EARTHQUAKE HAZARD CENTRE NEWSLETTER

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Contents

Editorial: Pounding between buildings during earthquakes

This Issue is about pounding. First, there is an article from Pune, India, where the susceptibility of buildings on one of the main streets to pounding is investigated and reported upon. Then a paper describes and analyses the pounding between buildings that occurred during the February 2011 Christchurch earthquake.

During the Christchurch earthquake, pounding was a reasonably common occurrence. The reason for it is straightforward: insufficient seismic separation gaps between buildings, and particularly those constructed before Codes of Practice required such gaps. To a lesser extent more modern buildings can also be affected where they have been provided by separation gaps, but which by the standards of modern Codes are insufficiently wide.

In many earthquake-prone countries seismic separation gaps are small, and so the relatively very generous gaps between buildings in Tokyo, Japan, are exceptions. Even in this city with its extremely expensive land prices, each building is separated from its neighbour by between 300 – 600 mm.

Several approaches for reducing damage caused by pounding are mentioned in the articles of this newsletter, but one other solution worth bearing in mind is that of tying adjacent buildings together. Where the floor diaphragms of such buildings are strongly connected, the two or three buildings so joined will no longer act as individual structures, but as a single entity. Pounding is prevented.

Few buildings have been retrofitted like this but one project using this strategy is about to commence in Wellington. A smaller low-rise building is being tied to a strong taller building next door. Not only will pounding be eliminated, but the cost of retrofitting the lower building is significantly reduced. Of course, any project like this has to be considered on an individual basis and tricky technical and legal aspects need to be very carefully resolved.

Shortly, a class of Fourth Year students from my School of Architecture will be given a challenge like this: how to deal with 'clusters' of buildings by tying them together. In their projects, which are sited along a well-known Wellington street with many historic buildings, they will explore the structural and architectural implications of this approach to retrofitting, and identify opportunities and constraints arising from this strategy to avoid pounding. It may well be that the technical issues will be minor compared to those related to land and building ownership, not to mention the need for the owners of neighbouring buildings to talk to each other and be convinced of the individual and mutual benefits of such an approach.

Virtual Site Visit No. 33: Early stages in the construction of a reinforced concrete apartment building, Wellington.

In this visit we observe the construction of the ground floor structure of a multi-storey apartment building. In this design the lateral load-resisting systems are separated from those that carry the gravity loads.

In the transverse direction, lateral loads are resisted by ductile moment frames. Figure 1 shows five closely-spaced columns and the bottom sections of the moment resisting beams. Beams and columns are relatively deep compared to the gravity-resisting members as can be seen by the reinforcement that projects from the end of the frame. Not only is that beam shallower, but the bottom reinforcement is turned up at the end and there are diagonal bars to transfer the shear force from the end of the beam into the column. This is essentially a pin jointed connection.

In the longitudinal direction, seismic lateral loads are to be resisted by two structural walls. Their vertical flexural reinforcing bars can be seen in Figure 2. They appear to be uniformly distributed along the lengths of the walls. To the right of the walls we can see some gravity-only structure consisting of slender columns supporting a continuous beam.

Figure 3 gives a clearer indication of the gravity-only floor structure. The columns are supporting shallow beams between which span hollow-core slabs. The concrete topping overlay has yet to be poured, but it will ensure a strong floor diaphragm that will transfer all the horizontal inertia forces from the gravity-only areas into the moment frames and structural walls. This diaphragm action allows the columns and beams to be much smaller and therefore more flexible than those in the transverse moment frames, but they still need to be detailed so that they can undergo the horizontal deflections induced in the frames and structural walls without significant damage, and certainly without loss of compression strength.

Fig. 1 One of two moment frames in the transverse direction.

Fig. 2 Vertical reinforcement for the longitudinal structural walls can be seen on the left of the image.

Fig. 3 A view of the gravity load-resisting columns and beams. Hollow-core slabs span between the beams.

LEARNING FROM EARTHQUAKES

A Summary of "Vulnerability Assessment of Building Stock at Historic City of Pune, India, with reference to Pounding Hazard", by Vasudha Ashutosh Gokhale and Deepa Joshi, from the Proceedings of the 15th World Conference on Earthquake Engineering.

Summary

The highly congested building systems in many metropolitan cities constitutes a major concern for seismic pounding damage as observed in past earthquakes. The majority of buildings located in Indian cities are very closely-spaced without adequate seismic separation. Such a building stock has to be identified and analyzed with reference to its vulnerability to earthquake damage to facilitate actions taken for its strengthening, and retrofitting to minimize pounding in case of earthquake occurrence. Pune is one of rapidly growing industrial cities of India located about 175 miles from Mumbai. In the historic city of Pune, with high land costs, the majority of buildings in the downtown are constructed with small or no separations. A large number of such buildings might suffer pounding damage.

Introduction

Building pounding can be defined as the collision of adjacent buildings as a result of seismic excitation. It is a complex phenomenon which requires a detailed knowledge of the dynamic performance of multiple buildings, as well as knowledge of how the buildings will react to very high magnitude but very small duration earthquake forces. Pounding of buildings imposes unexpected impact loading on buildings and may result in minor damage to total collapse of buildings as observed in past earthquakes. Damage to a considerable number of tall buildings in the 1985 Mexico earthquake, and the 1989 San Francisco earthquake is attributed to pounding. This paper presents the current state-of-the-art of building pounding, with particular emphasis on the fundamental concepts of pounding. Pounding of adjacent unreinforced masonry buildings resulting in shear failure of the brickwork leading to partial collapse of a wall was observed during the 1989 Loma Prieta earthquake. Pounding of a six-story building and two-story building in Golcuk, Turkey during the 1999 Kocaeli earthquake contributed to column failure above the third floor slab in the taller building, and shear failure of two second-floor piers in the smaller building. The 1999 Chi-Chi earthquake in Taiwan revealed hammering at the expansion joints in some bridges which resulted in damage to shear keys, bearings and anchor bolts.

Pounding damage was reported after the 2001 Bhuj earthquake in Gujarat, India. Based on the observations from past earthquakes, closely-spaced buildings can experience infill wall damage, column shear failure and possible collapse due to pounding. In Chengdu, a number of buildings greater than 3-storeys were located very close or adjacent to each other, resulting in pounding damage. More severe structural pounding was observed in Dujiangyan and Mianyang.

Case Study : Pune

A highly congested and a major traffic-carrying street "Kumthekar Street" was selected for detailed study. Buildings located on this street are surveyed with reference to floor plan, seismic separation with adjacent buildings, relative position with adjacent buildings, age of the buildings, material and technology used for construction, floor height, building height, facade treatment, presence and type of openings, building facade details, use of building, occupancy, access to the building. Some examples of buildings are shown in Figures 4 to 8.

Fig. 4 Building at Laxmi Road , Pune

Based on the survey, buildings susceptible for pounding damage are identified. It's estimated that 18% out of total 450 surveyed buildings at Pune might suffer pounding damage during major earthquake event.

Seismic Separation

Out of 450 surveyed buildings, 357 buildings were found with zero separation while rest of them have a little separation. Adjacent buildings with floors at different levels: There are 124 buildings identified which have floors at different levels. If a strong or moderate earthquake occurs the floor of one building is likely to collide into the columns of the adjacent building. Adjacent buildings with unequal floor mass: In the selected study area 14 buildings were identified which have an adjacent building with a large floor mass. This heavy building is likely to transfer large momentum into the adjoining buildings which have comparatively light mass and they may suffer large-scale damage. Buildings adjacent to each other: The major part of street has buildings in a row with no or negligible separation. In case of earthquake occurrence the buildings located at the corner are likely to suffer major damage because of pounding.

Conclusions

Based on the survey data and an analysis the potential pounding damage is evaluated. It is found that out of 450 surveyed buildings 14% will suffer pounding damage. Among them;

- 2.4% will collapse,

- 4.1% will suffer severe damage,

- 3.6% will suffer medium damage, while rest of them will suffer minor damage.

Study and analysis of the existing status of building stock in Pune city with reference to pounding damage and presence of seismic separation has found that many buildings are highly susceptible for pounding damage. Considering the potential pounding damage mitigation is urgently required. Buildings which are liable to suffer such damage have to be identified and retrofitted as a top priority in order to save life and reduce property loss in future.

Fig. 5 Building at Pune.

Fig. 6 Building in series, Pune.

Fig. 7 Building with façade setback, Pune.

Fig. 8 Adjacent building with different heights, Pune.

A summary of "Building Pounding Damage Observed in the 2011 Christchurch Earthquake ", by G. L. Cole, R.P. Dhakal, and N. Chouw, from the Proceedings of the 15th World Conference on Earthquake Engineering.

Summary

This paper describes the pounding damage sustained by buildings in the February 2011 Christchurch earthquake. Approximately 6% of buildings in Christchurch CBD were observed to have suffered some form of serious pounding damage. Typical and exceptional examples of building pounding damage are presented and discussed. Almost all building pounding damage occurred in unreinforced masonry buildings, highlighting their vulnerability to this phenomenon. Modern buildings were found to be vulnerable to pounding damage where overly stiff and strong 'flashing' components were installed in existing building separations. Soil variability is identified as a key aspect that amplifies the relative movement of buildings, and hence increases the likelihood of pounding damage. Building pounding damage is compared to the predicted critical pounding weaknesses that have been identified in previous analytical research.

Introduction

While pounding damage is generally accepted to occur during earthquakes, systematic investigation of this type of damage after a major earthquake has been rarely reported in literature. Following the 22nd of February 2011 Christchurch earthquake, two surveys were performed specifically documenting pounding damage. The first survey consisted of a building-by-building external inspection throughout the Central Business District (CBD) three weeks after the earthquake. The second survey was not restricted by area; however the extent of this survey was limited by the amount of time available to the authors immediately following the earthquake. Examples of notable building pounding damage were documented when observed.

It is also noted here that the results of the CBD building survey have been described and analysed in more detail elsewhere (Cole et al. 2012).

Pounding describes the collision of adjacent structures due to the structures' relative movement exceeding their initial separation. Pounding is usually associated with large relative velocities causing a massive and sudden force at the point of impact. However; it may be argued that many buildings without initial separation did not actually 'pound' in the Christchurch earthquake. This is because it is likely that these buildings were in constant contact throughout the earthquake, so a relative velocity between the two buildings never occurred. In such circumstances, the term 'building interaction' more appropriately describes this behaviour. This paper does not make a distinction between pounding and building interaction, since both can have detrimental effects and cause load transfer between the affected buildings.

Since these surveys were limited to external damage, no account of pounding damage between seismic joints, or collisions between structural elements of the same building have been made. However, it is acknowledged that these effects did occur in both the Darfield and Christchurch earthquakes.

Observations of Pounding Damage

Building pounding damage was observed in a small fraction of the overall CBD building stock. Most buildings surveyed within the CBD were observed to have effectively no building separation, meaning almost all surveyed buildings could interact with neighbouring buildings. In total, 6% of the 376 CBD buildings surveyed suffered significant damage that could be confidently attributed to pounding, while two building collapses were tentatively partially attributed to pounding damage. 22% of surveyed buildings were observed to have some evidence of damage due to pounding. The vast majority of significant pounding damage was observed in unreinforced masonry (URM) buildings. The severity of this pounding damage also greatly varied from localised glazing damage to building collapse.

Pounding damage to URM buildings (for example, Figures 9 and 10) occurred sufficiently frequently to enable identification of common damage patterns (Figure 11). Masonry cracking typically extended from the topmost point of contact between two buildings to the nearest window arch or lintel in each building. Cracking frequently extended further from the window opening through to the top of the building's parapet, although this parapet damage was not usually attributed to pounding. Multi-storey buildings occasionally also presented damage at lower floors, although this damage was observed to be progressively less severe as the distance from the topmost point of contact increased. Cracking was also observed to concentrate in stiff lateral elements, such as wall sections with wide spacings between window penetrations (Figure 11).

Occasionally, local crushing of masonry units was observed at the point where two floors collided. When buildings of differing height collided, the floor immediately above the topmost point of contact also frequently suffered notable cracking. Figure 12 presents an idealised load path diagram, which also reflects the typically observed masonry damage distribution. In reality, the damage 'struts' were not oriented at 45 degrees. This angle was instead governed by the building's wall penetrations. Modern buildings generally suffered less pounding damage. This is attributed to the greater building separations adopted in newer buildings and the presence of weaker adjacent buildings (for example, if a concrete reinforced frame building collided with a URM building, damage is more likely to occur first in the URM building due to its weak, brittle properties).

The primary source of pounding damage in modern buildings with separation was instead observed where building separations were infilled with cosmetic flashings (Figure 13). While flashings are intended to cover the gap between adjacent buildings, the detailing of some flashings created stiff and strong elements, which transferred significant force between the two buildings. In some instances the flashings caused failure of adjacent building elements, while in other instances the entire flashing detached from both buildings. Flashing detachment can cause a sizable amount of falling debris when the buildings have multiple storeys. Furthermore, this form of damage can be simply avoided by designing flashings to compress/crush and ensuring they are adequately anchored to one building only. Five instances of significant damage resulting from force transfer through building flashings were observed within the CBD.

Exceptional Examples of Pounding Damage

As was also observed in the Darfield earthquake, very little pounding damage was observed between buildings of

Fig. 9 Examples of URM pounding damage: minor damage.

Fig. 10 URM: Major damage partially caused by pounding.

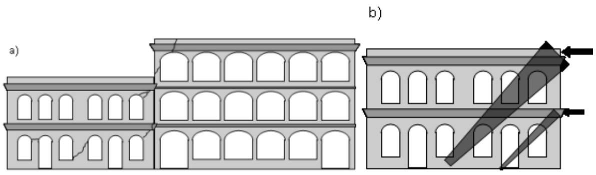

Fig. 11 Damage to URM buildings: typical pounding damage.

Fig. 12 Idealized masonry strut damage. Arrows denote floor collision points of the adjacent building. Width of the shaded zone indicates approximate severity of damage.

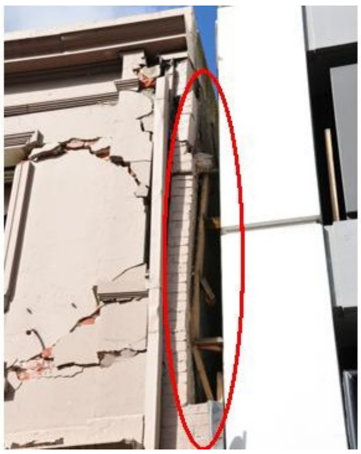

Fig. 13 Building damage caused by framed flashing.

greatly differing overall heights. This is again primarily attributed to the greater separations that generally surround taller buildings. However, Figure 14 presents one building configuration where extensive pounding damage did occur. Pounding between the central building and the taller rightmost building also occurred in the Darfield earthquake. The damage in the Darfield earthquake was minor, although it was noted that this damage occurred in the vertical elements of the primary gravity structure.

The Christchurch earthquake significantly increased the damage in the central building, and also caused damage at the boundary with the leftmost building. At the right interface of the central building the observed damage is predominantly spalling, although cracking also extended below the contact interface. The damage at the left interface is more severe. The masonry column of the central building has been offset approximately 30 mm due to collision with the left building. It is considered that the central building was crushed by the surrounding buildings, primarily due to the greatly differing earthquake response of the taller rightmost building. The range of buildings affected by pounding sometimes extended to buildings where pounding would not normally be anticipated. One single storey building was observed to suffer substantial pounding damage as a result of contact with a neighbouring four storey building.

Two building collapses within the CBD are partially attributed to pounding. Both these cases involve URM buildings that were constructed circa 1900. Figure 15 illustrates the damage caused to a two storey URM building that sustained pounding during the Christchurch earthquake (shown on the left). Significant damage has also been sustained by the adjacent right building. These buildings were externally surveyed after the Darfield earthquake and were found to be separated by approximately 50 mm at ground level, but were in contact at roof level.

It was concluded that the two storey building had begun to lean, although whether this was due to the Darfield earthquake could not be determined. As these buildings were in contact, pounding undoubtedly occurred during the Christchurch earthquake. However, the primary cause of collapse is attributed to the URM construction. Whether pounding appreciably contributed to this collapse is very difficult to determine, due to the level of destruction that has occurred.

Fig. 14 Pounding damage caused by buildings with greatly differing heights. Note image is distorted due to panoramic photography.

Fig. 15 Two storey building collapse involving pounding. Primary cause of collapse is attributed to URM construction.

Fig. 16 Building collapse involving building pounding. Primary cause of collapse is attributed to URM construction. Photo courtesy of Colin Monteath, Hedgehog House.

The damage shown in Figure 16 indicates that the central and leftmost buildings were likely to be constructed with a shared party wall. This can be observed where wall sections remain standing at the building interface. At the second level, a 100 mm thick brick wall appears to have supported both buildings. This evidence is also supported by the interior finishings that can be observed on the 'exterior' of this wall. Nevertheless, localised damage consistent with pounding is present between the central and rightmost buildings. Once again it is difficult to discern the level of influence pounding has had on the presented collapse. The primary cause of collapse is attributed to the URM construction. However, it is credible that the severity of this damage would have been greatly reduced if adjacent buildings had not been present.

Pounding between adjacent buildings can be avoided if a sufficient gap exists. In some cases, however, although the adjacent buildings are well separated, pounding can still take place. This is the case when the buildings are linked by pedestrian bridges. Previous studies on pounding responses between buildings linked by pedestrian bridges in near-source earthquakes have shown that neglecting soil-foundation-structure interaction can underestimate pounding potential and also the induced vibrations in the buildings.

Comparison with Previously Identified Building Pounding Hazards

Previously, six building characteristics had been identified that increase the likelihood of pounding damage. A brief comment is made on each of these characteristics below.

1. *Floor-to-column or floor-to-wall pounding*. Approximately one third of the observed pounding damage occurred between adjacent buildings with differing floor heights. This type of building configuration causes collisions between each building's floors and their neighbouring building's columns or walls. This form of collision is observed to cause more severe localised damage in vertical elements.

2. *Adjacent buildings with greatly differing mass.* Adjacent buildings with greatly differing mass were observed to have suffered pounding damage. However, this damage was not observed to be noticeably different to that of other pounding configurations.

3. *Buildings with significantly differing total heights.* Greatly differing overall building height was observed to amplify damage when contact occurred. However, it was also generally observed that buildings with this configuration usually also presented with greater building separations, which significantly mitigates this hazard.

4. *Similar buildings in a row with no separation.* Unlike the Darfield earthquake, evidences of damage due to interactions of more than two buildings were relatively common in the Christchurch earthquake. This type of damage was noted primarily between buildings with significantly different dynamic properties. Damage between similar buildings was less common, but was occasionally observed in the study. Previous studies have identified similar buildings in a row as being susceptible to pounding damage. In particular, the buildings at either end of the row are vulnerable to additional damage due to momentum transfer from the central buildings. In this study, however, no obvious amplification of end building pounding damage was observed.

5. *Building subject to torsional actions arising from pounding.* Torsional pounding interaction was found to be particularly difficult to identify from external inspection. Only one possible case of torsional pounding interaction was observed in the CBD.

Conclusions

The following conclusions are drawn from the observations discussed in this paper:

1. Pounding damage observed within Christchurch CBD ranged from cosmetic to partial and possibly complete building collapse. Evidence of interactions between adjacent buildings occurred in 22% of the surveyed CBD buildings. However, significant building pounding damage occurred in only 6% of the surveyed buildings.

2. Modern buildings were primarily endangered by pounding when flashings between buildings were constructed with stiff and strong materials that allowed force transfer across building separations. This hazard can be mitigated by using compressible flashings attached to one building (but not both).

3. Severe pounding damage was observed to occur almost exclusively in URM buildings. This is primarily attributed to URM's brittle response to any high magnitude force.

4. While very rare, building pounding damage can occur in buildings as small as one storey.

5. It is likely that the closing relative movement between adjacent structures is amplified by the spatially unequal ground movements due to the liquefaction at local site.

6. The influence of nonlinear soil behaviour on the dynamic behaviour of the adjacent structures and consequently on their pounding potential needs to be investigated.

Reference

Cole, G. L., Dhakal, R. P. and Turner, F. M. (2012). Building Pounding Damage Observed in the 2011 Christchurch Earthquake. Earthquake Engineering & Structural Dynamics **41**(5): 893-913.

Earthquake Hazard Centre
Promoting Earthquake-Resistant Construction in Developing Countries

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