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Editorial: High Building Standards in Chile

Last week the 16th World Conference on Earthquake Engineering was held in Santiago, Chile. Almost 3000 delegates from many countries prone to earthquakes gathered to learn about almost any aspect of earthquake engineering.

As would be expected by virtue of the conference being located in Chile, that country's seismic performance came under some scrutiny. For example, one keynote speaker described the seismic performance of concrete buildings while another shared the Chilean experience of confined masonry.

Findings from these speakers is relevant to us all because of Chile's very high level of seismicity. The country is long and narrow, and bounded along its coast by the Pacific trench where the Nazca Plate subducts under the South American Plate. Chile is reputed to have the highest level of seismicity in the world. Magnitude 8.0 or greater earthquakes occur less than every 100 years. And yet, in spite of these very large earthquakes, modern buildings have performed very well indeed. So what is the secret of Chile's success?

First, it has to be acknowledged that like in all countries, Chile's unreinforced adobe and masonry buildings have not performed well. Very high numbers of these buildings have collapsed during previous earthquakes. However their replacements and other new low-rise construction built in confined masonry, introduced in the late 1930s, have performed well even though no Chilean code for confined masonry was available before 1986. Usually, where confined masonry buildings have suffered heavy damage some aspects of recommended guidelines were not adhered to. In some case those buildings would be classified as only 'partially confined'.

The second reason for the very sound performance of Chile's engineered buildings is due to the inclusion of structural walls as the main system for resisting horizontal loads. Most buildings are of reinforced concrete and both residential and office buildings rely on shear walls for their seismic resistance. In residential buildings, partition walls often consist of RC shear walls, while in office buildings shear walls form a structural core near the centre of the buildings' plans. The shear walls lead to buildings that are strong and stiff. Their stiffness against horizontal loads also helps reduce the amount of non-structural earthquake damage. Where RC buildings have suffered earthquake damage it has often been caused by walls being poorly configured. Perhaps a large opening has been inserted or a notch formed at the base of the wall to facilitate circulation or car parking. Vertical structural irregularities like these always reduce the quality of seismic performance.

If you want to learn more about the very fine record of Chile's building stock in large earthquakes then please refer to the following two papers, both from the Proceedings of the 16th World Conference on Earthquake Engineering, Santiago, Chile, January 9th to 13th 2017.

1. *Confined Masonry Buildings: the Chilean experience, by Astroza, M., Andrade, F. and Moroni, M. O., and*
2. *Seismic Performance of Concrete Buildings in Chile, by Lagos, R., Kupfer, M. et al.*

Virtual Site Visit No. 44 Piled raft foundations for a RC shear wall building

On the perimeter of Wellington's central business district a multi-storey office block is under construction. Horizontal earthquake loads dominate the design of the lateral load-resisting elements of this building which in this case consist of RC shear walls. The site is underlain by a soft layer of soil so the first task was to install bored cast-in-situ RC piles (Figure 1). Next a RC raft foundation is prepared. Its task is to collect the tension and compression forces from the bases of shear walls whose ends are not located over piles. At approximately 1.5 m deep it is heavily reinforced to safely transfer wall bending moments and shear forces into the bored piles (Figure 2). It is important that the raft is designed using the Capacity Design principle so that the raft is stronger than the structural elements above. During the design earthquake it is they that should yield, absorb earthquake energy and undergo ductility before the raft experiences damage. While it is possible to repair shear walls, a damaged raft foundation is almost impossible to reinstate. Of course the piles also need to be designed for the maximum possible forces at the bases of the walls for the same reasons.

Figure 2. A worker adjusts reinforcing steel in the raft foundation. The vertical bars are the starters for the shear walls.

Once the raft is poured, including the bottoms of starter bars for the walls, construction of the RC walls proceeds. These walls rise up the height of the building and at each floor level RC diaphragms transfer earthquake inertia forces into them (Figure 3). The floor system consists of precast concrete ribs supporting cast-in-place floor slabs. The ribs resist gravity forces while the floor slabs fulfil two functions; first resisting gravity forces and then acting as a horizontal diaphragms.

Figure 1. Reinforcement for the bored piles projects above the soffit of the raft slab.

Figure 3. Two shear walls near one corner of the building. Other shear walls are placed around the plan to provide strength in both plan orthogonal directions and with reasonable symmetry to avoid excessive torsion.

Comparative Assessment of Performance of School Buildings in the 2015 Gorkha (Nepal) Earthquakes *A summary from the proceedings of the 16th World Conference on Earthquake Engineering, 16WCEE 2017, 9th to 13th January 2017, Paper No. 4657, by B. Pandey, R. Paci-Green, C. Ventura.*

Abstract

The 2015 Gorkha Earthquakes (M7.8 with M7.3 aftershock) destroyed more than 27,000 classrooms and damaged more than 26,000 classrooms in Western and Central Nepal. Several studies in the past had shown the vulnerability of the education infrastructure, resulting from insufficient earthquake resistant elements in school construction. Most of these schools were unreinforced masonry or non-ductile reinforced concrete frame buildings. Since early 2000, several schools have been seismically upgraded and other schools were reconstructed to meet the minimum building standards for seismic loading. The Gorkha earthquakes provided a rare opportunity to study whether those seismic upgrades or rehabilitations had, in fact, improved earthquake resistance as intended.

A study was carried out in the aftermath of the earthquakes to comparatively assess school buildings in four different areas characterised by low, moderate and high shaking intensities. A total of 25 school buildings were assessed in 12 school sites. Field surveys were carried out on school buildings, both those with conventional construction and those with seismic resistant features. Assessed school buildings included stone masonry with flexible and rigid diaphragms, brick masonry, steel truss buildings with brick and stone infill, and reinforced concrete construction. A transect survey of residential housing damage was also carried out around each school site.

This paper describes the results of the assessment and presents the key elements (or lack thereof) that govern the seismic performance of school buildings in Nepal. While most of schools buildings with seismic upgrading – including simple interventions like selective reinforcement, micro-concrete wall jacketing – performed well in the earthquakes, some other buildings retrofitted or considered to be earthquakes-resistant construction were damaged severely. In addition to structural factors in design and construction, the study also looks the aspects of construction standards and norms, technical oversight, quality of material and resource constraints that played role in earthquake-resistance of school buildings. The paper presents a review of those design and construction considerations and establishes key considerations for construction of earthquake-resistant schools in regions with high seismicity and significant resource constraints.

Keywords: schools seismic safety; post-earthquake damage assessment, retrofitting, masonry.

Introduction

The M7.8 Gorkha Earthquake on April 25, 2015 and its aftershocks including M7.3 on May 12 hit hard 14 districts of Nepal across its Western and Central regions. Education sector was among the hardest hit of the disaster. A total of 8,242 public schools were damaged in the earthquake with an estimated losses of US$313 million in education sector alone. The earthquakes destroyed more than 27,000 classrooms and damaged more than 26,000 classrooms and interrupted the education of approximately 1 million children Nepal.

When the Gorkha Earthquake struck on Saturday noon of April 25th, 2015, the schools were closed and a huge fatality among children was thankfully missed. However, it became clear from the damage assessment that the loss of infrastructure due to destruction of school facilities was immense and impacts to education sector were pronounced.

While the earthquake mostly destroyed school buildings built with no earthquake resistant elements in design and construction, it also tested hundreds of school buildings that were seismically upgraded in recent years. Unlike in most low-income countries where school retrofits are initiated only after a devastating earthquake, Nepal had been retrofitting schools for nearly two decades, thanks to advocacy and initiation by dedicated group earthquake engineering and subsequent program that the government implemented with supports from donor community.

In 1999, the National Society for Earthquake Technology-Nepal (NSET) began pioneering school retrofit projects to reduce the risk of school collapse in anticipated earthquakes. NSET's motivation for school safety was not limited to physical protection of school buildings but also to introduction of earthquake safe technology to the society through school system, a strong and visible platform in the communities. Schools could also serve as an opportunity for local masons and residents to learn how to build safer houses using familiar construction materials.

The 2015 Gorkha Earthquake provided an opportunity to assess the approach and method of Nepal's school retrofitting. The effects of the earthquake on Nepal's educational infrastructure serve as field test to study whether previous interventions have resulted in safer schools. In June of 2015, we conducted field assessments and interviews at 12 public school sites. The assessment compared schools that had been retrofitted or newly built as earthquake-resistant with schools built conventionally through the standard Ministry of Education design and construction process.

Nepal's school losses offer a rare opportunity to ask whether simple technical strategies adopted have resulted in safer schools. The primary question considered was: how did damage at purportedly disaster-resistant public school buildings, whether retrofitted or newly constructed, compare to damage of typical public school buildings with no intervention? The study included visual assessment accompanied with interviews of technical persons involved in school construction. In the study, it was also explored whether school retrofit projects do more than physically strengthen a school building and served as change agent to the community towards broader earthquake safety. The second aspect school retrofitting is discussed elsewhere.

URM School Buildings and Their Retrofit

The seismic upgrade of school buildings in Nepal focused mostly on unreinforced masonry wall buildings. A study conducted by NSET in 1999 on public school building stock in Kathmandu valley before launching their school retrofitting showed that more than 60% of buildings were built using traditional materials such as adobe, stone rubble in mud mortar or brick in mud mortar. The remaining school buildings had brick in cement mortar with no reinforcement and only 11% were reinforced concrete with URM infill. Traditional artisans build almost all of these schools without any inputs from an engineer. The major problem of the buildings was lack of connection between different components. Orthogonal walls were not structurally connected, flexible floors were constructed of timber planks or bamboo strips supported simply on timber joists. These joists were not tied up to the walls. Roof made of CGI sheets on timber battens were not firmly connected to walls. Gable walls were not tied to roof structures. Hence buildings were most like stacked material without interconnection. They were susceptible to loosing integrity even in small shaking. As floors and roofs were flexible, the orthogonal walls do not provide stability in lateral shaking. The unreinforced walls may fail in out-of-plane and also inplane damage is expected as they do not have enough shear and flexural tension resistance.

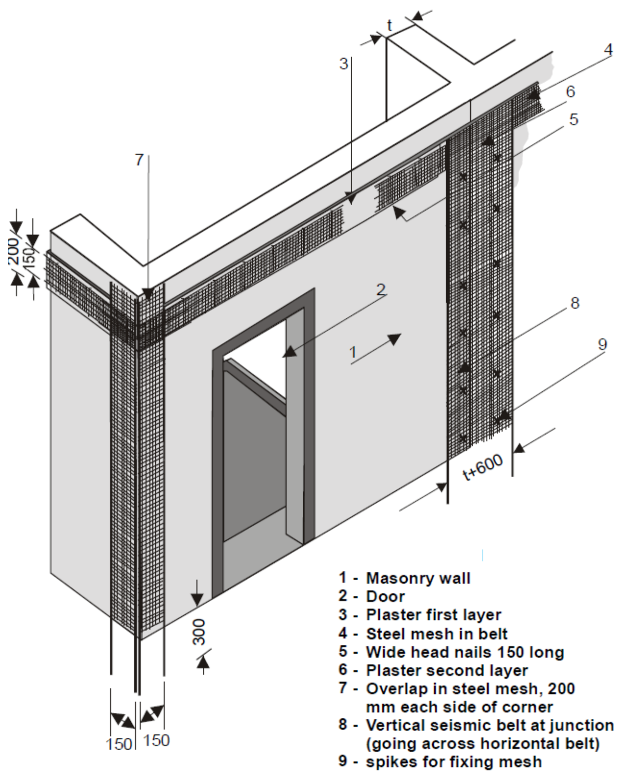

Fig. 4 Splint and bandage technique of retrofitting of unreinforced masonry wall.

Because of the inherent weakness of the URM school buildings and socio-economic condition of the society of the developing country, any strategy of seismic intervention to those buildings should have considered affordability along with safety. That demanded a simple and cost effective seismic upgrade with use of local material avoiding any complex construction system. NSET started seismic upgrade of URM school buildings with selective reinforcement in splint and bandage along with stitching of orthogonal walls. The focus was to enhance the integrity of the building. The connections between orthogonal walls were improved by continuous reinforced micro concrete strips in the corners and T-junctions. The vertical continuous strips, called splints, were provided from foundation to roof level. Similarly horizontal strips, called bandages were provided to run horizontally around all the walls on both side of walls. The splints and bandage were 50 mm thick reinforced micro concrete section applied on bare wall after racking mortar from the brick work joints. The two face of bandages were connected using staggered dowel bars. The bandages were provided at sill and lintel levels. Figure 4 shows a typical construction of splint and bandage.

Fig. 5 Two blocks in same school received different damage in the earthquake.

Survey Method

In four districts, we selected three public schools for the study in close physical proximity,typically within the same Village Development Committee. These schools represented three cases:

i. Standard Construction. The first case in each district was a school, chosen from the Nepal government's Ministry of Education (MoE) database, which had been constructed through standard school construction processes. The school under this category generally lacks earthquake resistant elements in design and construction.

ii. Technical Intervention. The second case was school that had been retrofitted or designed for earthquake resistance, but where the technical intervention had been accompanied by little or no technology outreach to surrounding community. In the Kathmandu Valley, the selected school retrofit projects had been managed directly by the District Offices of Education. The retrofit was carried out by outside contractors and technology transfer aspect is minimal. In Rasuwa and Sindhupalchowk, the school construction or retrofit had been funded by international nongovernmental humanitarian organizations.

iii. Technical Intervention with Community Outreach. The last case in each district was an NSET project school where technical intervention had been combined with community engagement in planning, design and construction.

The selection of schools was facilitated by the National Society for Earthquake Technology-Nepal (NSET)'s electronic list of school locations and retrofit status. Where multiple such schools existed, we selected the school with highest enrolment as these schools often had several school blocks, which allowed for direct comparison of building damage and documentation of multiple school construction projects at a single site. All schools were selected based upon the pre-determined selection criteria, without knowing the level of damage school buildings had sustained. In each district, the three schools were less than 5 kilometres apart to ensure that distance from the epicentre and shaking conditions could be considered substantially similar.

In some cases, different blocks in the same school site provided comparative assessment between buildings. These blocks usually were built from different resources using different method. Figure 5 shows an example of a Kathmandu school site with blocks with different construction systems. Here, two blocks built at same time performed very differently as one block was of unreinforced masonry wall upgraded later for seismic enhancement and other block with reinforced concrete. The reinforced concrete block with no seismic upgrade was moderately damaged and received a red tag. It will need to be repaired before it can be reused for classrooms. The block on the right was recently retrofitted with splint and bandage. It was undamaged and immediately able to be reopened.

Observations

Our field observations begin to explain some of the reasons for the damage and to differentiate between standard, retrofitted, and purportedly earthquake-resistant new construction.

Fig. 6 School building 101-1 experiencing only moderate shaking deemed unsafe.

Standard Construction

When schools were built through the standard construction process, they generally could not be immediately reoccupied; some collapsed. Reinforced concrete (RC) school construction and metal frame construction surveyed generally had minor or moderate structural damage. However, damage to the infill walls was often moderate to heavy. These damaged infill walls caused the school buildings to be closed. Stone and brick school buildings constructed through standard processes generally collapsed.

Infill Wall Damage

Infill walls had unreinforced brick or stone walls which form exterior walls or classroom partitions. During the earthquake, many cracked where connected with beams and columns. Others developed more noticeable damage at corners or even diagonal shear cracks. At the schools observed, the infill walls did not have vertical or horizontal reinforcing steel to support them, a common practice prescribed by international building codes and NBC as well. When they cracked, as is expected in an earthquake, they became unstable because of the lack of reinforcing or other means of holding the walls in place.

These infill wall cracks, although considered minor damage from a structural engineering perspective, were a serious problem in schools (Figure 6). Teachers and principals would demonstrate by pushing on the cracked walls, causing the walls to visibly move. With the risk that these walls could topple over and crush occupants in large aftershock or future earthquake, many schools with infill wall damage were given 'red tags' by Ministry of Education inspectors. A seemingly minor damage relegated untold thousands of students and staff to temporary learning spaces and tents.

Schools with Technical Interventions

School buildings that were said to be designed or retrofitted for earthquake safety generally performed better than other buildings, but not always. In the moderate intensity shaking of the Kathmandu Valley, the retrofitted and earthquake-safe schools observed were completely undamaged, even while other school buildings at or near the school experienced minor or moderate damage. In the heavier shaking of Rasuwa and Sindhupalchowk Districts,

Fig. 7 Complete collapse of retrofitted school building in Rasuwa

school building performance was most variable. Only some of the supposedly safer schools performed better than similar school buildings nearby.

The retrofit addressed the masonry walls of the school only. The retrofit did not jacket and strengthen masonry columns on the second floor balcony or add supports below the masonry columns. Without strengthening these masonry columns, these masonry columns could crumble in a larger earthquake, leaving the overhanging ceiling and floor slabs unsupported and in real danger of collapsing during the earthquake or when students filed out to evacuate.

A retrofit of a rubble stone school in Rasuwa fared even worse – it completely collapsed. The block had been retrofitted by a major INGO using stitch banding technology and the community had been told the school would be safer than any new construction. The project included little training and oversight, and even less adaptation to the limitations of the brittle stone building material. The donor organization sent a trained mason to

Fig. 8 Two neighboring schools in Sindhupalchowk both built through international donor support but taking different approach of community outreach for technology transfer.

the site for only two days to train local workers, none of whom had professional training as masons. During the middle of the construction process, the donor's engineer came only once, briefly. Local workers found it impossible to adapt the stitch band retrofitting technique to stone masonry; they simply could not drill through the stone walls to stitch bands together, but the project implementation had no plan for adjusting the technology or stopping an unsafe solution. The result was a catastrophic collapse (Figure 7). Donor-funded retrofit of a stone and mud mortar school in Rasuwa collapsed in the earthquake, as the principal captured and showed us on his smart phone. The left of Figure 6 was before earthquake and right is just after the earthquake. The rubble had been removed by the time of the survey. Little training of masons and nearly non-existent technical oversight ensured that when masons struggled to implement the retrofit design, the problems were not caught and rectified. The principal estimates 120 out of 140 students and staff would have died. Had technical experts been involved in community outreach, they may have better understood the challenges of stone retrofit in a remote village and may have modified or abandoned the project for something more likely to result in a safe school.

Where local masons were appropriately trained and where trained engineers oversaw the construction practice by very frequent visits or continuous onsite presence, school performed beautifully. They were completely undamaged and few signs of poor construction practice were evident. In Figure 8, the first was built without technical support. The second was built after the community was given an orientation on earthquake safe construction and local masons were trained in safer construction techniques. An engineer and lead mason, bot with experience in earthquake-safe school construction, carefully oversaw the process. After the earthquake, the second was operational; even the terrace had been covered and converted into a makeshift workshop for the local community. Clearly, the social supports of training and oversight are crucial to achieving safe school construction in Nepal.

Rubble Stone Construction

Rubble stone construction in schools is a vexed problem. It is a common local material and essentially free; in many mountain regions it is the primary construction material for schools and houses. Yet, to be used in school buildings, it must be at least life safe since attendance is mandatory and safe evacuation of all students during shaking is impossible.

The widespread rubble stone collapses, even in a case where a lintel band and vertical reinforcement had been used, suggests that constructing safely with rubble stone is fraught with difficulties. Further research is needed to understand how other rubble stone schools with earthquake-resistant features fared and what technical and social intervention seem to have worked well. However, until further testing or comprehensive field assessment, extreme care should be taken in building infill or load-bearing walls with this material in permanent, transitional, or temporary school buildings. Further, even if safe and appropriate technologies for rubble stone are identified, school reconstruction with this material will need to be carefully supported with robust programs for training, oversight and community outreach so that safety is achieved in actuality and communities can trust that these stone buildings will not collapse.

Conclusions

The 2015 Gorkha Earthquake provided an opportunity to assess the approach and method of Nepal's school retrofitting. With comparative assessment of schools built with different approach and methods, following key observations made:

- School buildings retrofitted to be earthquake-resistant generally perform better when coupled with mason training and on-site technical oversight.
- A school retrofit observed, which had been implemented without trained masons and close technical oversight, collapsed.
- School buildings with specific earthquake-resistant designs were observed to have high variability in performance – mason training and close technical oversight was crucial to success.
- Stone walls with mud mortar observed were unsafe, even when communities attempted to retrofit or built with earthquake-resistant features. Further testing or field assessment is needed to assess whether earthquake-resistant techniques used with rubble-stone construction can achieve life safety in schools.
- Unreinforced brick and stone infill walls were a primary cause of school buildings being 'red tagged' or deemed unsafe for immediate re-occupancy.

Even in simple method of seismic upgrade when executed with enough technical oversight and technology transfer to the community results to a safe school promotes safe community from earthquake hazards.

Earthquake Hazard Centre
Promoting Earthquake-Resistant Construction in Developing Countries

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