Earthquakes and Masonry: What can be learned from Nepal?

Terremoti e murature: cosa si può imparare dal Nepal?

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Il contributo prende spunto dal terremoto che il 24 agosto 2016 ha colpito due parti del mondo – l'area centrale appenninica in Italia e la pianura di Bagan in Myanmar, l'antica Birmania – per argomentare sulle carenze di una cultura sismica che a ogni latitudine, alla conta dei danni portati al patrimonio architettonico, è spesso più colpevole degli eventi naturali. A meno, come accaduto in Nepal, che la modernità si sposi con la tradizione costruttiva e ne trasformi in virtù le presunte debolezze.

Il confronto tra la distruzione, in Italia, di tanti borghi medio piccoli, e quella che in Birmania ha interessato in particolare l'area archeologica di Bagan, fitta di templi e pagode, non sembra lasciare dubbi sul fatto che le strutture sono crollate non tanto perché vecchie e povere, quanto perché malamente trasformate durante l'ultimo secolo col ricorso a materiali e tecniche, prevalentemente a base di cemento armato, che sotto l'azione dei sismi si sono rivelate pesantemente distruttive.

I resoconti portati dai luoghi dei due terremoti, in linea con un'onda emotiva e mediatica che ha stretto l'intero pianeta intorno al dramma delle perdita di patrimoni e vite umane, puntano in questo caso ad aggiungere altri argomenti ad una conoscenza che nonostante i progressi fatti negli ultimi decenni, manca ancora di piena consapevolezza circa la compatibilità fisico-chimica-strutturale fra le antiche strutture e quanto si aggiunge loro al fine di ampliarle, rafforzarle e consolidarle.

Ad Amatrice, foto e reportage internazionali dimostrano che tra le murature di pietra e mattoni di case e palazzi ci sono intrusioni di cemento armato assolutamente deleterie per la loro sopravvivenza, a dispetto delle premesse legate al miglior uso delle fabbriche e alla loro maggiore sicurezza; e a Bagan, le solide murature in pietra dei templi costruiti tra XI e XIII secolo sono crollate proprio nelle parti rinforzate con acciaio e malta cementizia dopo i danni portati dal terremoto del 1975, nel contesto di operazioni che la cultura internazionale aveva inutilmente bocciato per la poca attenzione agli stili, per l'uso disinvolto di materiali moderni e il poco ascolto prestato alle raccomandazioni dell'Unesco e dei migliori protocolli internazionali.

Eppure, più a nord della Birmania, in Nepal, la storia recente dei terremoti e delle ricostruzioni dimostra che la linea della tradizione è quasi sempre la migliore se si vuole garantire alla cultura sismica una crescita capace di associare sicurezza del patrimonio e mantenimento delle identità locali. È proprio partendo dal terremoto che ha colpito il Nepal nel 2015, uccidendo 9000 persone e causando il collasso di molte fabbriche non solo a Kathmandu, la capitale, ma anche ad interi insediamenti tra le montagne dell'Himalaya, che il contributo fissa le basi per arrivare a dimostrare che spesso, ad essere i più insicuri sotto l'azione dei terremoti sono proprio gli edifici in cemento armato. In effetti, il numero di vittime e le distruzioni del terremoto del 2015, per quanto grandi, sono circa un decimo rispetto a quelli registrati in Pakistan e in India col sisma del 2005, nonostante l'area interessata fosse più o meno simile per dimensioni e la magnitudo di poco superiore. Come mai questa differenza? Non sarà perché in Nepal l'uso intelligente di tecniche antisismiche tradizionali - maturate in secoli di esperienze da un paese che insieme al Tibet, all'Afghanistan, al Kashmir indiano e pakistano è in cima alla lista dei paesi più a rischio del mondo- è riuscito ad assecondare le onde sismiche ed assicurare vita più duratura al suo patrimonio?

Argomenti per rispondere positivamente a questa domanda vengono dalle ricerche fatte negli anni '80 sulla costruzione tradizionale di Srinagar, in Kashmir, che hanno portato all'individuazione di una tecnica basata sull'uso di travi dentro le pareti in muratura, secondo un doppio sistema. Il primo, conosciuto come dhajji dewari, *e consistente in un telaio in legno con riempimento in muratura, l'altro conosciuto come* taq *a Srinagar e come* bhatar *in Pakistan, costituito da muri portanti con travi che li suddividono in orizzontale. Ebbene, il terremoto del 2005 in Kashmir ha dimostrato che a resistere meglio sono state proprio queste strutture, mentre a collassare sono*

state quelle rurali in pietra con malta di fango e quelle delle città a base di cemento armato per murature, solai e pavimenti.
Dei due sistemi usati nel Kashmir la ricerca ha individuato per il Nepal il solo uso della muratura con travi a fasce orizzontali, rivelatasi con l'esperienza del terremoto del 2015 assolutamente capace di resistere all'azione del sisma soprattutto laddove, come in alcune parti del palazzo Dhoka di Katmandu, le fasce di legno non sono state seppellite sotto strati di intonaco ma lasciate a vista, e sottoposte a puntuale cura e manutenzione. Ed è sintomatico che la consapevolezza di un prezioso sapere come quello legato all'uso di questa tecnica sia in Nepal entrata nel codice edilizio sin dal 1994.
Oltre al sistema dell'allacciatura delle murature con fasce di legno, un'altra lezione che viene dal Nepal a favore della conservazione del patrimonio, è legata al ruolo da sempre riconosciuto alla malta di fango. Nonostante la malta di calce sia conosciuta nel paese, il suo uso infatti è sempre stato limitato a favore di quella di fango, scelta per secoli dal cantiere tradizionale e ancor oggi largamente preferita, in coerenza con le linee guida UNESCO e la Carta di Venezia.
L'apparente debolezza della malta di fango, usata in commistione con mattoni che sono altrettanto deboli, è infatti riconosciuta come un vantaggio, giacché rispetto alla malta di calce, più forte ma anche più fragile, questa non si frattura sotto l'azione del sisma, non frattura a sua volta i mattoni e assicura migliore stabilità a tutta la struttura, anche per il fatto che i suoi ingredienti, a base di argilla e sabbia, tendono col tempo a "migrare" attraverso i giunti e a fare pressione sui paramenti esterni durante i movimenti tellurici. Questa circostanza è solo meno efficace nel caso in cui, soprattutto in fabbriche monumentali, la malta di fango si associa all'uso di mattoni cuneiformi nei rivestimenti esterni allo scopo di ottenere giunti sottili altrimenti impossibili da realizzare. Il crollo parziale delle piccole pagode realizzate con questo sistema sembra dovuto proprio alla circostanza che le forze di compressione scatenate dal terremoto sui prospetti hanno fatto curvare questi verso l'esterno, lasciando il nucleo interno del muro schiacciato dal peso del sovraccarico superiore.
*Le virtù del cantiere tradizionale hanno in Nepal condizionato positivamente anche le strutture in telaio di cemento armato e muratura di tamponamento in mattoni, che da tempo caratterizzano le abitazioni di Kathmandu e della maggior parte delle città. La loro efficacia contro i terremoti è infatti stata riconosciuta dalla circostanza di basarsi su una tecnica che, per ragioni economiche e culturali legate alla carenza di risorse nella disposizione di impalcature e casseforme, ha portato prima alla costruzione delle murature e poi delle colonne e delle travi affiancate e appoggiate sulle stesse e destinate a fare da intelaiatura. Anche in questo caso una sorta di muratura armata, (*confined masonry*), che si è rivelata efficace contro il terremoto del 2015 molto più degli edifici risultanti dai precisi calcoli sulla resistenza elaborati dagli ingegneri. Alla stato attuale della ricerca sembra che in questo caso siano stati soprattutto i mattoni a salvare molte delle strutture a telaio, in virtù soprattutto della loro tecnologia pre-industriale, considerato che sono fatti a mano, essiccati all'aria aperta, e poi cotti ad una temperatura non elevatissima che ne limita la durezza senza diminuirne la solidità e tali, associati ad una malta altrettanto debole ma resistente, come già detto, da garantire la permanenza delle murature dentro il telaio.*
Sebbene il terremoto che ha colpito il Nepal nel 2015 abbia rafforzato la convinzione che l'uso del cemento armato è una misura preziosa contro i terremoti, rimane il fatto che senza i sistemi tradizionali si sarebbero avuti molti più danni di quelli registrati, a monito ed insegnamento di un approccio che sembra valido ad ogni latitudine, sia per garantire sicurezza al patrimonio, sia per preservarlo, per quanto possibile, nella sua specifica identità materiale e culturale.

Introduction
Two earthquakes on same day. A quarter of a world apart

On August 24th 2016 the earth had a busy day in terms of damage to architectural heritage. A quarter of the way around the globe but only 9 hours apart in real time, a shallow 6.2 earthquake struck near Norcia and Amatrice in Italy at 3:36 AM local time, and a 6.8 quake at 5:04 PM local time - now called the "Chauk earthquake" - struck the ancient site of Bagan in Myanmar, where instead of villages and towns one finds a vast open plane dotted with temples made of brick and stone. Bagan is an ancient city that from the 9th to 13th centuries was the capital of the kingdom of Pagan. During the kingdom's height between the 11th and 13th centuries, over 10,000 Buddhist temples, pagodas and monasteries were constructed in the Bagan plains alone, of which the remains of over 2200 temples and pagodas still exist. Many of these were solid masonry stupas, and others have interior spaces[1]. In Italy, a number of small historic hill towns were devastated and in Myanmar, a remarkably picturesque open plane known as the Bagan Archaeological Area and Monuments, already on the tentative list for a World Heritage site, was badly affected with partial collapses.

In the case of hill towns in Italy, the first impression was that the buildings fell down simply because they were old and of unreinforced stone masonry. In the case of Myanmar, likewise, many of the temples of brick masonry were damaged, largely by partial collapses of their upper sculptural pinnacles. When these collapsed, they damaged the ornate brickwork below on the way to the ground. The press photographs of Amatrice, Italy, and surrounding towns show shorn off walls and heaps of rubble stone masonry, but they also show broken bits of concrete with rebar sticking out, and whole slabs of what had been floors and roofs of concrete (fig. 1). One of the first teams of engineers to report on what they found were with the firm of Miyamoto International Engineers, and their report, entitled in part "Day 1" reported: "This is a rural region and most of the buildings are unreinforced masonry, mostly stone with mortar and concrete floors. Very often, concrete roofs have replaced the original wooden ones, but these performed very badly. The extent of these modern insertions or rebuilding is yet to be quantified; yet this very quick first impression upon arriving at the center of the damage district is revealing". The report also stated: "We are surprised that a palace and a tower from the 12th century remain standing without apparent damage…".

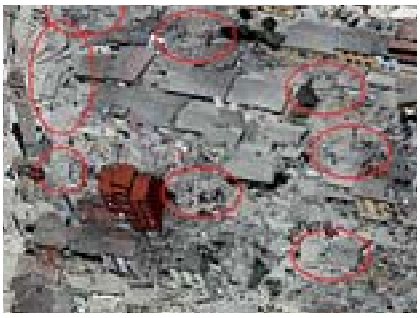
In the case of Myanmar, an important historical fact is that there was an 8.0 MM earthquake in 1975 in Bagan which also damaged many temples and, as was reported in a 2004 "National Geographic" article, the subsequent restorations "drew widespread condemnation from art historians and preservationists worldwide because they paid little attention to original architectural styles, and used modern materials." The "National Geographic" went on to say: "Restore the Sistine Chapel like this, and Adam would be sporting tattoos and a nipple ring"[2].

After the last earthquakes, these alterations done in the name of 'restoration' take on a new light. UNESCO is now involved - unlike what transpired under the military dictatorship which had refused to accept recommendations from UNESCO) - and ICOMOS ICORP colleague from Nepal, Kai Weise[3], has issued a report for UNESCO which clearly identifies much of the damage sustained in the August 24, 2016 earthquake as being a product of the collapse of those parts of the temples that were reconstructed with modern materials and technology – namely with cast concrete elements and steel reinforced masonry laid with cement mortar.

[1] D.J. Stadtner, *Ancient Pagan, Buddhist Plain of Merit*, Bangkok 2013.

[2] J. B. Tourtellot, *Dictators "Defacing" Famed Burma Temples, Editor Says*, in "Travel Watch, National Geographic News", Updated September 3, 2004, in http://news.nationalgeographic.com/news/2004/09/0903_040903_travelwatch.html

[3] K. Weise, *24 August 2016 Chauk Earthquake Response Coordination*, UNESCO, 6 September 2016: "Initial assessments show that the damage seems to have been mainly parts that were reconstructed after the 1975 earthquake using cement mortar and steel reinforcement…. In many cases we see that inappropriate construction has led to the destruction of the monument or at least the parts that were added using modern materials and techniques…. A major concern would be the reinforced cement concrete elements that have been integrated into the ancient monuments that would be practically 40 years old and would soon become obsolete with the reinforcement rusting away" . What this reveals is that what had seemed to be conventional wisdom about the vulnerability of heritage structures of unreinforced masonry, together with the belief that strong modern materials of concrete and steel are better, may not be as reliable as first thought.



1/ Amatrice after the 24th August 2016 earthquake showing evidence of reinforced concrete slabs in debris (AP photo).

Remarks on "seismic culture" in Nepal

In light of these observations, one must ask the following questions regarding the 2015 Nepal earthquake[4]: are these profound losses because the buildings were old and of unreinforced masonry construction? With the exception of pockets of damage to modern concrete structures, does the urban landscape of Kathmandu that appears as it did before the earthquake, except in the heritage sites of Kathmandu, Patan, and Bhaktapur, show that modern concrete buildings are indeed safer?

The news of the Nepal earthquake[5] ricocheted around the world and remained in the news far longer than many other large-scale disasters. There was a significant loss of life, but the attention revealed that there is a considerable international community that loves the country and is enriched by its extraordinary mountain environment.

Nepal's Himalayan chain was created by the collision of continental plates, creating the highest mountains in the world, along with one of the world's most active earthquake hazard areas. Historical records indicate that there was an earthquake in 1255 that killed a quarter to a third of the population of Kathmandu Valley[6]. By comparison, the death toll of the 2015 earthquake was a little over 1,100 in Kathmandu city, a small fraction of the city's population of 2.5 million. If any region would seem to have a reason for the emergence of a "seismic culture," one would think that Nepal would be close to the top of the list, along with neighboring Bhutan, Tibet, Indian and Pakistani Kashmir, and Afghanistan.

The question, which applies to both Italy and Nepal, is: why isn't the construction in these two parts of the world more resilient, given the repeated history of earthquakes?

In the case of Italy, the earthquakes have been so frequent in the central and southern parts of the country that there are many within the lifespan of the residents. Human memory of earthquakes within one's lifespan has always been a criterion for the development of what has been called a "seismic culture", that is a set of regulations and social practices, deriving from the practical experience, suitable to face seismic events. Yet, even ignoring the evidence of the mixture of potentially ill-fitting combinations of old and modern technologies described above, the photos also reveal the pervasive use of undressed round stones in the construction of the walls (fig. 2). Italy does possess many exemples of "seismic culture"[7]. However, when finding these piles of round stones from the collapsed walls in Amatrice, one must consider that it would seem empirically obvious to someone in the past that these structures would not work well in earthquakes, just as it would today.

In Nepal instead, the current local knowledge of more resilient forms of construction in masonry has largely been displaced by the belief that reinforced concrete construction is the only way to gain resistance, despite its unfortunate record in many earthquakes previous to the recent ones in Nepal[8].

It was in Srinagar, Kashmir[9], when on a fellowship in India during the 1980's that I first found and became interested in the historic use of timbers laid into the walls of masonry. When I moved to teach in California, where there is a significant earthquake risk, my research revealed that this construction was observed to be effective in resisting collapse in earthquakes that had occurred in the 19th century. There were two timber and masonry vernacular construction systems that proved to be resilient. One, known as *dhajji dewari*, is a timber frame with infill masonry (fig. 3 on right) and the other, referred to as *taq* in Srinagar (fig. 3 on left) and as *bhatar* in Pakistan, consists of masonry bearing walls with timbers that subdivide and reinforce

[4] This earthquake killed approximately 9,000 people and caused the collapse of many heritage structures in Kathmandu and levelled much of many traditional stone masonry settlements in the Himalayan mountains and foothills.

[5] Even while one cannot help but be saddened by the loss of life of thousands and the loss of housing for what is said to be 3.5 million people, it is important to compare it to the previous major earthquake in the Himalayan chain – the Kashmir earthquake of 2005, which killed about 80,000 in Pakistan and about 10,000 in India. This is fully ten times the casualty count of that in Nepal. It is important to note that both the Kashmir quake and the Nepal earthquakes had damage districts of approximately the same size. The magnitude of the April 25 earthquake in Nepal was 7.8, and that on 12 May was 7.3. The 8 October 2005 earthquake in Kashmir was 7.6. Inevitably, one must ask, with this comparison, why the casualties were not greater in Nepal than they were.

[6] Government of Nepal, National Seismologic Center, *Historical earthquakes*, in http://www.seismonepal.gov.np/index.php?linkId=56

[7] F. Ferrigni *et alii*, *Ancient Buildings and Earthquakes. The local Seismic Culture approach: principles, methods, potentialities*, Bari 2005.

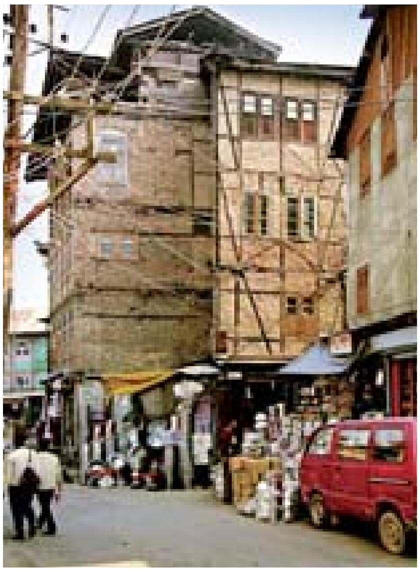
[8] R. Langenbach, *"Katcha is Pucca & Pucca is Katcha: How one of the oldest known construction typologies may be key to preventing pancake collapse of modern reinforced concrete buildings in earthquakes.* A lecture at the World Bank on December 6, 2011, in: http://tinyurl.com/WorldBank-Langenbach

For months after the earthquakes, the news reports were covered with stories and photographs showing collapsed heritage structures

2a, 2b, 2c, 2d/ Amatrice before and after the earthquake of 24th of August 2016. The photo 2c shows the round rock rubble with the image of the pre-earthquake buildings standing above the ruins. 2016).

and describing the breadth of the devastation to national heritage across the Kathmandu Valley. However, a closer look has revealed that the damage was not as sweeping as many of these reports described, and more interesting and pertinent, it has become evident that it could be parsed into one or a number of categories that applied to selected structures which proved to be particularly vulnerable.

[9] The earthquake that struck Kashmir in 2005 was centered on the Pakistan side of the border where the predominant construction – like that in the hills outside of the Kathmandu Valley – was rubble stone with mud mortar, but in the towns and cities it was cement block with reinforced concrete slabs for floors and roofs. As mentioned above, the Kashmir earthquake of 2005 killed approximately ten times as many as did the Nepal 2015 earthquakes. The deaths in Kashmir largely resulted from collapsing concrete frame, or cement block with reinforced concrete slab, or unreinforced masonry buildings, almost all of relatively recent vintage. In this earthquake both the *dhajji dewari* and the *bhatar* systems performed so well that eventually the Pakistan Government was persuaded to accept both methods for the reconstruction of houses in the remote areas of northern Pakistan. Now there are, as reported by UN-HABITAT, at least 150,000 and maybe as many as a quarter of a million new houses constructed in one or the other of these systems. IFRC&RC - International Federation of Red Cross and Red Crescent Societies, *World Disaster Report 2014, Focus on Culture and Risk*. Available at: http://www.ifrc.org/Global/Documents/Secretariat/201410/WDR%202014.pdf; see Chapter 5, “Culture, Risk and the Built Environment”.



3/ Srinagar, Kashmir showing taq *on left, and* dhajji dewari *on right.*

the masonry horizontally. It is the bearing wall system that has the most pertinence to construction in Nepal[10]. It is reported that there are examples in parts of Nepal of buildings with construction like that of *dhajji dewari* but I have not seen any, and there is no evidence that any of these were in the damage district of the 2015 earthquake.

Building techniques and materials in Kathmandu: taq or bhatar, mudmortar and wedge shape bricks

This raises the question of how many examples of the *taq* or *bhatar* system of timber lacing can be found in Nepal. Prior to the 2015 earthquake I saw many examples of masonry coming apart in the absence of tensile members: but after this earthquake I became aware of its existence in a minority of buildings– first through a young engineering graduate, Dipendra Gautam who had written a short paper on it[11], and then, after coming to Nepal, seeing it in the wings of the multi-winged Hanuman Dhoka Palace in central Kathmandu's Durbar Square.

What is particularly interesting about this complex is that the oldest brick colored wings, which date from the 16th to the 18th century, were visibly laced with timber bands, but no such timber lacing could be seen in the later white plastered and painted 19th and early 20th century wings (fig. 4). Moreover, it was those later wings which suffered collapses and heavy damage – far worse than the level of damage found in the earlier wings, which remained intact except for the loss of the top levels of some of the pagoda towers positioned at the intersection of the wings.

Further inspection of the later wings reveals that some of them had timber lacing, but unlike the earlier 16th to 18th century wings, the timbers that had been placed in the walls of these later wings were deeply embedded into the walls and by now had almost completely rotted out, leaving large voids within the walls. These voids contributed to the bowing out and partial collapses of the walls. It was odd to discover this because it would seem to be well known historically that such placement of the timbers in the walls without leaving their end grain exposed would inevitably lead to their deterioration, and that this deterioration would be unseen and thus not fall into a maintenance and repair schedule (fig. 5).

It was interesting to find the same mistake in the post-earthquake "Design Catalogue" published after the 2015 earthquakes by the Department of Urban Development and Building Construction (DUDBC) and produced together with JICA, the Japanese International Cooperation Agency[12]. This volume mandated the placement of embedded vertical timbers in the corners of their model dwelling constructed of stone or brick masonry with mud mortar. This presents the question of whether the buried timbers in the l9th and 20th century wings of the Hanuman Dhoka Palace represents a similar kind of loss of a traditional knowledge as do the buried timbers proposed and mandated by the DUDBC for post 2015 earthquake reconstructions.

Moving away from the palaces in Kathmandu to a less pretentious domestic structure in a rural environment is a house I observed in Dhading District, high in the foothills of the Himalayan Mountains. One of the houses we had a chance to survey was constructed several decades after the great earthquake of 1934, by a family with the last name of Nepal. It also had timber lacing in the walls, which the grandfather who had built it said was recommended to be done because of the 1934 earthquake. The timbers were still intact and sound and the house suffered very little damage in the 2015

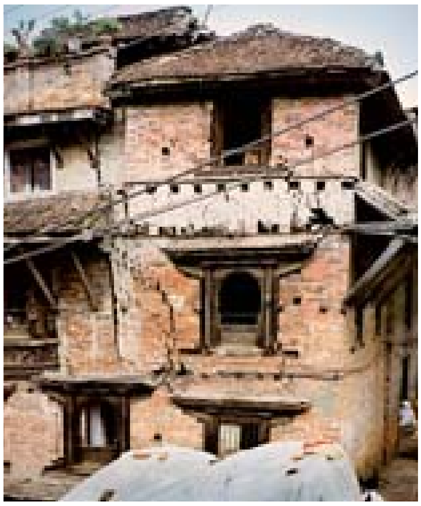
[10] R. Langenbach, *Don't Tear It Down! Preserving the Earthquake Resistant Vernacular Architecture of Kashmir*. UNESCO, New Delhi, 2009.

[11] D. Gautam, *The building features acquired from the indigenous technology contributing in the better performance during earthquake: A case study of Bhaktapur city*, in "Journal of Science and Engineering", 2014, 2, pp. 41-45.

[12] Government of Nepal, Ministry of Urban Development, Department of Urban Dvelopment and Building Construction, *Design Catalogue for Reconstruction of Earthquake Resistant Houses*, Kathmandu, vol. I, October 2015; vol. II, March 2017, in http://tinyurl.com/DUDBC-Volume1

earthquakes. Indeed, the value of timber bands as well as banded construction in general is recognized by the Government of Nepal and the Indian Government as well. It was incorporated into the Nepal Building Code when it was first published in 1994, as it had been in the Indian Building Code before it. The Nepal family house was only about a quarter of a mile from where we were undertaking the reconstruction of a house for another family whose house had collapsed in the 2015 earthquake, as a demonstration of an alternative way of introducing earthquake resistant bands – this time with wire, thus they have been named "gabion bands." This concept was originated because good quality timber was no longer easily available and affordable. This project was filmed and became part of the PBS NOVA television show called *Himalayan Megaquake*, broadcast in the United States[13].

Returning to the heritage structures in Kathmandu, in the months after the 2015 earthquakes, it gradually became evident that buildings which were recently restored consistently survived the earthquake with very little damage. Those which have undergone regular maintenance have also done better than those that had not been maintained. Many of the historical monuments also had been damaged or partially collapsed in the 1934 earthquake. Those that did best in the 2015 earthquake were those that had undergone a subsequent restoration over the past 10 to 20 years, rather than just being reconstructed after the earthquake of eighty years earlier. These included the Malla Period Palace of Fifty-five Windows in Bhaktapur, originally constructed in 1427, and what is now the Patan Museum in the former Malla Period palace in Patan, originally constructed in 1734 (figs. 6-7). The successful ones also included approximately fifty structures restored by the Kathmandu Valley Preservation Trust (KVPT), an International NGO. A large percentage of these KVPT restoration projects were the smaller pagoda-style temples that dot the city and are clustered around the palaces. Of those that were restored, only one had collapsed, and that one had been restored with a reinforced concrete ring beam which contributed to its collapse[14]. At the time it was installed reinforced concrete ring beams were considered to be the



4a, 4b/ Kathmandu, Hanuman Dhoka Palace (4a) built with timber bands. For comparison (4b), this building in Bhaktapur photographed in year 2000 that does not have timberbands. It thus shows the effects not of earthquakes, but of differential settlement.

[13]See: www.traditional-is-modern.net/Nepal.html.

[14] Kathmandu Valley Preservation Trust (KVPT), *Earthquake Damage to Buildings & Monuments Restored. Preliminary Field Report*, May 2015, in http://www.kvptnepal.org/

5-6-7/ *Fifty-five Windows Palace (18th century), Bhaktapur, after the 1934 quake (6a); in year 2000 (6b) showing tilted and deteriorated front brick wall with the windows after being rebuilt without their historic projection after the 1934 earthquake, but prior to the full restoration in 2005; view after the 2015 earthquake (6c) showing no damage. Photo's source:* Images of a Century, *Editor: Andreas Proksch, Deutsche Gesellschaft fur Technische Zusammenarbeit (GTZ) GmbH, 1995*

8-9/ The 1625 Vishwanath Temple in Patan Durbar Square showing the earthquake disruption of the bricks in clay mortar, which left the structure with a dangerous tilt. This temple was restored with a grant from UNESCO after the upper and part of the lower roofs collapsed in 1989, maybe whitout restore the brickwork of this lowest story level. The confining effect of the timber frame work appears to have kept the structure from collapsing. It was left with a noticeable lean, making for a difficult problem for restorers to right it back to vertical without risking its collapse.

10/ Temple in Kathmandu, Dubar Square showing the brick wall with a convex bowing after the earthquake from the wedge shake bricks.

state of the art in seismic retrofit (similar work in Italy has also proven to fail in later earthquakes).

What has also been significant is that there are some construction characteristics that had a big role in resilience. This may all seem to fit with the conventional wisdom that near-term restoration and maintenance would make a difference. However, in this case it plays an outsized role because of a specific characteristic of Nepali heritage construction – the use of mud mortar rather than lime mortar. Despite the fact that limestone is common in Nepal, mud mortar has been the default choice for centuries. For designated heritage properties it often continues to be the choice under the banner of restoration accuracy, consistent with UNESCO guidelines and the Venice Charter.

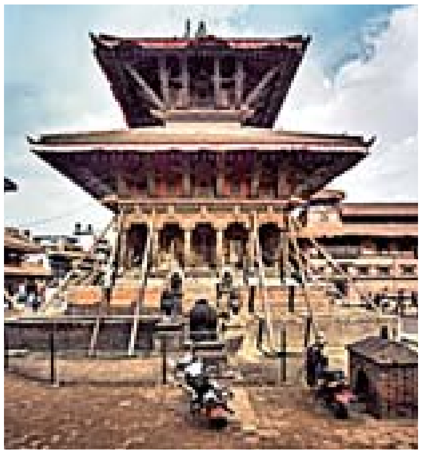
The question raised here is not usually cited by engineers, who often simply recite the truth that mud mortar is a weak mortar. While that is true, weak mortar may actually be an asset, especially because of the fact that the traditionally made bricks in Nepal are themselves quite weak. Strong mortar could have resulted in more collapses from the fracturing of the bricks, leading more rapidly to loss of stability.

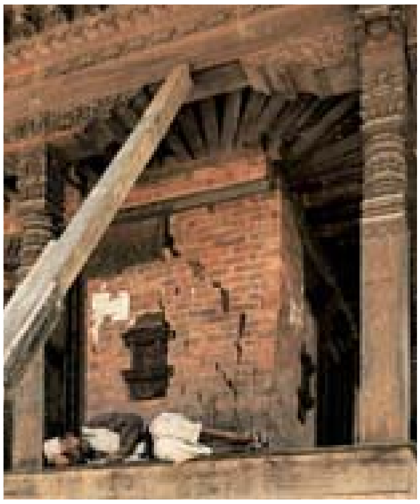
There is one characteristic of mud mortar that may be relevant here, which is that mud mortar may migrate and wash away over the decades to a greater degree than does lime mortar because it does not take on a polymer set and then retain that set indefinitely, as lime mortar does. Lime mortar sets from the reaction between the lime, water and the carbon dioxide in the atmosphere, while mud mortar is only held together by the meniscus forces of water plus a mechanical compression bonding from the weight of the masonry. Lime mortar is made from lime putty without the addition of Portland cement or ingredients which turn it into a strong but more brittle hydraulic mortar. The importance of this is now well understood within the conservation field where one is taught from the first day to avoid the use of Portland cement in traditional masonry construction. This is particularly important where low-strength handmade bricks of the kind still made in Nepal are in use.

One consequence of this problem is that the clay and sandy ingredients of the mud mortar tend to remain in the wall, but they can dry out or wash out and then migrate down through the collar joints and then impart pressure on the outer brick layers of the wall during the earthquake vibrations (figs. 8-9). Lime mortar does this to a much smaller degree, and remains intact over a much longer period of time, sometimes for centuries. The evidence of this phenomenon was clear in the partially damaged walls where the bricks were often found after the earthquake to be loose and jumbled in the core of some walls, with the outside surfaces having been pushed out by the rocking motion and high frequency vibrations.

Another even more unusual artistic feature found in the masonry work of the more important monuments, but which was not found on more ordinary buildings, is the manufacture and use of wedge-shaped bricks for the exterior brick layer (fig. 10). The purpose was to enable the pencil-thin mortar joints that contribute so much to the visual quality of the Nepal historic architecture of the temples and palaces. Such thin joints would otherwise be impossible, particularly with mud mortar, without a method to make for an enlarged space behind for the mortar. The same level of refinement cannot be achieved simply by putting a “frog”[15] in the brick.

The wedge shaped bricks have an unfortunate side effect during earthquakes. The compression forces on this exterior brick layer from the rocking of the whole structure serve to compress the bricks, which forces them into a convex curvature that separates them from the core of the wall – essentially weakening the wall by removing one layer of masonry (figs. 11-12). This prob-





[15] A “frog” is a term-of-art for the depression on one of the flat sides of the brick often with the brick maker’s name in it.

lem is made worse when the mortar has partially migrated out or dried out and shrunk.

This goes along with another visually attractive attribute that is structurally unfortunate during earthquakes: the bond courses are not possible in such a wall if the full visual effect is to be achieved with the thin mortar joints.

This problem does not affect most non-monumental houses and other buildings, but it is particularly severe for the smaller pagoda-style temples which are top heavy, especially because their height and small footprint and the size of the doors in their lowest story reduce the length of the brick walls.

An earthquake – particularly with the long period motion experienced in Kathmandu in these two earthquakes – can cause the whole structures to rock back and forth, which causes the outer wedge-shaped brick outer layer to fall away, and then the softer inner core of the wall crushes from the overburden weight of the rocking mass above, leading to the overturning of the entire structure[16].

11-12/ Small pagoda temple in Kathmandu Durbar Square which almost was toppled by the earthquake, showing the shedding of the wedge shaped face bricks which lack bond courses and bow outwards when compressed during an earthquake.

The modern reinforced concrete frame buildings in the 2015 earthquake

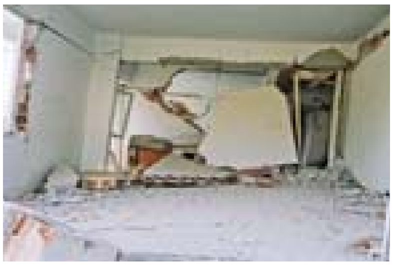
We now return to the questions raised earlier about the performance of the concrete frame-with-masonry-infill structures which now dominate Kathmandu and most of the smaller towns in valleys across Nepal, a story that also relates to the continuing manufacture of soft hand-made under-fired bricks in Nepal. When dealing with the conspicuous extent to which heritage structures crumbled in Nepal in 2015, the proverbial elephant in the room is the still standing buildings of reinforced concrete. Why did the great preponderance of the reinforced concrete frame structures seem to do so well?

It may seem counter intuitive to look to the brick masonry infill in these buildings and the archaic local brick making technology for part of the answer – but I believe that it is precisely these traditional soft under fired bricks that kept many more of these buildings from collapsing. To understand this story we must first turn back a hundred years in time, and go to the opposite side of the planet. Just before 1900, the engineering analysis and calculation of frames became a major new factor in structural engineering, but it took an additional fifteen years or so before the analysis of building frames incorporated the contra-flexure method of calculating the design of steel and concrete moment frames. This method allowed the calculation of the bending stresses on multi-story frames by mathematically separating the frame into parts at each neutral point of bending reversal in the columns and beams. This allows the forces to be calculated using the three equations of equilibrium. Since the masonry could not be included into those calculations, masonry infill was dropped from the engineering analysis and treated only as dead weight. However, masonry was not eliminated from the construction because buildings need walls, but it went from being an accepted and contributing part of the engineering of multi-story buildings to one of corrupting the very behavior on which the calculations for the building designs are based. Here we are a century later, and it is *still* a problem[17]. Then the inevitable question must be why wasn't it more of a problem in Nepal, when it was so conspicuously a problem in many of the previous earthquakes in India, China, Turkey and elsewhere.

There have been many theses written and building codes drafted which explore how best to handle these infill masonry walls, including recommending that the masonry be structurally separated from the frame, despite how difficult that is to accomplish. More recently has been the discovery within

[16] To see the motion of the April 25 earthquake a short distance from Durbar Square in video and GPS plot, see: http://www.traditional-is-modern.net/Nepal/Videos/GorkhaMotion.mp4

[17] R. Langenbach, *Saga of the Half-timbered Skyscraper: What Does Half-Timbered Construction have to do with the Chicago Frame?*, in *Proceedings of the Second International Congress on Construction History* (Cambridge University, 29th March- 2nd April 2006), Newcastle upon Tyne 2006, pp 1845-1865. Id., *The Great Counterintuitive: Re-evaluating Historic and Contemporary Building Construction for Earthquake Collapse Prevention*", in *Proceedings of the Second International Conference on Structures and Architecture* (Guimarães 24th - 26th July 2013), London 2013, pp. 25-41.



13a (top left) / 13b (bottom left) / Chautara, Sindhupalchok, four months after the earthquakes. This building did not collapse during the earthquakes, but it is condemned and under demolition. In this building, the infill brick masonry was only one brick thick, but the kind of crack patterns seen in the upper right view is unusual when compared to recent earthquakes in other countries, which demonstrates the advantages of having softer, slightly underfired bricks laid with a weak rather than a strong and brittle mortar. The evidence of this is the tremendous amount of movement and cracking that occurred along the mortar joints. It is unusual to see such walls subjected to these forces without developing the characteristic diagonal tension "X" cracks which often leads to the collapse of the buildings as seen in Fig 15. (Photos courtesy of Jason Ingham & Dytro Dizhur)

14 (top right) / Golden High rise Condominium Complex, Kathmandu, showing that the brick infill wall thickness is two layers. These failures are concentrated in walls that are outside of the concrete frame so that the bricks were not confined as they are in other parts of the building. The confined masonry contributed to the survival of the structure from collapse. (Photo courtesy of Miyamoto International)

15 (bottom right) / 1999 Kocaeli earthquake, Gölcük, Turkey: A view of an infill wall in a building in which the stories below collapsed after the infill walls suffering brittle failure which is manifested here by with the development of diagonal tension cracks in the high fired, but brittle, hollow clay tile "tula" block infill masonry. These "tula" blocks are now common in Turkey for infill walls. They are made in large modern factories such as that seen in Fig. 17.

the engineering community of what is now called "confined masonry" – where the masonry walls are constructed first and the columns and beams are poured around and onto them. I say "discovery" as this kind of construction simply emerged as an economical and practical form of building, often by poor people who could not afford the scaffolding, shoring, formwork and technical training that is otherwise required. Over time, people began to notice that such buildings often proved to be more resilient in earthquakes than the so-called "engineered" reinforced concrete moment frame buildings around them. Indeed, Earthquake Engineering Research Institute (Oakland, CA, USA) now has a committee to research them – comprised of architects and those engineers with leanings towards accepting empirical evidence[18] .

Why does confined masonry work so well? Two simple reasons: first, the walls, almost by definition, must go to the ground. Because of this, soft story problems only happen if this rule is violated; second, the walls must be as thick as the reinforced concrete columns or else the two sided shuttering does not work. As a result, the walls are thick and carry shear forces to the ground resulting in much less likelihood of building collapse in an earthquake. This leaves the question of whether the "equivalent diagonal strut" of the walls will jack the frame apart. This has been known to happen, of course, but the redundancy of walls in the building tends to be protective because the system is only useful for buildings, like housing, that have many walls, or there is too much need for pre-casting much of the frame without the contribution of the infill walls.

What is interesting is that most of the buildings in Nepal did not have their walls constructed first, but because of the brick making technology and the resulting need for the taller buildings to compensate for the weaker brick by building infill walls two layers thick, they have often performed like confined masonry. Also, most buildings in Nepal also had rooms with walls on the ground floors, a feature which reduces the risk of a soft story collapse.

[18] R. Langenbach, *Rubble Stone Walls and Reinforced concrete Frames. Heritage Structures Reveal the Hidden Truth about Risk and Resilience during the Haiti Earthquake*, ISCARSAH - *International Scientific Committee on the Analysis and Restoration of Structures of Architectural Heritage*, Newsletter Issue, 5, 2014, in https://iscarsah.files.wordpress.com/2014/11/iscarsah-newsletter_5.pdf

16/ Brick kilns photographed in 2000 near Bhaktapur in the Kathmandu Valley. There are now reports that uncontrolled development is leading to a disappearance of the land from which the clay for bricks is made in the Kathmandu Valley.

17/ A "tula" (hollow clay tile block) factory near Afyon, Turkey, photographed in 2003, showing the tula blocks being loaded onto a truck. The broken blocks below the conveyor belt provide convincing evidence of how brittle the blocks are.

18-19/ Two views of Patan taken in 2005, the first of the remarkably beautiful historic Patan Durbar Square World Heritage Site, and the second taken just a couple of blocks from the first well within the heritage district showing the visually disruptive effect of new reinforced concrete construction with brick infill.

After the Nepal earthquakes there were reports of a number of the taller more sophisticated and engineered apartment buildings in which there was a lot of cracking to the masonry infill walls, but in which the post-earthquake engineering surveys turned up no damage to their structural frames what so ever. In a lecture to the New Zealand Society of Earthquake Engineering, Jason Ingham (The University of Auckland) said that for these "more sophisticated buildings, we were getting a lot of questions from the engineers about [whether they should] strip out the brick infills and replace them with infills that did not attract the same amount of cosmetic damage"[19]. These questions from the local engineers are particularly pertinent to the broader phenomenon of how engineering as a discipline has changed in the modern era – distancing engineers from what had for many millennia been the principal system of construction worldwide of all buildings, except for huts and small structures in tropical climates. After witnessing the more extensive failures of such buildings in other countries where the brick making had been fully industrialized, and where the infill walls had been attenuated to single layers of brittle brick as is common in Turkey, China, India, and even Italy, I would strongly advise them *not* to do so. Instead, they should spend their time and effort to recommend to the occupants that they "kiss each crack" because these cracks are evidence that the infill bricks may have just saved their lives. More seriously, in other words they should teach the other engineers and occupants alike about energy dissipation and about the role of the masonry to share the loads with the frame in a unified way. This is exactly what I learned from traditional *dhajji dewari* in nearby Kashmir, and *hımı* in Turkey, and even from *opus craticium*, the ancient Roman construction rediscovered when Herculaneum was excavated.

Learning from the ruins of Chautara in Sindhupalchok District (Nepal)

It is important to note that the ground shaking in Kathmandu was quite different in different soil zones. In many areas in the Kathmandu basin it had, as described above, a combination of very long period sway, with short period vibrations[20]. Many of the lower rise reinforced concrete buildings were most likely less affected by these short vibrations, and the long period sway only resonated with very tall buildings such as the Golden Highrise Condominium (fig. 14). However, in different areas surrounding the Kathmandu Valley with its deep layers of alluvial deposits, the earthquake subjected buildings to different frequencies and intensities. In these other locations the lower rise buildings proved to be more vulnerable. This can be seen in some of the valley rim settlements where many reinforced concrete buildings were tipped over or otherwise destroyed. For example, if they were in areas affected by strong shaking close to their frequency, many of those that had open ground floors did suffer soft-story collapse. One notable example where many reinforced concrete buildings were toppled or otherwise destroyed is Chautara in Sindhupalchok District[21].

In this area, even though in many cases the concrete frames were ruptured very badly (figs. 13a, 13b), the single-brick-thick walls of soft brick masonry in this compromised condition did not collapse out of their frames and may account for why these buildings did not pancake collapse. My hypothesis is that in Nepal in 2015 the bricks saved many of the reinforced concrete frame structures in Kathmandu, even though the frames, not the walls, were constructed first as the term-of-art "confined masonry" is meant to signify. The frames in much of the Nepali construction can be found to have acted much as they would in confined masonry – particularly in the taller buildings which

[19] New Zealand Society of Earthquake Engineering Nepal Earthquake LFE Seminar-03) Prof. Jason Ingham, 23.07.2016, in https://www.youtube.com/watch?v=7mFeNu3BVEA

[20] See http://www.traditional-is-modern.net/NEPAL/Videos/GorkhaMotion.mp4

[21] Sindhupalchok District was the district with the largest number of casualties from both earthquakes. Here, as documented by Jason Ingham and Dmytry Dizhur (The University of Auckland, New Zealand), a much larger percentage of mid-rise and low-rise concrete frame buildings were destroyed. Having arrived after initial demolitions were underway, they managed to look into and photograph some of the rooms from the street. Their photographs show the post-elastic fracturing of the infill masonry walls.