Building Pounding Damage Observed in the 2011 Christchurch Earthquake

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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.

Keywords: 2011 Christchurch earthquake; pounding; impact; survey; damage evaluation

1. 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 (Bertero 1986; Kasai and Maison 1997; Cole et al. 2010a). 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 extent of this survey was roughly bordered by Oxford Tce, Armagh St, Madras St and Tuam St; however the internal streets of the central exclusion zone (bordered by Colombo St, Hereford St, Madras St and Lichfield St) were not surveyed due to safety concerns. This survey was performed in a similar, but more thorough, manner to the pounding survey performed after the September 2010 Darfield earthquake (Cole et al. 2010a). 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.

In this paper, the pertinent features of the CBD survey are presented in a similar format to the 2010 Darfield earthquake paper (Cole et al. 2010a) to allow direct comparison. The effects of subsoil on pounding damage are then discussed and illustrated using damage observed outside the CBD. 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). Readers interested in the details of the survey and its results are recommended to read this reference (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.

2. 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 (Cole et al. 2012). 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.

It is considered that the high frequency and severity of the observed pounding damage is primarily due to the lack of separation between adjacent buildings in Christchurch CBD. The absence of separation is common between older buildings and has been frequently observed in many other New Zealand cities, including Wellington and Dunedin; thereby making them prone to severe pounding damage in a strong earthquake.

Pounding damage to URM buildings (for example, Figure 2.1) occurred sufficiently frequently to enable identification of common damage patterns (Figure 2.2). 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. Multistorey 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 2.2a).

Figure 2.1 Examples of URM pounding damage. Left: minor damage. Right: major damage partially caused by pounding

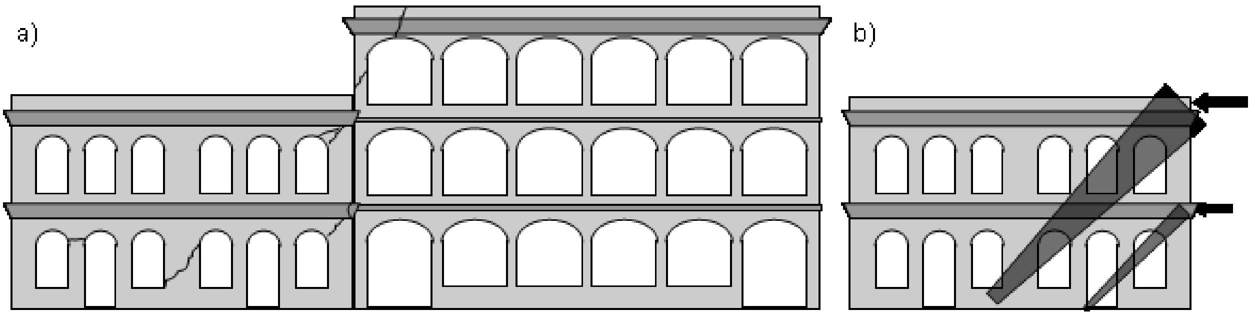

Figure 2.2 Damage to URM buildings. a) Typical pounding damage. b) Idealized masonry strut damage. Arrows denote floor collision points of the adjacent building. Width of the shaded zone indicates approximate severity of damage. Figure reproduced from (Cole et al. 2012).

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 2.2b 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 2.3, Left). 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.

Figure 2.3 Left: Building damage caused by framed flashing. Right: Detail of spalling damage shown in Figure 3.1

Collisions where one building’s façade is set back from the adjacent building’s façade amplified the damage at these locations. This damage was also reported in the Darfield pounding observations (Cole et al. 2010a). Buildings that suffered setback damage in the Darfield earthquake were further damaged in the Christchurch earthquake, however none were observed to cause any catastrophic failures.

3. EXCEPTIONAL EXAMPLES OF POUNDING DAMAGE

As was also observed in the Darfield earthquake, very little pounding damage was observed between buildings of greatly differing overall heights. This is again primarily attributed to the greater separations that generally surround taller buildings. However, Figure 3.1 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 (Cole et al. 2010a).

Figure 3.1 Pounding damage caused by buildings with greatly differing heights. Note image is distorted due to panoramic photography

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 (Figure 2.3, Right), 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 (Figure 3.2). The neighbouring four storey building was substantially damaged during the Christchurch earthquake, however this damage is not attributed to pounding. As a result of this damage, the lateral stiffness of the neighbouring building reduced, causing greater building deflection. It is considered that this effect has increased building damage, although its significance is unknown. Approximately 10 mm building separation was observed between these buildings.

Figure 3.2 Pounding between 1 storey and 4 storey buildings. Damage to four storey building not attributed to pounding

Two building collapses within the CBD are partially attributed to pounding. Both these cases involve URM buildings that were constructed circa 1900. Figure 3.3 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.

Figure 3.3 Two storey building collapse involving pounding. Primary cause of collapse is attributed to URM construction

The second building configuration suffering collapse was also documented after the Darfield earthquake, as shown in Figure 3.4 (see also Figure 2 in (Cole et al. 2010a)). Figure 3.5 displays the damage following the Christchurch earthquake. Figure 3.4 is located at the first floor between the left and central buildings, and is quite possibly the initiation point of the global collapse.

The damage shown in Figure 3.5 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.

Figure 3.4 Masonry damage after the Darfield earthquake

Figure 3.5 Building collapse involving building pounding. Primary cause of collapse is attributed to URM construction. Photo courtesy of Colin Monteath, Hedgehog House

4. EFFECT OF SUBSOIL ON POUNDING DAMAGE

One of the main causes of relative building responses is the difference in the dynamic properties of the adjacent structures. An assumption of spatially uniform ground motions can be justified when the structures are very close to each other, e.g. neighbouring buildings. However, even if all participating structures experience the same ground excitation relative responses will occur owing to their different dynamic properties.

The condition of supporting soil is normally non-uniform. In earthquakes the dynamic soil stiffness is complex. To describe the influence of subsoil on the dynamic properties of the whole soil-foundation-structure system, for simplicity it can be assumed that the soil stiffness is constant, the footing is rigid and the influence of the vertical soil stiffness is negligible. It should be noted that in reality the soil stiffness depends on the vibration frequencies of the footing (see e.g. (Sieffert and Cevaer 1992)), and the stiffness can also be nonlinear due to plastic deformation of soil, e.g. in the case of soil liquefaction. The influence of the subsoil on the fundamental period of the soil-foundation-structure system can be estimated from the following equation.

$$\widetilde{T}_i = T_i \sqrt{1 + \frac{k_i}{k_{ix}} \left(1 + \frac{k_{ix} h_i^2}{k_{i\phi}} \right)} \tag{4.1}$$

where $\widetilde{T}_i$ and T_i are the fundamental period of the i^{th} structure with subsoil and with an assumed fixed base, respectively;
k_i, k_{ix} and $k_{i\phi}$ are the bending stiffness of the i^{th} structure, the static soil stiffness for horizontal and rocking movements of an assumed rigid footing of the i^{th} structure, respectively;
h_i is the effective height of the i^{th} structure;
$i = 1 \ldots n$, and n is the total number of the participating structures.

Equation 4.1 shows that the fundamental period of the whole system is determined by the ratio of the structural bending stiffness to the horizontal soil stiffness, the rotational soil stiffness and the effective height of the structure. In the case of long extended structures, e.g. long bridges, non-uniform site conditions and thus unequal system periods are to be expected also for adjacent structures with the same fixed-base fundamental period.

Even if the foundation of two adjacent structures is the same, i.e. $k_{1x} = k_{2x}$ and $k_{1\phi} = k_{2\phi}$, and the fixed-base fundamental periods of the structures are equal, i.e. $T_1 = T_2$, the adjacent structures will still have different fundamental periods $\widetilde{T}_1 \neq \widetilde{T}_2$ if they have unequal effective heights $h_1 \neq h_2$. Consequently, the two structures will respond differently to the same ground excitation and relative responses will occur.

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 as the buildings at the Christchurch Polytechnic Institute of Technology along the Madras Street in Figure 4.1(a) show. The upper and lower pounding locations are indicated by the circles. The damage due pounding of the upper floor of the pedestrian bridge is displayed in Figure 4.1(b). The residual opening relative movement can also be clearly seen as indicated by the arrow. Figure 4.1(c) shows the damage to the unreinforced masonry wall due to pounding of the lower RC floor of the pedestrian bridge. In the case considered both adjacent buildings have different fundamental periods owing to their dissimilar building configuration, and thus different oscillation patterns are to be expected. Previous studies on pounding responses between buildings linked by pedestrian bridges in near-source earthquakes have shown that neglecting of soil-foundation-structure interaction can underestimate pounding potential and also the induced vibrations in the buildings (Chouw 2002).

(a) (b) (c)

Figure 4.1. Pounding damage to buildings at the Christchurch Polytechnic Institute of Technology. (a) Adjacent buildings with pedestrian bridges, (b) upper and (c) lower pounding locations.

5. COMPARISON WITH PREVIOUSLY IDENTIFIED BUILDING POUNDING HAZARDS

Previously, six building characteristics had been identified that increase the likelihood of pounding damage (Cole et al. 2010b). 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 (see Figure 2.3, Right and Figure 3.1).

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 (for example, Figure 3.1 and Figure 3.5). 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 (Jeng and Tzeng 2000). 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 (Figure 5.1).

6. *Buildings made of brittle materials*. As was also observed in the Darfield earthquake, URM was found to be the defining characteristic of pounding damage in this earthquake. Approximately 3/4 of pounding damage was observed to involve URM buildings. All moderate to large pounding damage was found in URM buildings.

Figure 5.1. Possible torsional building pounding due to irregular plan layout

6. **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.

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