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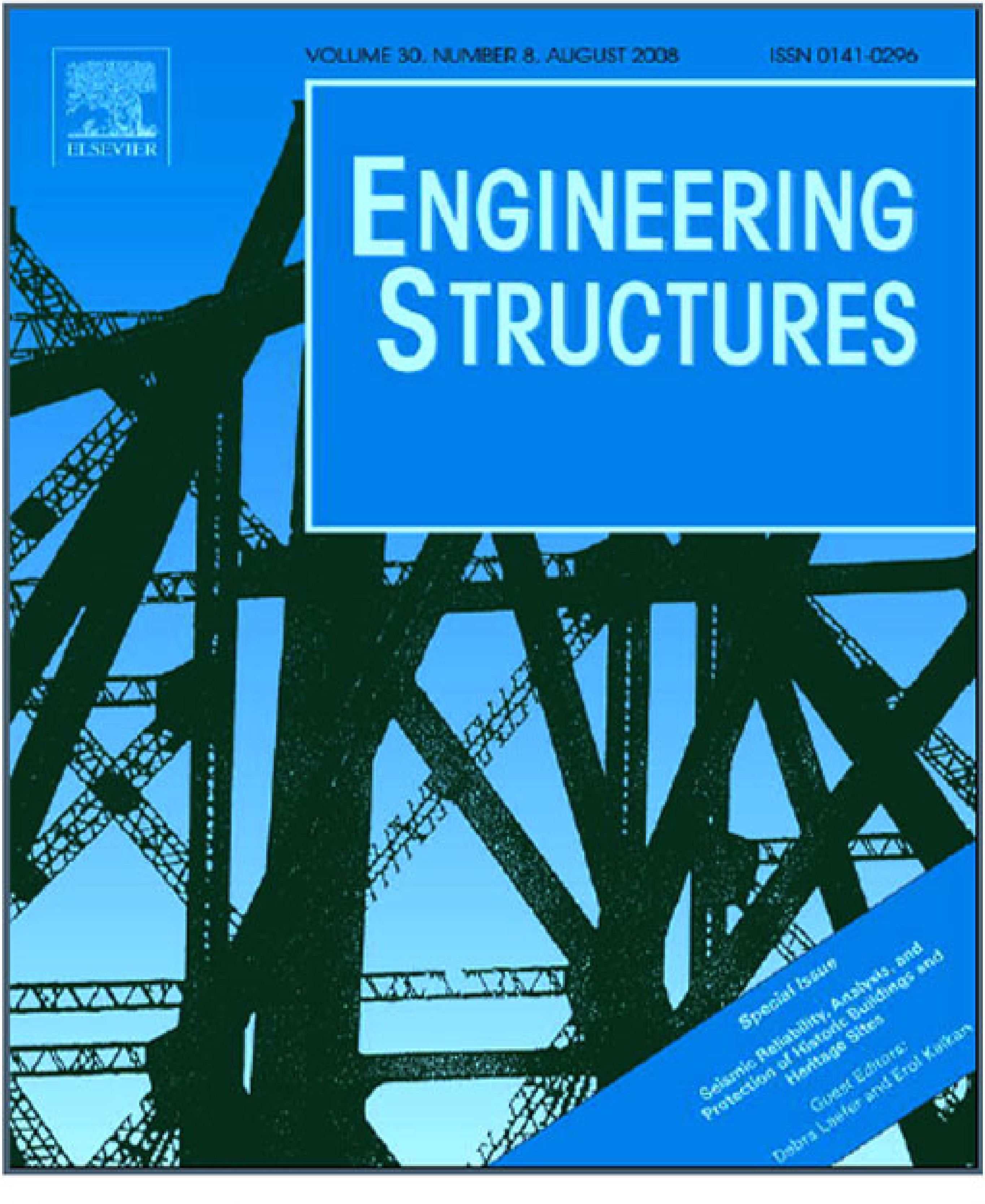

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# Learning from the past to protect the future: Armature Crosswalls

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## Abstract

It seems counter-intuitive to assert that simple, unsophisticated, non-engineered, timber and masonry structures that now seem so archaic as to be more easily associated with the medieval rather than modern world might be safer in large earthquakes than new structures of reinforced concrete, but such has proven to be the case in a number of recent earthquakes. Indeed, in many different regions of the world, the earthquake record for contemporary structures of reinforced concrete (RC) frequently has been abysmal, while certain types of traditional masonry structures with timber-lacing have survived earthquakes that have felled their concrete neighbors.

Before the advent of the strong materials of reinforced concrete and steel, many societies had developed an approach to seismic resistance based on flexibility rather than strength that is only slowly being re-learned in the present. This paper will explore what can be learned from these historical construction practices, by describing the concept for "Armature Crosswalls," a construction technology inspired by Turkish and Kashmiri traditional construction but designed for use in reinforced concrete infill-wall buildings. The value of this approach for heritage conservation is that when people understand historic structures not only as archaic and obsolete building systems, but also as repositories of generations of thought and knowledge of how to live well on local resources, societies can begin to rediscover the value of these traditions once again by seeing them in a new light – one that, at its most fundamental level, can save lives.

*Keywords:* Traditional construction; Reinforced concrete; RC; Masonry; Timber; Earthquake; Heritage; Infill-frame; Turkey; Portugal; Kashmir

## 1. Introduction

The superior performance of many traditional timber and masonry buildings over newer ones of reinforced concrete during recent earthquakes in Turkey, India (Gujarat and Kashmir) and Pakistan raises fundamental questions about the assumptions made over many decades that simple, unsophisticated, non-engineered, timber and masonry structures (seemly more medieval than modern) are less safe in large earthquakes than newer structures of reinforced concrete (RC). Despite the frequently abysmal record of contemporary RC structures under seismic loading, certain types of traditional masonry structures with timber-lacing have survived the same earthquakes with only minor damage. This gives rise to the question of whether one can employ aspects of traditional technology Fig. 1 to enhance the seismic performance of modern constructions.

As described below, the concept of "Armature Crosswalls" is derived from *hımış* (in Turkey) and *dhajji dewari* (in Kashmir) as an alternative to the otherwise nearly ubiquitous conventional infill masonry in RC moment frames. Although experimental evidence is still preliminary, and issues of scalability from small experiments and low-rise traditional buildings to multi-story RC buildings have yet to be rigorously addressed, a re-examination of traditional structural systems may furnish an example of how a reinvention of an indigenous building technique may simultaneously provide guidance for safe modern construction using local materials and skills, and encourage the preservation of cultural heritage. Exploring this premise is designed to help facilitate a paradigm shift to one where the goals of historic preservation are not necessarily viewed as incompatible with seismic safety. Yet, to do this may require a fundamental rethinking of current analysis and analytical tools to encompass the use of masonry as an interactive part of the primary lateral-force structural system of modern frame structures.

## 2. Background

Before the advent of strong materials such as RC and steel, masonry was predominant for construction in most

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Fig. 1. This long abandoned and unmaintained 2.5 story *hımış* house in Gölcük survived the 1999 earthquake with little additional damage, despite the widespread collapse of the surrounding RC structures.
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parts of the world, but, with the judicious use of timber, a moderate degree of flexibility could be achieved. With regional variations, traditional construction with timber-laced masonry and masonry-infilled timber frames can be found in many earthquake-prone areas. The recent large Turkish Marmara earthquakes in 1999, in which tens of thousands died in collapsed new RC buildings – Fig. 2, provide juxtaposed cases against which to study the behavior of traditional structures. While poor design and bad construction are reasonable explanations for many RC collapses, arguably a system that depends for basic life-safety on a level of quality control that is rarely achieved is unwise.

By contrast, the traditional buildings that survived the earthquake were not engineered, and lacked both steel and concrete. No plans for them were ever inspected, because none were ever drawn. They were only rarely erected by anyone who could remotely be characterized as a professionally trained designer or builder, nor could many of them be characterized as having been carefully constructed. On the contrary, they were constructed with a minimum of tools, with locally acquired materials, and employed only a minimum of nails and fasteners. Often the timber was not even milled, being only cut and debarked and sometimes put together with only a single nail, before being infilled with brick or rubble stone in mud or weak lime mortar. Thus, arguably the traditional buildings which survived inherently possess the type of construction deficiencies usually identified as reasons why the modern buildings fell down. As such, the argument that engineering design and strong materials can consistently provide seismic protection must be questioned, especially where construction quality control is unreliable [6].

Fig. 2. Partially collapsed RC frame with infill masonry apartment block, Gölcük, Turkey, 1999.
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Fig. 3. Partially demolished *taq* construction (Srinagar, Kashmir, 2006) showing timber lacing laid into the wall. Timber bands at floor level and at the window lintel levels.
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Fig. 4. Partially demolished *dhajji dewari* construction Srinagar, 2007). Timbers form a complete frame with only a thin single layer of masonry infill; interlocking of timber joists with the exterior wall is visible — a key seismic feature to *taq* and *dhajji dewari*.
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These observations were repeated in the Indian and Pakistani administered parts of Kashmir where the traditional construction systems of *taq* (solid bearing-wall masonry with timber lacing –Fig. 3) and *“dhajji dewari* (brick-infilled timber frame construction – Fig. 4) are found. Both use timber within the plane of the masonry walls. *Dhajji dewari* has a complete timber frame, with a single layer of masonry forming panels within the frame [2]. *Taq* includes mud mortar of negligible strength, lacks bonding between the masonry in the window bays and the piers, has weak bonding between wall wythes, and until recently had heavy sod roofs. Yet, good seismic performance has been documented, as in the case of the contemporary account by British visitor Arthur Neve in 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* [7].

Nearly 100 years later, the October 2005 Kashmir earthquake showed that surviving timber-laced construction near the epicenter has inspired those who lost their rubble-stone houses to revive these traditional practices for reconstruction Fig. 5. Structural engineering professors Durgesh Rai and Challa Murty of the Indian Institute of Technology—Kanpur observed:

> *“In Kashmir traditional timber-brick masonry [dhajji-dewari] construction consists of burnt clay bricks filling in a framework of timber to create a patchwork of masonry, which is confined in small panels by the surrounding timber elements. The resulting masonry is quite different from typical brick masonry and its performance in this earthquake has once again been shown to be superior with no or very little damage.”*

Fig. 5. Pakistan 2005, the carpenter and owner standing in their new *dhajji dewari* home to replace rubble stone house. The Pakistani government initially refused assistance for rebuilding with timber-laced masonry, but later accepted and promoted this kind of construction.
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They cited the fact that the “*timber studs... resist progressive destruction of the ...wall ...and prevent propagation of diagonal shear cracks ... and out-of-plane failure.”* They went on to recommend that: *“there is an urgent need to revive these traditional masonry practices which have proven their ability to resist earthquake loads”* [9].

**Reinforced concrete infill-wall construction:** The rapid spread of RC construction has nearly replaced traditional vernacular building methods in many countries within a single generation [5]. This rapid transition from indigenous to imported technologies has resulted in a shortage of knowledgeable specialist builders adequately trained as to the seismic implications of RC construction, further exacerbated by frequent construction defects (e.g. honeycombing, exposed rebar, poorly mixed and hydrated concrete) hidden beneath troweled plaster.

The almost universal acceptance of the concrete moment frame for construction, and of linear elastic portal frame analysis as the basic engineering approach, fails to recognize that most buildings are solid wall structures once rooms and exterior enclosures are finished. If the enclosure and partition walls are made of stiff and strong materials attached rigidly to the frame, as is frequently the case with infill masonry, the structural system can no longer be defined correctly as a “frame.” However, nearly all of the engineering and codes that underlie the design of these buildings is based on their being modeled as frames, with the infill masonry walls treated only as dead weight, even though earthquakes have repeatedly demonstrated that the infill corrupts the frame behavior on which the portal frame analysis method is based. There have been attempts to find ways to separate the infill from the frame, but these efforts have encountered problems related to finishing the enclosure, soundproofing the rooms, and ensuring out-of-plane stability of the masonry infill.

## 3. “Armature Crosswalls”

While it may seem far fetched to propose that an answer to collapsing modern RC buildings is within *hımış* houses, it certainly is worth examining why these seemingly weak and unengineered buildings have such a better seismic track record [1]. I believe that the good seismic performance of *hımış* and *dhajji dewari* houses can provide an inspiration for retrofitting RC, despite their much smaller scale. I am proposing use of the "Armature Crosswall" system described herein for both new buildings and retrofits of existing RC moment frame buildings in seismic areas.

The term "crosswall" seemed most appropriate based on how it is defined in the American *International Existing Building Code*, Appendix A, Chapter A1 [11]. A crosswall is an interior partition wall that is not a shear wall but nonetheless provides structural support and hysteretic damping. The term "armature" refers to use of a "sub-frame" to subdivide the masonry infill walls. Armature Crosswalls are, thus, infill masonry walls modified by the introduction of a sub-frame of studs and cross pieces (the "armature") and the deliberate use of a weak lime-based mortar. These studs and cross-pieces (of timber, steel, or pre-cast concrete) would be securely attached to the RC frame, with bricks tightly packed in between. By generating less initial stiffness than standard infill masonry walls, multi-story frame action can occur, thereby reducing the likelihood of soft-story collapse. The studs would also serve to impede the development of an equivalent diagonal strut, while substantially increasing resistance to out-of-plane collapse. As the building deflects, the "Armature Crosswalls" would be expected to increase in stiffness, as the confined masonry panels of the walls begin to pinch. This would transfer loads from the RC frame into the walls. Thus, the walls would aid in collapse prevention, while simultaneously producing a great deal of frictional energy dissipation [3,4]. In summary, "Armature Crosswalls" are intended to address initial stiffness, diagonal strut formation, out-of-plane collapse, and energy dissipation issues that exist for RC infill buildings.

If infill masonry can damage modern RC frames, then why are much weaker traditional timber frames not crushed? The answers appear to be in the subdivision of the walls into many smaller panels with studs and horizontal members, combined with the use of low-strength mortar. Both of these features reduce the initial stiffness and prevent the formation of the large diagonal tension cracks that can lead to the collapse of the entire infill wall, while the redundancy and energy dissipation provided by the continued working of the many interior and exterior walls that exist in a standard residential building reduce the likelihood of catastrophic failure of the RC frame Fig. 6.

As the stresses on the individual masonry panels within the "Armature Crosswall" increase, shifting and cracking first begin along the interface between the panels and the sub-frame members, and then in the panels themselves. The use of the weak mortar serves to protect the masonry units from fracture so that the ultimate wall strength is the masonry crushing strength (post substantial deformation), thereby far exceeding the elastic capacity. The mesh of hairline cracking that develops in the mortar joints produces multiple interfaces; each of which promotes energy dissipation and helps preclude the brittle failure commonly found in modern infill construction. Laboratory tests by the Laboratório Nacional de Engenharia Civil in Portugal and India have shown immediate strength loss in such construction upon initial development of the diagonal tension "X" cracks [10,8]. With fully developed "X" cracks, the walls cease to dissipate much energy and often suffer complete collapse. By contrast, laboratory tests on small-panel confined masonry walls support the finding that such walls are far more robust over many cycles with large amounts of hysteretic behavior, even though their initial elastic strength is low. While traditional *hımış* and *dhajji dewari* structures do not have much lateral strength, they do possess lateral capacity.

One reason why engineers have failed to recognize the benefit of modifying the infill masonry in RC buildings, or to include contributions from it in their calculations, is the reliance on linear elastic models in seismic design, therefore ignoring in an overly conservative manner any post-elastic strength and energy dissipation. Reports that are based on such analyses will show unrealistically high levels of vulnerability for the affected buildings.

**Challenge:** One problem that plagues existing buildings is establishing a norm for earthquake safety and performance when "no damage" is not a viable objective. This is because a "no damage" objective is economically unfeasible. This is so because the potential earthquake forces are so great, while the return period is so long that the relative risk of injury or death is low as long as collapse is prevented. Thus, how does one evaluate the post-elastic performance of archaic non-engineered structural systems constructed of materials that do not appear in the codes, and for which there are no codified test results? Earthquake damage of traditional timber-laced masonry construction has often been examined with little understanding of what it represents in terms of loss of structural capacity. The standards applicable to reinforced concrete, where a small crack can indicate a significant weakness, are often wrongly applied to archaic systems where even large cracks do not represent the same degree of degradation or risk of collapse. This can result in the unnecessary condemnation of buildings.

## 4. Conclusions

Modern construction materials and methods have brought with them extraordinary opportunities for new spaces, forms, and ways of building, but in many parts of the world they have also been disruptive of local culture, resulting in building forms and ways of building that are alien to the local society, and which, when adopted, displace time-honored crafts that have been handed down for generations. As a result, the local people are left with a diminished control over their environment and livelihoods.

The earthquake risk is just one way in which we can observe what this revolution in construction practice represents in terms of a loss of cultural and technical knowledge and memory. Earthquakes have proven to be particularly unforgiving when the new ways of building are not sufficiently well understood or respected to be carried out to an acceptable level of safety. Moreover, by learning from indigenous pre-modern examples of earthquake resistant technologies, we can learn to preserve the surviving examples of these now seemingly ancient ways of building in a way that respects what these buildings are, not just how they look.

(a) Exterior of partially collapsed building after the 1965 San Salvador earthquake.

(b) Detail of upper floor wall with "Armature Crosswall" subframe division denoted by the dotted lines.

Fig. 6. This building suffered soft-story collapse, but progressive pancake collapse was avoided by the resistance proved by the upper story infill walls, which had sub-frames in the locations marked that worked as "armatures."
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Recent catastrophes including the tragic Sichuan earthquake in China this year, with their sizeable death tolls, show there is much to learn about how to build in a safe and durable manner. Just as many have begun to rediscover the value of ancient Indian ayurvedic medicine or Chinese acupuncture, earthquakes can reveal the value of forgotten indigenous knowledge – as well as shortcomings in the modern methods. Well-engineered and constructed modern buildings have fared well in earthquakes, but efforts to meet the needs of a broader range of rural and urban populations lacking access to well-trained engineers and builders remain unaddressed. When people understand historic structures not only as archaic and obsolete building systems, but also as repositories of generations of thought and knowledge of how to live well on local resources, societies can begin to rediscover the value of these traditions once again by seeing them in a new light – one that, at its most fundamental level, can save lives.

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