Damage Assessment and Seismic Retrofit of Buildings Following the 2015 Nepal and 2016 Ecuador Earthquakes

H. Kit Miyamoto, PhD, SE and Amir SJ Gilani, PhD, SE
Miyamoto International
Los Angeles, CA

Abstract

The M-7.8 earthquakes (Nepal 2015 and Ecuador 2016) caused massive damage to the built environment and affected societies severely. In Nepal, the earthquake caused nearly 9,000 fatalities and destroyed more than 600,000 structures. Economic impact was roughly a quarter of Nepal's GDP and keeps increasing. The Ecuador earthquake resulted in more than 650 casualties and close to 28,000 injuries and triggered the collapse of hundreds of structures; it was even felt in Quito nearly 180 km away. This earthquake severely damaged the 200-kilometer-long coastline. Scores of cities and towns are damaged and economic impact to this small country will be large. Both earthquakes occurred on Saturday during the daytime. This reduced the number of causalities, including schoolchildren. More than 7,000 schools were heavily damaged or collapsed in Kathmandu and several hundreds were damaged in Ecuador. In Katmandu, which is built in an ancient lakebed and was far from the epicenter, site amplification resulted in large spectral acceleration at periods of 2 to 4 sec, which in turn excited the large or tall buildings with fundamental periods in this period range, resulting in significant damage to these modern concrete buildings. After almost one year of political and environmental stalemate, reconstruction is just about to start. In Ecuador, similar to Katmandu, many affected cities such as Portoviejo are situated on soft soil and thus susceptible to site amplification. Not only was older non-ductile construction again shown to be dangerous, but many modern code-conforming buildings sustained structural damage (flexural hinging of members) and nonstructural damage that resulted in the loss of occupancy for these structures. Modern building codes may save lives, but certainly are not able to provide resiliency in communities affected by major earthquakes. Society's expectation is far higher than what is routinely provided by minimum code requirements of life safety.

Introduction

The 2015 Nepal and 2016 Ecuador earthquakes were not extreme events and occurred away from major population centers. Nonetheless, they had unprecedented (but not unanticipated) consequences; see Table 1. In both cases, two key findings, also seen in other recent earthquakes, stand out:

- Structures not designed per modern seismic codes such as unreinforced masonry and nonductile concrete buildings were severely damaged or collapsed. These buildings are dangerous structures and are the primary cause of large fatalities in earthquakes. Seismic retrofit of these buildings is time-critical.
- Buildings designed and detailed using provisions of modern seismic codes protected life and did not collapse, however, they experienced damage causing loss of occupancy and/or operation. These buildings performed as expected according to building codes. Nonetheless, many residents had to evacuate them and thus, from their perspective, the performance was less than adequate.

Table 1. Key consequences of earthquakes

Event	2015 Nepal Earthquake	2016 Ecuador Earthquake
Moment magnitude	7.8	7.8
Fatalities	9,000	670
Injuries	22,000	27,700
Damage	>600,000 structures >500 schools	10,000 buildings >700 schools
Economic impact	$6 billion US	$3 billion US

2015 Nepal Earthquake

Overview

On April 25, 2015 at 11:56 am local time, a M-7.8 earthquake struck central Nepal, near the Kathmandu capital region with a population of 2.5 million. This was the largest earthquake in the area since the 1950 M-8.6 earthquake in Assam, eastern India. The epicenter of this earthquake was located approximately 80 km northwest of Kathmandu, but most of the aftershock activity was much closer.

Strong motion data. In Katmandu, which is built in an ancient lake bed far from the epicenter, strong motion data from the Earthquake; see Figure 1, was available and the peak ground acceleration was approximately 0.10-0.15g. However, site amplification resulted in large spectral acceleration at periods of 2 to 4 sec; see Figure 2. These peaks at larger periods in-turn excited the tall buildings with fundamental periods in this period range, resulting in significant damage to these modern concrete buildings. As seen in the figure, the spectral acceleration demand on buildings; in particular for structures with periods of larger than 1 sec, is significantly larger than the spectrum used to design these structures (NBC 1994 and IS 2002). Accordingly, buildings (in particular mid- and high-rise) designed per code would experience larger forces and displacements than were anticipated. As a result: i) for buildings with ductile detailing, the larger demand would result in plastic hinging and damage and ii) for buildings without ductility, severe damage and collapse could occur.

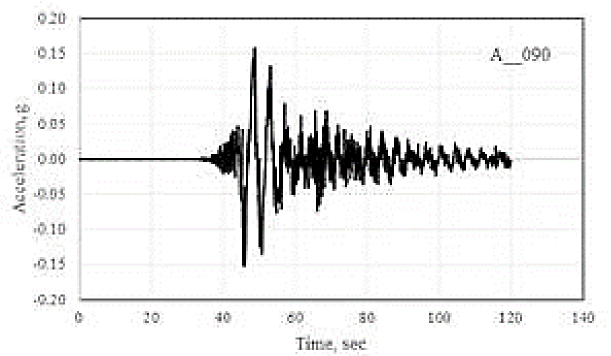

Figure 1. Acceleration record

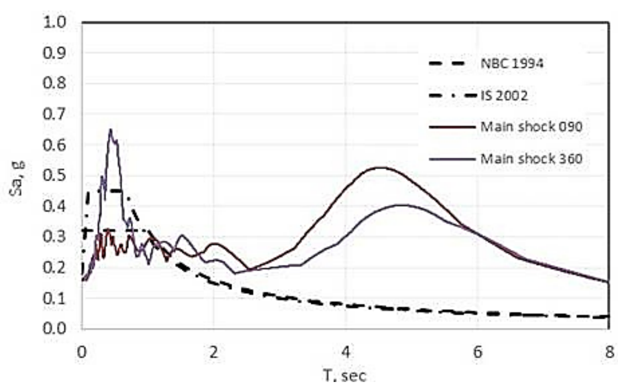

Figure 2. 5%-damped response spectrum

Damage Summary for Schools

In past earthquakes in developing countries, school buildings have been especially vulnerable to damage from earthquakes (Miyamoto et al., 2011). The same was the case in Nepal; see Figure 3 and Figure 4. In the aftermath of the 2015 main event, data from the Department of Education (DOE 2015) was analyzed by the authors. Initial findings are shown in Table 2. It is noted that damage to school buildings was extensive and widespread. Fortunately the number of school casualties was limited because the earthquake occurred on Saturday when schools were not in session.

Figure 3. Collapsed school building

Figure 4. Collapsed school building

Table 2. Initial school damage statistics

District	Kathmandu	Lalitpur	Bhaktapur	Sum
Schools	299	200	126	625
Buildings	673	602	389	1,664
Classrooms	3,604	2,454	1,717	7,775
Students + Staff	166,000	77,500	36,000	27,9500
Damaged	78	149	36	263

schools				
%	26%	75%	29%	42%

Damage Assessment in Everest Region

The Everest region, one of the most popular tourism destinations in the country, is located in the northeast of Nepal. Following the 2015 main earthquake and aftershocks, with funding from the World Bank's International Finance Corporation (IFC) and on behalf of the government of Nepal through the Ministry of Culture, Tourism and Civil Aviation, an assessment team was assembled and dispatched to the region to survey and record the earthquake damage along the main trekking routes. The aim of these efforts was to promote tourism to Nepal, which would support the overall economic recovery and return to normalcy there. The Everest region is located approximately 200 km from the epicenter of the main shock and 60 km from the main aftershock. This region experienced the level of shaking of MMI of V to VI. In the Everest area, typical hotel construction used either wood or bearing wall systems. Traditional buildings used bearing walls of uncut stone with mortar and bearing walls of cut rectangular block stone with or without mortar (mud and cement for older and newer buildings). Some accommodation structures in Everest utilized horizontal concrete bands spaced intermittently in the stonewall construction.

The level of damage in traditional construction depended on the construction practice. The buildings with stone and mortar generally performed well. By contrast, in older buildings where either no mortar was used or when mud was used as mortar there was significant damage. For these buildings, see Figure 5, the out-of-plane failure of walls was the most common mode of failure, where stone walls fell over or stones fell out, generally at the top of the walls. Since these bearing walls carry both seismic and gravity loading, their out-of-plane failure can compromise the gravity load path and can result in collapse of roofs and floors. For the surveyed buildings, a secondary wood beam supporting the roof was observed in many of the buildings. This member supported the roof after the failure of walls and prevented collapse of the roof. For an example of an accommodation structure built with cut rock, cement and ring beams that performed well; see Figure 6. Wood structures were mostly undamaged. The structural assessment of the buildings was conducted in accordance with the internationally recognized ATC-20 (ATC 2005) and the national guidelines for post-earthquake damage assessment specified by the Department of Urban Development and Building Construction (DUDBC) of the Government of Nepal. Out of approximately 710 surveyed buildings, earthquake damage of structural concern was observed in 120 buildings (17 percent); 83 percent of buildings were given a green tag per ATC-20 and DUDBC guidelines. It was found that most of the damaged buildings were repairable.

***Figure 5.	Out-of-plane failure of wall building***

***Figure 6.	Undamaged accommodation building***

Seismic Evaluation and Retrofit of Mid-rise Buildings in Katmandu

As mentioned previously, the soft soil underlying the Katmandu region produced large spectral accelerations in the 1-4 sec period range and excited mid-rise buildings. Many of these buildings are of newer construction vintage and had ductile detailing, and as such did not experience collapse. However, damage to these tower buildings was widespread; see Figure 7. Most of the mid-rise buildings used reinforced concrete moment framing as the lateral force resisting system. In addition, unreinforced infill walls were used for these buildings. The damage to the infill walls was extensive; see Figure 8, which caused the tenants to relocate temporarily from these units. It is noted that these are high-end condominium units.

Figure 7. Exterior cracking, tower

Figure 8. Interior diagonal cracking of infill walls

Seismic Retrofit of a Mid-rise Building in Nepal with Viscous Dampers

The new 70m tall hotel building has 15 stories and 3 basement levels, see Figure 9, reinforced concrete moment frame exterior shear walls comprises the lateral load resisting system. The structure was designed per IS 2002. Following the 2015 earthquake, it was decided to add the additional requirement of limiting the drift ratios to approximately 1.5 percent for a seismic event comparable to that earthquake. As shown in Figure 10, the building nearly met this criterion in the transverse direction. However, in the longitudinal direction, at the lower three levels, drift ratios exceeded this limit. To reduce the drift ratios, viscous dampers were added at these levels along the longitudinal direction. As shown in the figure, in the new configuration, drift ratios were limited to approximately 1.5 percent.

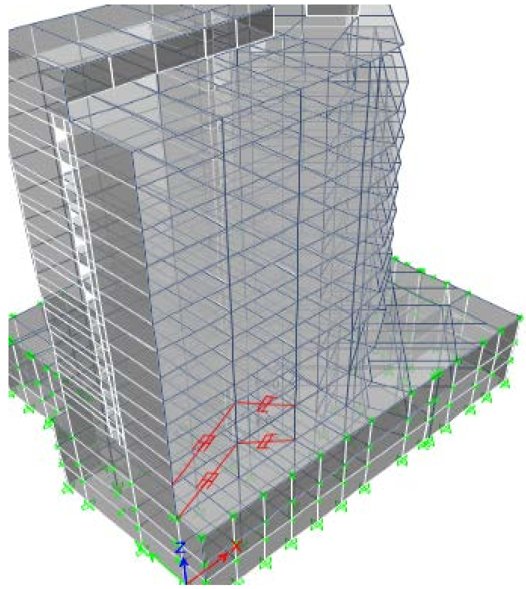

Figure 9. Building model

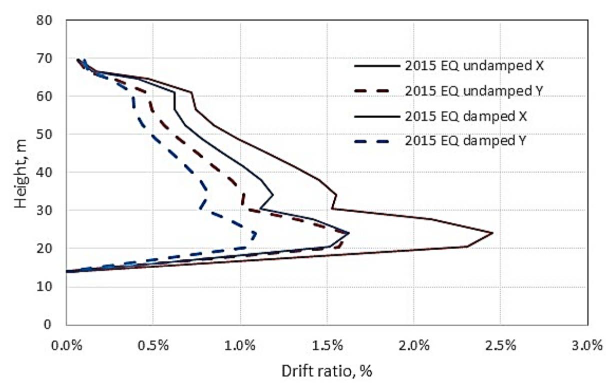

Figure 10. 2015-earthquake analysis

2016 Ecuador Earthquake

Overview

On April 16, 2016 at 18:59 local time, a M-7.8 earthquake struck coastal Ecuador, near the towns of Muisne and Pedernales and 170 km away from Quito, where it was felt strongly. There was significant damage in the areas close to the epicenter of the earthquake.

Earthquake Damage Survey

In the aftermath of the earthquake, a reconnaissance team comprised of local civil and structural engineers was assembled and visited the impacted area to survey the damage, document findings and assist the locals with damage assessment and recovery. The findings are summarized here. At the time of the team's visit, the damage estimates included that some coastal area communities were 80 percent destroyed, however, some of the smaller coastal communities had not yet even been reached. The team met with local officials and discussed the process of training local engineers in conducting ATC-20 (ATC 2005) damage assessments.

Portoviejo

Portoviejo's previously vibrant downtown of 223,000 citizens was a fenced off, 40-block red zone; see Figure 11. More than 200 people died in this city. In the red zone, heavy machinery was used to tear down damaged structures. A command center was set up on a campus. The recovery organization team and the prepared map of damage zone was quite adequate. The local officials had a plan to identify and demolish the dangerous buildings and then reduce the size of the corded-off zones to allow normalcy to return to the city. It was also envisaged to set up a public-private partnership to assist in recovery and seismic-retrofit efforts. A drone was used to conduct aerial reconnaissance and prepare a detailed damage assessment map. The buildings were marked in green (inspected), yellow (damaged, limited entry), red (dangerously damaged, do not enter) and black (collapsed).

Figure 11. Downtown Portoviejo

The team was divided into two teams and conducted damage assessment. Overall, 50 to 60 percent of buildings appeared undamaged and 30 percent had slight to moderate damage. The remaining 10 to 20 percent of buildings were severely damaged or collapsed. A multi-story tower building, see Figure 12, was severely damaged and presented life safety hazard to nearby buildings and the adjacent street.

Figure 12. Multi-story damaged building

The municipal building, housing the mayor's office, was damaged. However, the damage, although substantial, appears repairable and primarily is nonstructural. The building framing, including reinforced concrete columns, was undamaged. The damage to nonstructural components and contents, including furniture and cabinets was widespread. Next, a nearby school building housing 400 students was inspected. At the ground floor, structural damage was limited to superficial cracking of walls and concrete framing was intact. Upstairs, an interior brick wall dividing classrooms had collapsed and had fallen in one of the classrooms; see Figure 13. Fortunately, the earthquake occurred on a Sunday when the school was not open.

Figure 13. Infill wall failure school building

A communication company's building also had collapsed. Nearby, the upper-floor of a four-story building had collapsed into a two-story apartment building. The residence itself was undamaged except for the repairable damage caused to its roof by the impact of the adjacent structure.

To provide training, local assessors were incorporated into assessment teams. The groups then conducted damage assessment surveys of some buildings to provide first-hand training so local engineers and volunteers could then continue the work for the rest of buildings, see Figure 14.

Figure 14. Damage assessment training

The Centro Municipal Commercial, taking up an entire city block, is a popular downtown market and includes a large department store on one floor, with small, subterranean independent vendor's stalls below it and an eight-floor office building. A large section of the market was severely damaged. The damage interrupted business for more than 180 vendors on this site and caused economic hardship. Damage assessment of the building was conducted. The older part of the building is the eight-story portion, and the department store is the new addition. The eight-story tower only sustained minor damage. However, sections of the market were deemed unsafe by the team, see Figure 15.

Figure 15. Damaged market

Bahía de Caráquez

Bahía de Caráquez, located on a sandy peninsula at the mouth of the Chone River, suffered heavy earthquake destruction. A row of tents was set up to house displaced people from damaged buildings and others who were frightened to return home. The exterior wall of a five-story building was on the verge of out-of-plane failure. In the downtown area, about one-third of the buildings were severely damaged or collapsed. Next, we visited two eight-story twin towers that had been recently constructed. One tower appeared undamaged, but the second building had suffered complete collapse and caused 12 fatalities. Such occurrences, noted in previous earthquakes, are attributable to variations in site condition, architectural detailing, material quality and means of construction. In a neighborhood of oceanfront high-rise condominiums, nearly all towers had exterior cracks. There were no fatalities, however, the extent of damage hampered recovery efforts. In one of the towers, there was major cracking of infill walls, see Figure 16. However, the concrete columns appear to have suffered only limited damage.

Figure 16. Damaged plaster and infills

Pedernales

The coastal town of Pedernales, with 172 fatalities, was perhaps the worst hit by the earthquake. Many buildings collapsed here including a number of reinforced concrete structures with questionable material, inadequate strength and detailing, see Figure 17.

Figure 17. Poor detailing of reinforced concrete

Chamanga

Chamanga is a humble fishing village tucked into a bay. Typical houses are rotted wood or concrete. The area regularly floods and sits in a tsunami zone without a warning system. More than 50 percent of the buildings collapsed, see Figure 18, and 6,000 people were living in temporary tents. One of four schools, constructed of bearing walls and a tin roof, had collapsed walls. Locals said the other schools had performed similarly.

Figure 18. Partially collapsed school, Chamanga

Application of BRB to a Mid-rise Building in Ecuador

The 41m tall building has 7 stories and 2 penthouse levels, see Figure 19. Reinforced concrete moment frame comprises the lateral load resisting system. Typical beams measure 350 x 450 mm and square columns vary in size from 450 to 700 mm. The structure was designed per Ecuador building code. Following the 2016 earthquake, it was decided to add the additional requirement of limiting the drift ratios to approximately 1.5 to 2 percent for the MCE event. BRBs were added to the building model, see Figure 20. As shown in Figure 21, the drift ratios for moment frame alone exceeded this limit and were 2.8 percent at the middle of the building. To reduce drift ratios, BRBs were added to the building and this reduced the maximum drift ratio to approximately 1.8 percent.

Figure 18. Photograph of mid-rise building

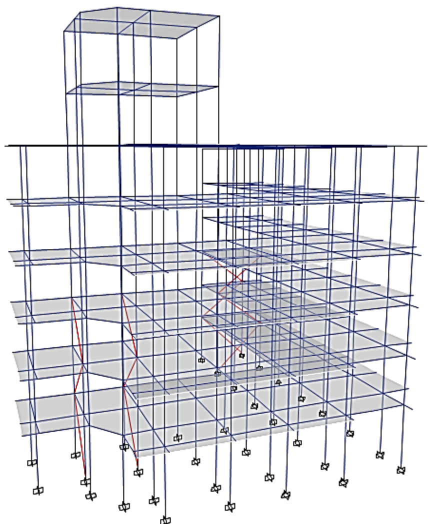

Figure 19. Building mode

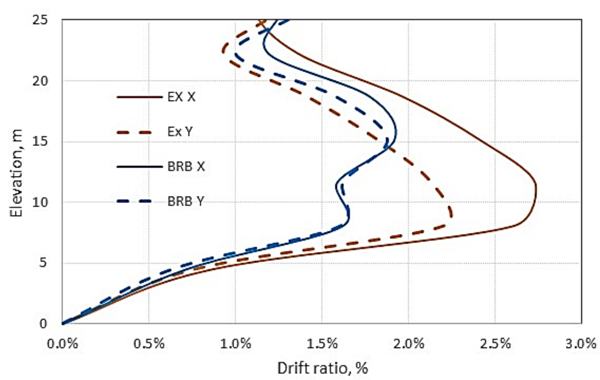

Figure 20. MCE analysis

Conclusions

The 2015 Nepal and 2016 Ecuador earthquakes resulted in significant casualties, collapsed buildings and economic losses. Although the countries have different construction practices there were many similarities in responses.

- School buildings were hard hit, similar to recent earthquakes elsewhere.
- Many older URM and nonductile reinforced concrete buildings collapsed.
- Many taller buildings suffered extensive damage to their infill walls.
- New technologies such as dampers and BRB can be used to retrofit tower buildings cost-effectively.

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References

Applied Technology Council (ATC), 2005. ATC-20: *Set Procedures for Post-Earthquake Safety Evaluation of Buildings & Addendum*, Applied Technology Council, Redwood City, CA.

DoE (2015), Department of Education, government of Nepal, *Personal communications.*

IS (2002), Bureau of Indian Standards, Criteria for Earthquake Resistant Design of Structures, *Part 1 general Provisions and Buildings*, New Delhi, India.

Miyamoto, H.K., Gilani, A.S.J., and Wong K. (2011), *Massive Damage Assessment Program and Repair and Reconstruction Strategy in the Aftermath of the 2010 Haiti Earthquake*, Earthquake Spectra, Volume 27, No. S1, pages S219–S237, VC 2011, EERI, Oakland, CA, US.

NBC 105 (1994), Government of Nepal Ministry of Physical Planning and Works, Department of Urban Development and Building Construction, *Nepal National Building Code, Seismic Design of Buildings In Nepal*, Babar Mahal, Kathmandu, Nepal.