EARTHQUAKE HAZARD CENTRE NEWSLETTER

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Contents

Editorial

During last year large earthquakes occurred in Afghanistan, Chile and Nepal. So far, after only the first six months of 2016 we have witnessed even larger earthquakes in Taiwan, Japan and Ecuador. In this issue we feature damage to reinforced concrete frame buildings in the Kumamoto and Nepal earthquakes.

The purpose of highlighting damage to buildings is to remind us designers that the vast majority of existing buildings will not perform well in moderate to large earthquakes. Damage such as shown in the two articles in this newsletter can be expected in many countries. That is, unless buildings are designed, detailed and constructed according to modern codes. Furthermore, the materials and construction standards must be subject to quality assurance in order to achieve good seismic performance. Meeting these requirements is certainly not easy. For example, just designing and detailing a ductile RC frame building requires a high level of engineering expertise as well as a sound structural concept from the architect. If the structure is irregular in terms of column heights and spacing then even the best engineering may not be good enough to ensure safety and the ability to repair the building after a large earthquake.

Both articles from reconnaissance reports illustrate a number of failures that can be attributed to Critical Structural Weaknesses (CSWs). The most common CSW is the soft storey. This is where one storey, usually at ground floor, is weaker than the storeys above. This weakness may be due to one of a number of factors. For example, the ground floor columns may be higher than those of the floors above, some columns might stop at first floor level and 'float', or the ground floor columns might just be weaker than the first floor beams. When earthquake damage concentrates in this weaker storey the columns at that level are forced to sway horizontally so much further than they are capable of. They are damaged by either failing in shear or forming plastic hinges at their tops and bottoms. And this damage reduces the amount of vertical load they can resist – often leading to that soft storey collapsing.

Other CSWs are evident in the buildings damaged by these two earthquakes. Several buildings are badly affected by their torsional eccentricity. Corner buildings are especially vulnerable to this type of damage since their two rear walls are usually so much stiffer than the two open frontages. When buildings twist in plan about the centre of resistance, located near the rear corner of the building, the front-most columns are subject to large horizontal deflections they are usually unable to withstand without severe damage or collapse.

The problem of short or captive columns is also raised. Unfortunately, short columns are by nature brittle. They usually fail in shear and then are unable to carry the gravity loads they have been designed for. This CSW usually results in partial collapse since the walls that cause the shortness of the columns can resist gravity loads and may prevent the floor slabs pancaking. There are also plenty of other examples of seismic damage. Particularly in the Nepal Earthquake, damage to masonry infills plus the damage to RC frames caused by infills was enormous. There is more information about preventing this type of damage in the Virtual Site Visit and in the previous issue of this newsletter.

Virtual site visit No. 42 Reinforced concrete infill frames, Turkey

Figure 1: The front of the apartment building as seen from the street.

Figure 2: An end wall of the building.

In this virtual site visit we consider a reinforced concrete frame apartment building under construction in Turkey. The building is three storeys high, consisting of a RC frame with hollow clay brick infills (Fig. 1). Let's consider its likely seismic performance.

The first issue we notice is the use of masonry infill walls built at the tip of the cantilever slab. First, there is no problem concerning this layout from the perspective of gravity loads. Clearly the cantilever is strong enough to take the dead loads of the wall. It might deflect a little over time as its concrete creeps, but let's assume any additional deflections are within the acceptable range. However there is likely to be a problem during an earthquake. When the ground shakes parallel to the street, because the wall supported by the cantilever is not separated from the cantilever slab above, any horizontal deflection of the floor above will push the top of the wall in the direction of its length. The wall will experience shear forces and its bending moment will induce additional vertical compression and tension loads onto the cantilever. Since the cantilever won't have been designed for the additional compression loads it is likely to fail. Falling masonry will pose a considerable risk to life.

The next issue we note is the possible absence of primary structure to resist loads parallel to the street. The columns and beams of frames normal to the street are clearly seen (Figs. 1 and 2) but there is little strength in the other orthogonal direction. Perhaps the columns nearest to us are expected to form a frame in that direction. But this is unlikely. The front beams do not frame directly into the column. This situation is even worse at the second floor where the beam is set-out from the end of the column. Perhaps there are some concrete walls or a strong RC frame at the rear of the building. That would definitely improve seismic performance, but then quite a high torsional moment would occur due to the resistance in that direction not being placed symmetrically in plan.

Another aspect of this building that is of concern is the hazard created by unreinforced and unrestrained masonry infills. All these walls are likely to perform poorly in an earthquake. Due to both the interstorey deflections of the frames and the inertia forces acting on the faces of the walls it is highly probable that collapse will occur in a moderate to severe earthquake. We just need to look at photos of this sort of construction that are taken during post-earthquake reconnaissance missions to how dangerous it is.

So how might we improve similar buildings? First, we would use non-masonry lightweight walls above the cantilever slabs. Due to their relative flexibility any additional vertical loads they would apply to the cantilever during an earthquake would be negligible. Next we would place a strong moment frame along the front of the building. This would consist of far deeper columns and perhaps deeper beams as well. And finally, we would either separate the infill walls from their frames and provide some them with some type of reinforcement and steel connections to the main structure to prevent collapse, or alternatively design and construct them as confined masonry walls.

How safe is my house?

The full brochure can be obtained from the Philippine Institute of Volcanology and Seismology, www.phivolcs.dost.gov.ph

Below and to the right are two sides (Figs. 3 and 4) from a six-sided brochure intended to encourage homeowners to think about the seismic safety of their houses. Towards the back of the brochure reasons for the questions are elaborated upon. Also photographs of well and poorly built full-scale houses after shaking table tests are provided. Such an initiative to raise homeowners' appreciation of how a seismic-resistant house should be designed and built may well have applications in other countries.

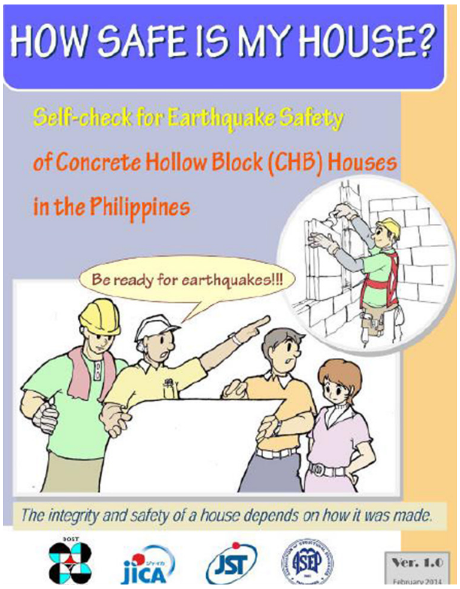
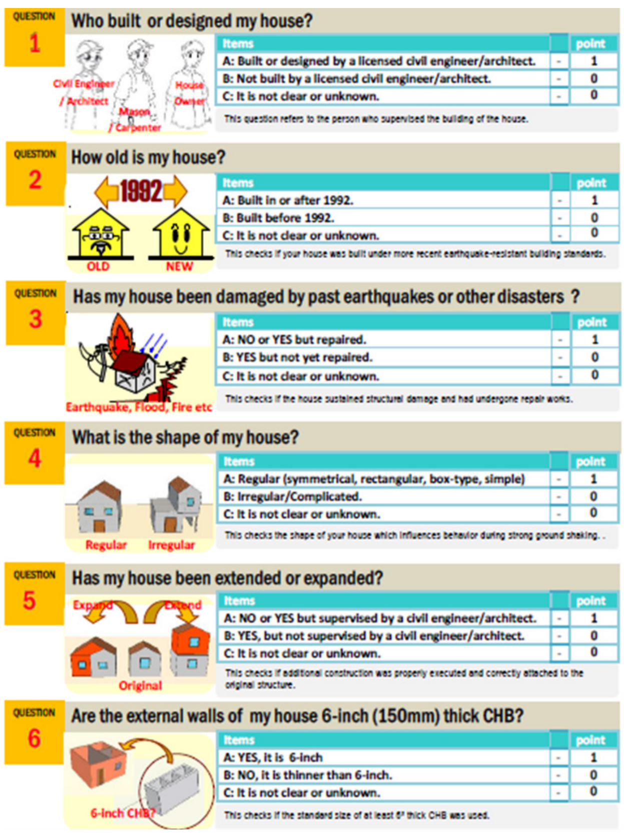


Figure 3: a page from the brochure "How Safe is my House?"



QUESTION 1 Who built or designed my house?

Items		point
A: Built or designed by a licensed civil engineer/architect.	-	1
B: Not built by a licensed civil engineer/architect.	-	0
C: It is not clear or unknown.	-	0

This question refers to the person who supervised the building of the house.

QUESTION 2 How old is my house?

Items		point
A: Built in or after 1992.	-	1
B: Built before 1992.	-	0
C: It is not clear or unknown.	-	0

This checks if your house was built under more recent earthquake-resistant building standards.

QUESTION 3 Has my house been damaged by past earthquakes or other disasters ?

Items		point
A: NO or YES but repaired.	-	1
B: YES but not yet repaired.	-	0
C: It is not clear or unknown.	-	0

This checks if the house sustained structural damage and had undergone repair works.

QUESTION 4 What is the shape of my house?

Items		point
A: Regular (symmetrical, rectangular, box-type, simple)	-	1
B: Irregular/Complicated.	-	0
C: It is not clear or unknown.	-	0

This checks the shape of your house which influences behavior during strong ground shaking.

QUESTION 5 Has my house been extended or expanded?

Items		point
A: NO or YES but supervised by a civil engineer/architect.	-	1
B: YES, but not supervised by a civil engineer/architect.	-	0
C: It is not clear or unknown.	-	0

This checks if additional construction was properly executed and correctly attached to the original structure.

QUESTION 6 Are the external walls of my house 6-inch (150mm) thick CHB?

Items		point
A: YES, it is 6-inch	-	1
B: NO, it is thinner than 6-inch.	-	0
C: It is not clear or unknown.	-	0

This checks if the standard size of at least 6" thick CHB was used.

Figure 4: Another page from the brochure "How Safe is my House?"

Preliminary Reconnaissance Report on Building Damage from the 2016 Kumamoto Earthquake

This article is a portion of an April 24, 2016 report by a team from the University of Tokyo led by Professor Seitaro Tajiri. *The full report may be obtained at http://peer.berkeley.edu/pdf/KumamotoEQ.pdf.*

Seven damaged buildings in the Kumamoto area are presented to show the seismic damage, often caused by critical structural weaknesses. Contemporary designers should do all they can to avoid these types of structural damage.

1. Structure: 7-storey reinforced concrete, without basement, setback on the top floor
Building use: Apartment
Damage outline: Storey collapse of 1st storey
Building description : L-shape floor plan with first floor columns.

- 5 bays in the longitudinal direction and 4 bays in the transverse direction
- 1st storey collapsed due to formation of plastic hinges at the top of the columns in the main shock (Figs. 5 - 7)

Figure 5: South elevation of the building

Figure 6: Soft ground floor or 1st storey collapse in the north east frame

Figure 9: Southern view. The whole ground floor has been lost.

Figure 7: Crushed column in south frame

Figure 10: A crushed column

2. Structure : RC 3-storey building
Building use: Office
Damage outline: First storey collapse

- 4 bay by 2 bay building structure
- West and south facade at the first floor had no walls due to shop windows.
- Longitudinal and transverse reinforcement of column found to be round bars.
- First storey collapsed with the south side of the second floor touching the ground (Figs. 8 - 10)

Figure 8: View from the west

3. Structure: Two-storey reinforced concrete frame
Building use: Office
Damage outline: Shear failure of one of the columns (Figs. 11 - 12)

- Building frame consists of three bays in the longitudinal
- direction and one bay in the transverse direction. Exterior frames on the south and west are infilled with concrete shear walls with small windows.
- Shear failure was observed in a first storey column on the side facing the road.
- No other damage was observed in the structural system otherwise.

4. Structures: Two-storey RC building (south part), Three-storey RC building (north part)
Building use: School
Damage outline: Minor cracks in the school building, flexural failure of the first storey columns of connecting corridor, and buckling of the braces in gymnasium (Figs. 13 – 16).

- Two parallel school building are joined by two connecting corridors. This connecting structure exhibits flexural failure at the top and bottom of columns, and is inclined largely in transverse direction. Residual drift ratio

Figure 11: Overall view from the east of the building

Figure 14: Story drift in the east corridor

Figure 12: Shear failure in a column

Figure 15: Inside of the gymnasium showing the steel

is 6 % in the west corridor, and 20% in the east corridor.

- The south building consists of 8 bays in longitudinal direction and 2 bays in transverse direction. No obvious damage was observed.
- The north building consists of 9 bays in longitudinal direction and 2 bays in transverse direction.
- All the steel braces in the second storey of the gymnasium show buckling. Because the braces are designed to withstand tension and not compression they can be expected to buckle provided they can still resist tension when the earthquake loading direction reverses.

Figure 13: Elevation of the damaged east raised corridor

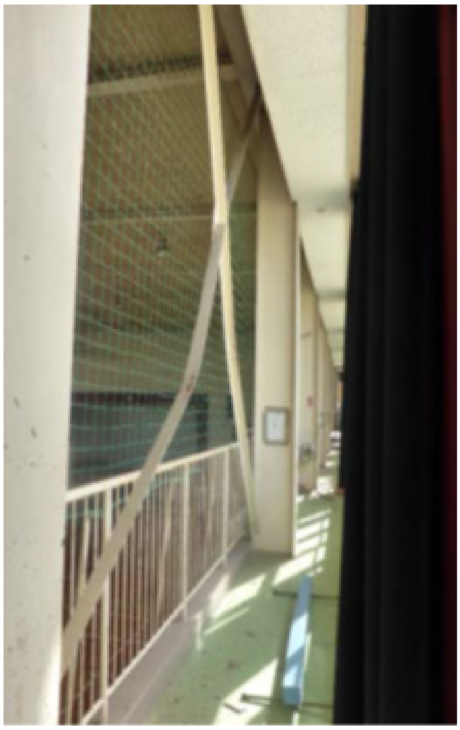


Figure 16: A buckled tension brace

5. Structure: Five-storey RC building
Building use: Commercial and residential complex
Damage outline: Collapse at the first storey

• First floor of the building is for office use and the floors above are for residential use.
• Framing consists of four bays in the longitudinal direction. Outside staircases are located at both gable ends of the building (Figs. 17 and 18)

Figure 17: Overall view of the building from the east

Figure 18: Failure of the southern wall due to the soft storey collapse

6. Structure: Three-storey RC building
Building use: Hospital (dental office) with a penthouse
Damage outline: Collapse of the columned first floor

• Building is supported on stilts, having a parking area and an entrance hall at the first floor.
• Walls are arranged at an angle to the span direction.
• Walls at the first floor are located on the north side eccentrically.
• The south side of the first floor collapsed completely resulting in an inclined building (Figs. 19 and 20)

Figure 19: The soft storey collapse from the north-east

Figure 20: Southern columns crushed in the soft storey

Excerpts from "EERI Earthquake Reconnaissance Team Report: M7.8 Gorkha, Nepal Earthquake on April 25, 2015 and its Aftershocks"

by Bret Lizundia, Surya Narayan Shrestha, John Bevington and others. *See the whole 185 page article on the EERI website, www.eeri.org.*

Performance of RC Frame Structures with Brick Infill

RC frame buildings with masonry infill walls are commonly constructed in urban and semi-urban areas throughout Nepal. Most of the new government buildings and a large number of privately constructed new buildings fall into this category as there is a general perception that such buildings are much safer than the URM buildings. However, most privately built buildings are non-engineered and lack basic earthquake resistant features. Depending on functional requirements, lowrise, medium-rise, and high-rise buildings are all constructed as RC frame structures. RC frame buildings of all heights suffered damage ranging from minor to severe, and even to collapse, depending on their location and configuration (Figure 21).

Damage was more prominent in buildings constructed on ridge tops perhaps due to ridge-top shatter amplification of ground motion. Interestingly, masonry infill walls were found to be more or less intact in large number of buildings that had permanent displacement, implying a foundation failure. Generally, a geotechnical investigation for the project site is not carried out in Nepal, except for some important projects, which often results in inappropriate foundations on slopes. A large number of buildings constructed on slopes collapsed or suffered permanent displacement/tilt due to foundation or slope failure.

Severe in-plane and out-of-plane damage was observed in masonry infill walls of RC frame buildings constructed on proper foundations. These buildings dissipated a large amount of energy by cracking along both the in-plane and out-of-plane directions (Figure 22). Similarly, severe damage was observed in long infill walls due to diagonal and shear sliding crack at mid-height in a school building at Sankhu (Figure 23). As observed in several past earthquakes, such long walls are also quite susceptible to out-of-plane failure.

Figure 21: Damage sustained by RC frame buildings with masonry infills with different heights: (a) three-storey building in Chautara, and, (b) six-storey building in Balaju, (photos: Hemant Kaushik)

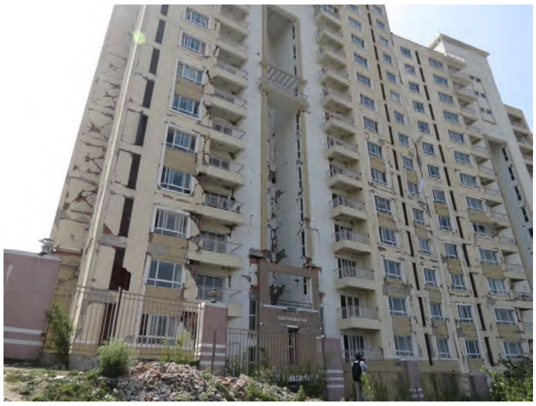


Figure 22: Severe damage to infill walls along both in-plane and out-of-plane directions in the high-rise apartment building at Dhapasi (photo and annotations: Hemant Kaushik)

Figure 23: Severe damage to infill walls due to diagonal and shear sliding crack at mid-height of walls in a school building at Sankhu (photo and annotations: Hemant Kaushik)

Non-seismic reinforcement detailing in RC members was another important reason of poor performance for RC frame buildings. Poor design and detailing in combination with poor configuration resulted in 'pancake' style collapses, failure of beam-column joints, and shear failure of columns near door or window openings due to short column effects (Figure 24).

Poor geometric configurations of buildings further reduced the seismic capacity and redundancy in many RC frame buildings resulting in poor performance. Large overhangs (progressive increase in floor area in upper stories by extending beams/walls beyond column grid lines), trapezoidal plan buildings with one end too narrow, floating columns, and soft stories were quite commonly observed in many buildings; this resulted in severe discontinuities in lateral stiffness, lateral load transfer path, and subsequent failure (Figure 25 and 26).

Figure 24: Poor seismic design and detailing in combination with poor geometric configuration resulted in severe damage in RC frame buildings with masonry infill walls: (a) collapse of a four-story building at Irkhu, (b) failure of beam-column joints in the same building, (c) rupture of reinforcing bars in first-story columns of the same building (photos and annotations: Hemant Kaushik)

Figure 25: Large overhangs in both directions at building in Sankhu (photo and annotations: Hemant Kaushik)

Figure 26: Large overhangs in one direction at building in Dhulikhel (photo and annotations: Hemant Kaushik)

Poor quality of materials and workmanship are other considerations that reduced capacity and exacerbated damage to RC frame buildings, particularly in non-engineered RC construction. At various locations, it was observed that damage was a result of low-quality, non-engineered construction by labourers with insufficient skill, supervision, or both. Unplanned and unsupervised construction practice has also resulted in haphazard construction without sufficient gaps between buildings. Several buildings that were otherwise undamaged by earthquake shaking suffered severe damage due to pounding with adjacent building.

Severe ground failure and cracking in various areas also resulted in damage and failure of several buildings. For example, severe ground cracking and settlement was observed along the Araniko Highway at Lokanthali near Kathmandu. Several buildings sustained severe damage (mostly tilting of buildings due to foundation failure) on both sides of the highway.

Earthquake Hazard Centre

Promoting Earthquake-Resistant Construction in Developing Countries

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