country, either for repointing mortar or for bedding mortar.

It is no doubt controversial to advocate a reduction in mortar strength in code-conforming restoration work with an expectation that plastic deformations will occur in the masonry. One of the problems with weaker mortars is that of controlling the out-of-plane failure of walls with a high h/t ratio (height over thickness), but, as found by the researchers of the ABK method, if the movement of the whole building is dampened by yielding of its internal fabric, the out-of-plane forces are lower.[37]

When unreinforced masonry begins to crack, in terms of engineering analysis, it is usually described as having "failed," even if collapse does not occur. The internal elastic strength of the wall drops, and in repeated cycles, the wall undergoes plastic deformations through movement along the mortar joints (in-plane), or in bending (out-of-plane). The most important attribute of soft mortar is that, when the mortar strengths are below that of the masonry units, when the wall does crack, it does so along the mortar joints, resulting in greater overall stability.

Conclusion

What can be learned from buildings such as those in Kashmir? Certainly it cannot be concluded that a single method of indigenous construction provides a direct model, either for new construction or seismic retrofit in the United States. It does, however, provide a useful balance to our notions of what *"unreinforced masonry"* is and how it can be made to behave, As a material, unreinforced masonry generally performs in a brittle, nonductile manner, and thus is recognizably dangerous in earthquakes. As a system, however, these examples show that brittle failure does not automatically lead to collapse; further, the creation of a system which overcomes some of the limitations of the material can provide an inspiration, especially for the design of compatible systems, for conserving buildings.

Buildings such as those found in Kashmir, if encountered in the United States, would probably be condemned immediately as unsafe. The progress of modernization and industrialization threatens to result in the eventual demolition of these buildings in Kashmir, a process which has already begun. With reinforced concrete, a greater degree of life safety can be promised, but as seen in Armenia, promise does not always mean delivery. Perhaps by forgetting the unwritten knowledge of past generations, in preference for the seeming certainty of an imported industrialized alternative, a greater risk may result in the end.

These insights about building structure must be focused on issues of the locally available construction techniques. It is not engineering *"know how,"* but rather the local economy, labor supply, materials production and delivery, available engineering expertise, and thoroughness of inspection which will determine what is actually built. Between the possible and the practical in most earthquake-affected cities exists a great gap. The enactment of more stringent engineering regulations is simply not sufficient. In many developing countries, sophisticated engineering and the delivery of materials of uniform quality may not be possible. What is needed is a combination of traditional vernacular construction techniques with modern materials and technology.

For engineering purposes masonry may be properly modeled as *a "rigid block on soil springs"* or as *a "non-ductile, rigid mass on a fixed base,"* but in truth it has life. It moves, it changes color, it ages, and it responds to our own images and dreams of what buildings should be. *"Moves"* does not refer to falling down in an earthquake, but rather to slow and subtle movement by the heat of the day, by the gradual settlement of the foundations, or by the slow erosion or change of the nature of the mortar bed or of the bricks or stones themselves. This almost organic nature is essential to the aesthetic quality of historic masonry. If we could arrest the effects of time, traditional masonry might lose its magic. Even in earthquake country, this essential quality of the buildings must be preserved.

The least recognized but most important issue is the tremendous cultural loss which inevitably would accompany the rebuilding of Srinagar and other cities with similar pre-modern vernacular buildings. Kashmiri houses, for example, are ancient regardless of whether the physical fabric has been replaced in time, because they represent the embodiment of a tradition. The replacement of these structures with buildings of a new reinforced concrete technology is destroying that continuity. The work has been taken out of the hands of the people who have traditionally done it and put into the hands of specialists trained in a new way. An alien form is making its appearance on the landscape.[38]

Our perceptions of the structure of buildings have been transformed in modern times. Traditionally, most major buildings were solid walled structures with the walls bearing directly on the ground. With the current predominance of steel and reinforced concrete as the materials of choice for larger buildings, we are now used to the erection of frames onto which the enclosure cladding system is attached, but often the results simply fail to capture the kind of texture and meaning which is found in older buildings. As engineers work hard to convert the highly indeterminate, ambiguous and sometimes uncertain historic masonry buildings into something which can be understood with mathematical certainty, architects struggle to wrest control of the seemingly rigid and unyielding materials of modern day conventional building systems, trying to breathe the kind of subtle life into them that they find at the root of the aesthetic quality of historic structures.

At least in terms of historic conservation, there are examples which show promise of progress in this direction. In Greece, other parts of Europe, and even in New Zealand, some strengthening projects have been carried out using cables wrapped around the masonry structure. Utilizing the strengthening effect caused by tying the masonry together to create horizontal bands similar in their purpose to the timber runners of the Kashmiri Taq system, these buildings continue to bear their own weight on the existing masonry.39

This building in New Zealand was strengthened by cables wrapped around the masonry structure. The cables function similarly to the runners in the TAQ system.

Such systems have the advantage of causing little disruption to the historic masonry surface. The condition of the cables can be readily inspected, and they can be removed and replaced without damaging the historic masonry. What is radical about this and other surface mounted strengthening systems is the acceptance of visible changes to a building's interior and exterior appearance, Sometimes it is important to recognize that greater damage may be incurred by hiding changes behind rebuilt walls, than by exposing the changes in front of intact walls.

There are many different techniques and systems which might be proposed, but the important point is that historic structures have something to tell us which transcends their formal architectural language. This gift from the past may be lost if the integrity of the, original structure is destroyed to meet the demands of hazard mitigation,

Understanding both the positive and the negative attributes of masonry construction can guide us toward methods which may be less destructive of original fabric. Some of these methods may even be more effective over the long term, not only because they build on strengths which already exist, but also because they are more closely derived from local social and economic conditions.

The purpose of historic preservation is not limited to the static freezing of artifacts. It also has to do with preserving continuity within the slow evolution of building traditions - a continuity which may in the end provide the most effective and lasting defense against earthquakes.

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FOOTNOTES

1: "Unreinforced Stone, Cement Collapses," San Francisco Examiner (December 9, 1988); p. A17.

2: These older unreinforced masonry buildings (URMs) are not to be confused with the partially reinforced masonry and concrete frame buildings which did suffer heavy damage. The URMs were usually not as tall, and one explanation for their comparatively good performance is that the frequency of the ground shaking resonated with the taller modern buildings, rather than the shorter, stiffer URMs The nineteenth century URM cathedral was destroyed, but the multistory URM (with timber floors) public buildings in the city center survived with damage limited to the top story walls and gables.

3: Fred Krimgold, Lecture for the EERI Armenian Earthquake Briefing, February 1, 1989 (El Cerrito, CA: Earthquake Engineering Research institute).

4: This article is intended to focus primarily on the problems associated with masonry walled buildings constructed with regular horizontally bedded brick or stone, i.e., without unreinforced masonry floors or roofs. There are special problems with rubble wall construction and with unreinforced masonry vaults and domes which are not necessarily related to the observations about the behavior of masonry made in this paper.

5: While pointing to a photograph of the ruins of central San Francisco in 1906 taken following the fire which swept the city after the earthquake, one California seismic safety official recently stated that "masonry buildings have traditionally shown little resistance in earthquakes." In the images taken before the fire, the scene is different. With a few exceptions, rather than seeing whole collapsed buildings, the views show damage concentrated at the tops of masonry structures. Chimneys and parapets have fallen and walls of the top floors of multistory buildings are often missing, leaving the roof in a state of partial collapse, Masonry gables were particularly vulnerable, but the walls below them were often left undamaged. if the entire masonry facade had fallen, usually the interior of the building remained standing like an open doll house bearing securely on the unreinforced party walls between the buildings. Interestingly enough it was often the monumental buildings, such as those at Stanford University that were the hardest hit, but even in these, the ruins showed that the primary failure was caused by the fact that few of these buildings had ties to hold the walls together with the roof and floors. In addition, the ornamental stonework may not have added to the effective wall thickness, but only to the mass because of the lack of ties.

In the Long Beach and Coaling earthquakes in California, there was a greater level of masonry damage. There are many reasons which might explain this, but one observation is that a contributing factor may be that the multi-story buildings of San Francisco show a greater resistance than the one and two story buildings because the greater height gives the lower walls a greater thickness and overburden weight. The upper walls of the taller buildings may be protected by the larger degree of energy dissipation provided by the upper story diaphragms and crosswalls which the lower buildings do not have, and by higher standards of construction quality. (See the description of the ABK Method.) It is also important to note that the period and duration of an earthquake has an important effect on the nature of URM damage.

6: John Worsley, "Structural Upgrading," APT Bulletin 20, No. 1 (1988), pp. 17-26.

7: James S. Bailey and Edmund W. Allen, "Seismic Isolation Retrofitting," APT Bulletin 20, No. 2 (1988), p. 34. It should be pointed out that the principle reason why the Uniform Building Code compliance would have required the complete gutting of the building is primarily a result of the fact that the Code does not recognize that unreinforced masonry has any lateral strength. it simply does not appear in the Code. The results, therefore, are not based on whether this degree of work is necessary, but rather the need to substitute an unrecognized archaic structural system for a new one recognized by the Code.

8: John Kariotis, et al., "ABK Methodology for the Mitigation of Seismic Hazards in URM (Unreinforced Masonry) Buildings," ABK, A joint Venture (Washington, DC: National Science Foundation Topical Report 08, 1984). The ABK Method recommends that the diaphragms, together with existing or new timber frame crosswalls be designed to yield in an earthquake, and thus dissipate energy, reducing the likelihood of destructively amplified force levels in the building.

9: Bailey and Allen, "Seismic Isolation," p. 36.

10: John Kariotis, interview, March 6, 1989; see also "ABK Methodology," pp. 2-4

11: In addition, similar to Mexico City, the building is constructed on an old lake bed, resulting in the prediction that earthquake shaking would be of longer period. When tests were done, it was discovered that this soil's period would be approximately 1.4 seconds. Normally, except for the tower, this would mean that the masonry building with a period of .6 seconds would not amplify the shaking. When this was discovered, the base isolation system had to be redesigned to avoid the possibility of aggravating the amplification, rather than reducing it (Bailey and Allen, "Seismic Isolation," p. 37; also, Mason Walters, interview, March 14,1989).

12: Phil Erickson, interview, March 9, 1989.

13: Mason Walters of Forell/Elsesser reports that the masonry and mortar in the building were in unusually poor condition, and that the building showed evidence of prior earthquake damage. He felt that there was reasonable concern that the system had to substantially reduce the predicted loads expected to be carried by the walls (Walters, interview).

14: It is estimated that close to a a million dollars of professional time were spent on the seismic component of this project. Four engineering firms and a computer modeling consultant were involved.

15: The engineers were E.W. Allen Associates, Salt Lake City, with the San Francisco firm of Forell/Elsesser as consultants on the base isolation system. The architects for the project were James McElwain, AIA, and Burtch Beall, Jr., FAIA, in Salt Lake City, and The Ehrenkrantz Group in San Fransisco.

16: Another problem to consider is that base isolation requires a permanent commitment to inspection and replacement of the parts. The base isolators can be removed, tested and replaced as they age, but consideration has to be given for what happens a hundred or two hundred years from now. At that time, people may have ceased to know how to take care of the system. The introduction of steel reinforcing into a building can also be a problem when looked at in terms of an extended life. Steel reinforcing bars in concrete and especially in masonry are vulnerable to decay, which has the potential of ruining not only the strength of the retrofit system, but also the building itself if the elements cannot be removed and replaced.

17: Arthur Neve, Thirty Years in Kashmir (London, 1913).

18: Seismicity of 8-9 on the Modified Mercalli Scale (A.S. Arya. interview, August 1988).

19: This system, sometimes incorrectly identified as Dhajji-Dewari, actually has no specific name in Kashmiri to identify the construction method. The closest name identified by local experts to describe it is Taq. Taq refers to the modular layout of the piers and window bays, i.e., a 5-Taq house is 5 bays wide. The piers are almost always 1-1/2 to 2-feet square, and the bays are approximately 3-1/2 feet in width. This

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traditional system with the piers and horizontal wooden runner beams was in common usage before the Dhajji-Dewari came into use. The bricks were usually small in size, rough-surfaced, and hard-fired. They are known as "Maharaji bricks"-the reason for the name is unknown. Bricks of this type can be found in Mogul period buildings as early as the sixteenth century, but the houses which survive date from the eighteenth and nineteenth centuries. This construction can be found in Afghanistan and Kashmir, but not in Nepal (Arya, interview). Houses found in parts of Greece affected by earthquakes also have horizontal wood members. The use of horizontal wood ties is also common in seismic areas of Turkey. The bond beams in Turkey are credited with "incorporating ductility to the adobe walls, substantially increasing their earthquake resistant qualities." [Alkut Aytun, "Earthen Buildings in Seismic Areas of Turkey," Proceedings of the International Workshop on Earthen Buildings, Vol. 2 (Albuquerque, 1981), p. 352.1 The brick-nogged type of construction is also found in Greece, where it is sometimes used for the upper part of the houses where the stability of the wall is not assisted by the weight of the overburden.

20: Dhajji-Dewari comes from Persian and literally means "patch-quilt wall." This method of construction appears to have emerged into common usage alongside of the Taq system during the late nineteenth century when bricks of a more standard large size became available. This larger-sized brick (2 1/4 x 4 1/2" X 9") set into the timber frame enabled the construction of one-wythe-thick brick walls. Dhajji-Dewari buildings constructed with unfired mud bricks were also common, especially in the villages.

21: N. Gosain and A.S. Arya, "A Report on Anantnag Earthquake of February 20, 1967," Bulletin Of the Indian Society of Earthquake Tecbnology (fn4), No. 3 (September 1967).

22: INTERTECT, Vernacular Housing in seismic zones of India (Albuquerque: University of New Mexico, 1984). (It should be noted that it can be argued that the buildings of this type, and the other types being discussed here are reinforced rather than unreinforced masonry. Indeed, the Dhajji-Dewari buildings are not conventional unreinforced masonry structures, but neither are they the same as reinforced masonry. The timbers run only horizontally, and do help to restrain the masonry from failing apart, not unlike diaphragm cords in modern strengthened URM buildings. The restraint, however, would not work unless the soft mortar also existed, together with the bearing weight of the masonry above. The Dhajji-Dewari also falls into the category of restrained masonry. The large panels of brick are unreinforced, but in this case, the wood carries part of the vertical load.)

23: Neve, Thirty Years, p. 38.

24: Gosain and Arya, "Anantnag," p. 29 (italics added). In this case the authors are referring to the Taq system.

25: The division of the wall into piers and infill panels, without an interlocking masonry bond between them is one of the most perplexing anomalies in this system. it would seem to violate all of the other provisions to hold the wall together while allowing it to deform. This aspect needs to be investigated further, but it may have been intended as a relief joint between areas of different thickness, and therefore, stiffness. if the separation were not there, a crack might develop at the joint before the damping begins to take place within the piers.

26: For example see: Panayotis Carydis, "The Extent of the Problem of Earthen Buildings it Greece," International Workshop on Earthen Buildings (Albuquerque: University of New Mexico, 1981), p. 120. (The buildings constructed "have withstood the various earthquakes quite well.")

27: Arya, interview. (Arya participated in the preparation of this code.) Note that the com parison here is with other forms of masonry construction which are still commonly used in India. Neither this nor the Taq system are as resistive to seismic forces as properly constructed steel and reinforced concrete buildings.

28: Earthquake Engineering Research Institute, Managua, Nicaragua earthquake of December 23, 1972: Reconnaissance Report (El Cerrito, CA: EERI, 1973); J.R. Freeman, Earthquake Damage and Earthquake Insurance (New York: McGraw-Hill, 1932).

29: Earthquake Engineering Research Institute, Managua, Nicaragua Earthquake, p.

30: Freeman, "Earthquake Damage" (see also: S. Tobriner, "La Casa Baraccata: Earthquake Resistant Construction in 18th Century Calabria," Journal of the Society of Architectural Historians 40 (1985), p.2.

31: Earthquake Engineering Research Institute, Managua, Nicaragua Earthquake p. 347.

32: R. Wright and S. Kramer, Building Performance in the 1972 Managua Earthquake (N.B.S. Technical Note 807, 1973). This report documents that the timber framing in 1972 was frequently found to have been weakened by termites.

33: For information on the Equivalent Strut, see: R.E. Klingner and V.V. Bertero, Infilled Frames in Earthquake-Resistant Construction (Berkeley, CA: EERC, 1976); N.J.N. Priestley, "Masonry," in Design of Earthquake Resistant Structures ed. E. Rosenblueth (New York: John Wiley & Sons, 1980), p. 216.

34: As a result of the danger of the equivalent diagonal strut, and of the shear failure of the infill walls, many engineers have developed methods to provide a gap between the infill from the structural frame. Then the structure can be engineered to resist the code-defined earthquake forces within the more easily calculated strength and ductility of the moment resisting frame itself. This can prevent much nonstructural damage in a minor earthquake. However, in a major earthquake, the frame can collide with the infill, causing a more dangerous condition than if there had been no gap. When the infill is designed without the gap, if the frame is stressed beyond its capacity, the infill can provide an important secondary resisting element-if it is designed so as not to cause failure of the columns.

35: "In designing to resist earthquake forces, we not only have to consider ... member strengths ... but also consider the performance at great overloads .... In earthquake resistant design, it is not sufficient to make a member ‘strong enough’ it must also have a reserve of ductility." Henry Degenkolb, quoted in Kirk Martini, Unreinforced Masonry Buildings, Seismic Behavior and Renovation (Berkeley: University of California, 1982), p. 29.

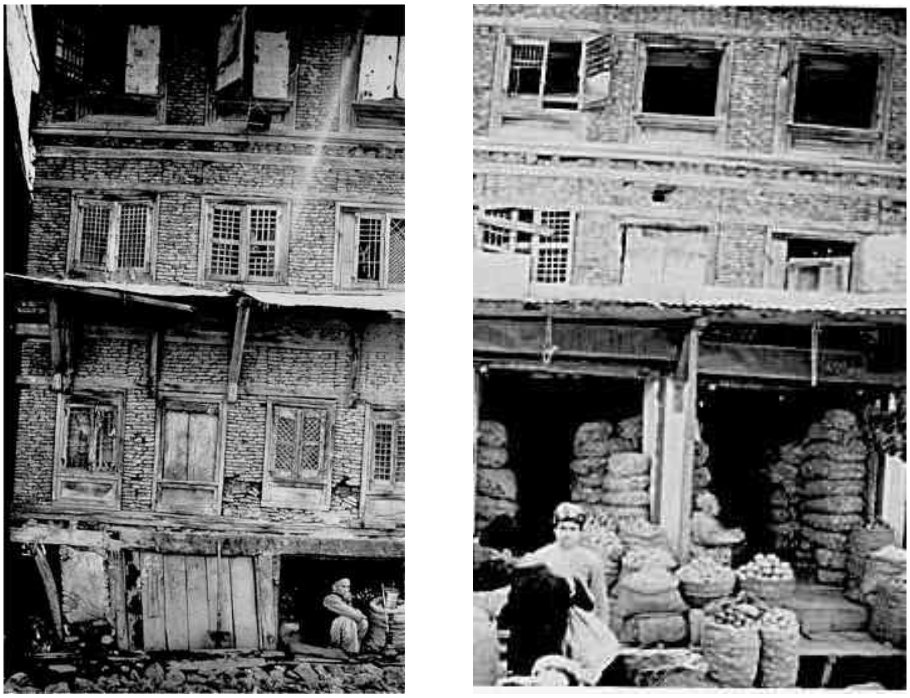
36: Harley McKee, Masonry (Washington, DC: National Trust/Columbia University Series, 1980), p. 61. (tense changed for clarity)

37: For example, at the 1988 International Brick/Block Masonry Conference in Dublin, a paper by Dr. W. Mann, University of Darmstadt, generated criticism around the assertion that masonry bedded in mortar with *"low cohesion [is] favorable"* because it contributes to *"a type of ductile"* behavior. It should be noted that in the traditional examples described here, the weak mortar is combined with the overall flexibility of the building structure, the restraint provided by the timber beams, and the precompression provided by the weight of the overburden. The flexibility and internal damping of the structure serves to change the building's response, and thus reduce the out-of-plane forces in the masonry walls, while the timber serves to keep the weaker masonry in place. The use of a weak mortar/strong masonry system in conservation work (or new construction) without some means of spreading the stresses, and controlling the displacements in the masonry is not advocated.

For a good review of recent research on infill walls, see R. Mayes and Ray Clough, State of the Art in Seismic shear strength of Masonry (Berkeley: EERC, 1975). Research with mortar strengths exists, but is usually related more to reinforced, rather than unreinforced walls, and to grouted block, rather than solid brick or stone. Many of the tests have been designed to relate to non-bearing infill walls, and the results show a large difference between the performance of walls under vertical load and those without. The confining of unreinforced masonry beneath vertical load and the horizontal restraint provided by external elements such as strengthened diaphragm cords, makes for a system of very different performance than that shown by unreinforced masonry prisms subjected to strains in a laboratory lacking such elements. An interesting observation was made by Doc Nghiem of the Los Angeles Building Department, who found that the mortars which worked best were either very strong, or very weak, because the in-between strengths tended to cause the unit masonry to fail in tension from the spreading of the mortar (see also: Priestley, "Masonry," p. 182). If the mortar is very strong, the strength of the wall is sufficient to stay within the elastic range. If it is very weak, when it yields, breakage of the masonry units is avoided, and stability is maintained.

38: It should be recognized that although reinforced concrete is a marvelous material when used well, it is very dangerous if either the engineering, materials manufacture or construction is inadequate, yet the faults are often invisible. it is a high technology material which is available in areas where the technology is not understood or safely undertaken because of economic or social reasons.

39: The effectiveness of horizontal reinforcement (in this case external to the wall) is supported by the observation that horizontal shear reinforcing is more resistive of shear failure displacement than vertical reinforcement (Priestley, "Masonry," p. 208). Bernard Fielden has also said that a reinforcing system of placing stainless steel cable in horizontal mortar joints could have great value in conservation work. It would only require the cutting out of a joint, rather than the heavy drilling and coring which -has been done for vertical steel placement on some projects (Fielden interview, 1985).



Eight years after the photo on left, the storefronts have been rebuilt inspite of the antiquity of the building. Only the upper part of the building remains. The old man is also still there, however, in the shop on the right.