Building pounding state of the art: Identifying structures vulnerable to pounding damage

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ABSTRACT: Due to recent legislation, the past three years has seen a radical increase in the evaluation of potentially Earthquake Prone Buildings (EPBs) in New Zealand. Using the Initial Evaluation Procedure (IEP), EPBs' vulnerability to seismic pounding must be assessed. Engineers currently have little knowledge of this highly specialised field. This paper aims to assist engineers undertaking either preliminary or in depth assessment of buildings with pounding potential. An international state of the art review is presented with particular emphasis on the loadings caused by pounding. Floor-to-floor collisions are identified as a fundamentally different process to floor-to-column collisions. Current methods of building pounding assessment are reviewed, specifically assessing each method's applicability and weaknesses. Existing mitigation options are also evaluated in terms of practical application to existing structures. Finally, critical building weaknesses that are vulnerable to pounding are presented. It is intended that this paper will provide a useful contextual background on pounding for all engineers using the IEP or higher order analyses.

1 INTRODUCTION

Building pounding describes the collision of adjacent buildings as a result of some form of excitation; typically seismic excitation. This phenomenon has been the subject of much research over the last 20 years. Unfortunately, almost all of these works have been contradicted by other researchers at some point. This is mainly due to the high level of complexity inherent in the problem. Characterising pounding 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 impulsive forces. Pounding is thus very expensive to model physically and very complicated to represent analytically. This paper presents the current state of the art of building pounding, with particular emphasis on the fundamental concepts of pounding. Pounding building scenarios can be generally categorised as either floor-to-floor or floor-to-column pounding (Figure 1.1). Modelling methods for each category are presented in separate sections, which explain in detail the simplified modelling techniques, methods to estimate required building separation, mitigation methods, and vulnerable building configurations. References to experimental data are also provided.

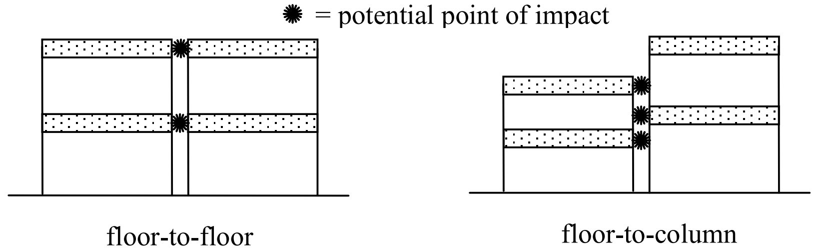

Figure 1.1 Pounding categorisation

2 MODELLING FLOOR-TO-FLOOR COLLISIONS

Research in pounding has predominantly focused on the analytical modelling of buildings. The general floor-to-floor modelling method consists of either a single node, or multiple nodes slaved together, to create a rigid diaphragm at each floor of each building (Mouzakis and Papadrakakis 2004; Muthukumar and Desroches 2006; ULIEGE 2007).

2.1 Modelling using stereo mechanics and rigid diaphragms

Studies aimed to investigate pounding of buildings invariably require a method to represent contact between the buildings. Early research typically used the theory of stereo mechanics to represent contact (Conoscente 1992 for example). While this method is infrequently used nowadays, it introduces an important concept. Stereo mechanics determines the post-collision velocity of lumped masses when contact occurs by considering conservation of momentum over the duration of impact (Goldsmith 1960). Typical mathematical expressions for post-collision velocities of two colliding objects based on stereo mechanics are;

$$v_1' = v_1 - (1+e)\frac{m_2}{m_2+m_1}(v_1 - v_2) \quad \text{and} \quad v_2' = v_2 - (1+e)\frac{m_1}{m_1+m_2}(v_2 - v_1) \quad (1\ \&\ 2)$$

where v_1 = initial velocity of mass 1; v'_2 = final velocity of mass 2; m = object mass; and e = coefficient of restitution. The coefficient of restitution is a measure of plasticity in the collision. If e = 1.0 then the collision is completely elastic. If e = 0.0 then the collision is completely plastic and the two masses end up with the same final velocity and remain in contact. Stereo mechanics has two major drawbacks;

1. The equations of stereo mechanics are applied when contact occurs and thus an instant collision is modelled. This means contact force, contact floor acceleration, or contact duration cannot be calculated.
2. Stereo mechanics can not be easily incorporated into time history programs. Its use generally requires rewriting of a program's code since the node velocity (not the node displacement) is updated by Equations 1 & 2.

2.2 Modelling using contact elements and rigid diaphragms

Typically a contact element is used instead of stereo mechanics because it can be directly incorporated into time history analysis programs as a conditional spring and dashpot element. Contact elements provide no force to either structure until a specified initial separation is closed. At least four different contact elements are available (Jankowski 2005; include a reference for the fourth), but the damped linear spring is the most common (Figure 2.1). This element uses a linear spring of stiffness k and a linear dashpot with damping constant c.

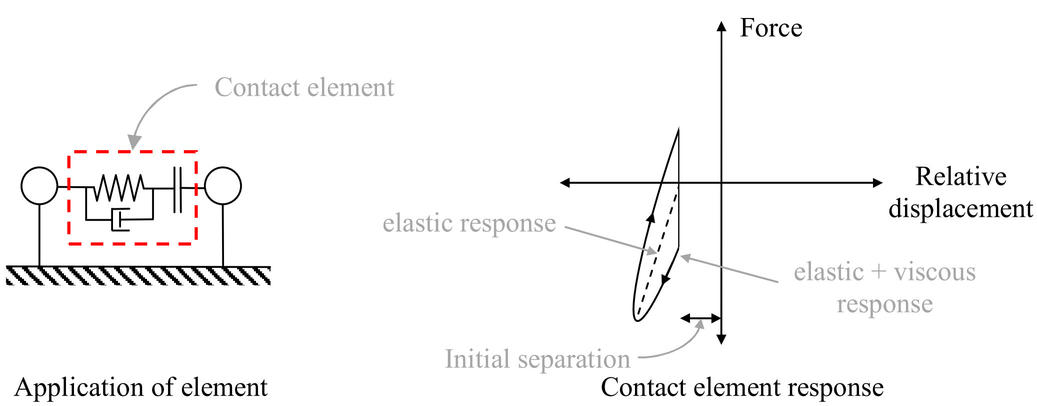

Figure 2.1 Linear contact element characteristics and application

One major advantage of the damped linear contact element is that the damping constant can be related to the coefficient of restitution. This is derived by considering the system's energy before and after the contact (Anganostopolous 2004);

$$c = 2\zeta\sqrt{k\frac{m_1 m_2}{m_1 + m_2}} \qquad \text{where} \qquad \zeta = -\frac{\ln e}{\sqrt{\pi^2 + (\ln e)^2}} \qquad (3\ \&\ 4)$$

where k and c are the linear stiffness and damping constant, respectively, and ζ is the damping ratio for the collision element. Building pounding researchers usually express collision damping in terms of the coefficient of restitution; e. Recommended value of e ranges from 1.0 to 0.4, however typically 0.65 is used (Conoscente 1992; Zhu et al 2002; Shakya 2009). Unfortunately, there is little directly applicable experimental evidence to calibrate the value of e. Recent experimental work has also shown that the value of e changes depending on the relative collision velocity (Jankowski awaiting publication). For the collision of two lumped masses the contact spring stiffness, k, is typically set as 10 times the stiffness of the larger axial floor. This value is largely arbitrary, however its value is found to not significantly affect the displacement envelope of buildings modelled with distributed mass (Anagnostopoulos 1988).

Figure 2.1 shows a positive (tensile) force acting in the member just before the end of the contact. This is due to the viscous force opposing the separation of the two objects. At this point the spring force tends towards zero due to the reduction in element compression (Jankowski 2005; Muthukumar 2006). The positive force is physically inaccurate and while solutions to this problem exist, they make equations 3 & 4 invalid. This is because the assumptions made in the equations' derivations are no longer valid (Anagnostopoulos 2004).

2.3 Modelling contact with distributed floor mass

So far all research described in this section has been based on the assumption of a rigid diaphragm. In reality, diaphragms have both axial stiffness and distributed mass. This can significantly affect how a collision occurs. Pounding of distributed masses was first investigated by Watanabe and Kawashima (2004) to model colliding bridge decks. They focused on calibrating the collision element stiffness when each colliding object is modelled with multiple axial elements. The modelled collisions were completely elastic. The optimal collision element stiffness was found to be the adjacent *element* stiffness. Thus if five elements were present in each object, the collision element stiffness is five times the diaphragm stiffness (Figure 2.2)

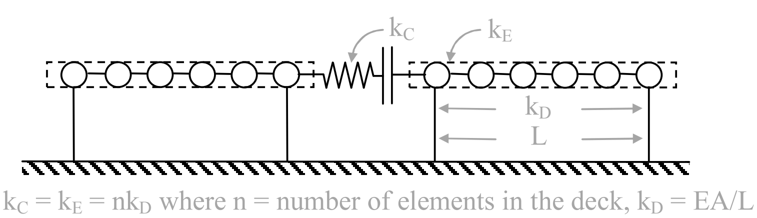

Figure 2.2 Optimum collision stiffness for multiple element object collisions

The change in building pounding behaviour between the lumped mass (Figure 2.1 with no damping) and the distributed mass assumptions (Figure 2.2) can be significant (Cole et al 2009a, Cole et al 2009b). This change is dependent on both collision velocity and physical properties of the two diaphragms. At least two axial elements are required in each distributed mass to sufficiently model the collision. Using wave theory, a theoretical maximum collision force can be calculated for two distributed masses (Cole et al 2009a);

$$F = \frac{v_1 - v_2}{\dfrac{1}{\sqrt{m_1 k_1}} + \dfrac{1}{\sqrt{m_2 k_2}}} \quad (5)$$

where v = velocity at time of impact; m = the total mass; and k = the total floor stiffness (i.e. k_D). Contact duration can also be theoretically determined (Cole et al 2009a). The inclusion of multiple axial elements introduces further complications to the energy dissipation in a collision; which means equations 3 and 4 are no longer valid. Appropriate collision damping for distributed masses is the subject of ongoing research by the authors.

2.4 **Other considerations when modelling**

The effect of soil and soil structure interaction on pounding has received little attention. Rahman (2001) and Shakya (2008) have both investigated the effects, using lumped parameter models at the foundations. Soil effects are found to have an influence on pounding, although opinions on how they affect pounding differ between researchers.

While many researchers acknowledge pounding induced torsion as a potential failure causing mechanism, 3D modelling of pounding has received little attention. The only widely reported full 3D modelling of pounding was undertaken by Mouzakis and Papadrakakis (2004). This work assumed a fully rigid diaphragm. The contact element requires additional parameters including friction effects in the plane of the collision surface.

2.5 **Recommended modelling of floor-to-floor collisions for design engineers**

The following properties are recommended for floor-to-floor pounding models. Model both buildings in an inelastic time history program. Include inelastic building properties. Place at least two axial elements in each floor. Include soil flexibility as described in Shakya (2008). Run two types of analyses, one with rigid diaphragms using e = 0.65, and one using an elastic collision element with diaphragms able to axially oscillate. Note the collision element stiffness will differ between the two cases. Results from both cases should be reviewed together. Demand loadings may be taken from the most conservative response, or some rationalised intermediate between the two analyses. Note these methods have drawbacks as stated above, but they represent the current best practice that is available to design engineers. Refer to relevant standards for the minimum required number of earthquake histories.

3 **MODELLING FLOOR-TO-COLUMN COLLISIONS**

Until recently the research community focused almost exclusively on modelling floor-to-floor collisions, primarily due to its simpler geometry. However, floor-to-column collisions are recognised to have more serious consequences. The majority of floor-to-column research has been undertaken by Karayannis and Favvata (2005a; 2005b; 2008). In these studies, an undamped linear contact element was used to model the contact. This is because the majority of the plastic action occurs in the column undergoing contact. The contact column requires more detailed modelling, so specially developed distributed plasticity elements were used. All elements were two dimensional with rigid diaphragms.

Recent works by the authors have used multiple beam elements instead of distributed plasticity elements when modelling floor-to-column collisions. Results of this work are yet to be published. Note that the equations presented in Section 2 are not valid for floor-to-column collisions because the collision mechanism is different. The response is governed instead by the behaviour of the column undergoing contact. Two studies have included soil effects for modelling floor-to-column collisions, again using lumped parameter models (Shakya 2008, 2009). To date no 3D floor-to-column modelling has been reported. Recommendations for modelling the floor-to-column collision cannot be currently produced in a form that design engineers can readily use.

4 SIMPLIFIED POUNDING MODELS

Due to the complexity of pounding mechanism, few simplified prediction models exist. Simplified models provide predictions for one of two forms of pounding damage; local damage and global damage. Local damage is caused directly by the physical contact of the two buildings, while global damage is caused by the momentum and energy transferred between buildings due to contact. Global damage can thus increase the maximum deflection of a building when compared to a standalone (no pounding) analysis.

Early simplifying attempts included an ETABS add-in called SLAM (and later SLAM2) (Maison and Kasai 1992). SLAM2 can be used to predict global damage. The program used modal decoupling to model pounding between two buildings. There are major drawbacks to this approach; only one point of contact can be modelled in the configuration. This is inappropriate for many building configurations, including adjacent buildings with no separation between them. Floor-to-column collisions cannot be modelled. The analysis is also elastic (since it is based on modal decoupling), which is a major simplifying assumption. Finally to the authors' knowledge, this piece of software is no longer publicly available.

The Pseudo Energy Radius (PER) method treats pounding as an exchange of energy between buildings (Valles and Reinhorn 1997). The PER method predicts global damage and involves identifying the highest energy state of each involved building. The energy transfer between buildings is calculated assuming a collision occurs at this energy state. The PER method can be carried out by hand, however it is also subject to many drawbacks; it assumes an elastic response of the buildings (although 'equivalent' nonlinear parameters can be used), it cannot be used for floor-to-column contact, and it is also a very complex process that does not have a simple physical explanation. Thus any mistakes by a user of the method are difficult to identify.

A local damage prediction method has also been investigated (Favvata 2008). Non linear pushover analyses of two buildings are used to predict the shear and ductility demands of the contact column resulting from building pounding. While this method is reported to show promise, it still requires further development (Favvata 2008). This method is only applicable for floor-to-column contact.

Currently there are no reported simplified solution methods that provide the required level of detail to model pounding situations. Note that all methods require analysis of both buildings involved in the collision. As a result, inelastic time history is the only accessible tool currently available to the design engineer.

5 PREDICTION OF REQUIRED SEPARATION TO AVOID COLLISION

This is another field which has received significant attention by researchers. Probabilistic methods are used to determine the likely separation required between two buildings to prevent pounding. Recently the available methods in this field have been reviewed and compared to the basic Square Root Sum of the Squares (SRSS) method (Lopez-Garcia and Soong 2009). The advanced methods can accurately predict separation distances for linear systems, but they do not consistently perform for non linear systems. Thus the SRSS is the most reliable method to calculate separation (Lopez-Garcia and Soong 2009).

6 MITIGATION METHODS

Mitigation of existing structures for pounding can take one of three forms; adding structural systems to replace elements that may be lost due to pounding, improving individual buildings to reduce displacements or increase resilience to pounding, and linking adjacent buildings with energy dissipating devices to reduce the severity of collisions.

The first two methods can be performed without further research. Improving individual buildings may include the addition of damping devices or increasing the shear capacity of elements likely to undergo contact. The calculation of demand loadings for these improvements remains difficult, as described in earlier sections.

Linking adjacent buildings with any type of element significantly changes their loading distributions and dynamic properties. Many damping devices have been proposed including viscous, visco-elastic, friction and tuned mass dampers (ULIEGE 2007). Research in this area has focused on testing various types of dampers, as well as the optimisation of damper placement between structures (Dogruel 2005).

However, major technical and non technical issues surround the use of linking elements (ULIEGE 2007). Existing buildings with small separations provide little room to install damping elements. Furthermore, linking elements require time history analyses to determine their effectiveness, so they require considerable design time. A major social and legal barrier also is likely to prevent the linking of two buildings with different owners since linking typically requires alterations to both buildings. Finally, the addition of linking elements can affect buildings in unexpected ways. The building loading profile can significantly change, thereby affecting beam and column demands throughout the structure. Considerable care must be taken when using these elements.

7 BUILDING CONFIGURATIONS THAT ARE VULNERABLE TO POUNDING

Review of earthquake damage caused by pounding has identified six critical building configurations that greatly increase the likelihood of structural collapse (Jeng 2000). Refer also to

Figure 7.1.

1. Floor-to-column pounding (Figure 1.1). In particular, the columns that suffer collision are subject to very high shear forces. Typically these columns fail in shear, although column ductility requirements may also be exceeded.
2. Adjacent buildings with greatly differing mass. The momentum transfer from the heavier building can greatly increase the velocity in the lighter structure during impact. Thus the lighter building is susceptible to collapse.
3. Buildings with significantly differing total heights. A collision between a tall and a short building changes the taller building's displacement mode. The floor that suffers collision in the taller building is restrained, while the rest of the building is 'whip-lashed' over top. This creates a major increase in shear and ductility demands in the taller building in the storey immediately above the top floor of the shorter building.
4. External buildings of a row when all buildings have similar properties. This scenario is analogous to Newton's cradle. If there is a street of similar buildings with little or no building separation, then the end buildings suffer increased damage due to the momentum transfer from the interior buildings. Subsequently the interior buildings may actually suffer less damage than if pounding were not to occur.
5. Building subject to torsional actions arising from pounding. Certain building configurations can excite torsional modes in one or both structures which can lead to greatly increased loading demands. This is particularly dangerous if floor-to-column pounding occurs.
6. Buildings made of brittle materials. Unreinforced masonry is particularly vulnerable to any lateral loading. Collision causes a very high temporary force which may cause explosive failure of brittle structural elements.

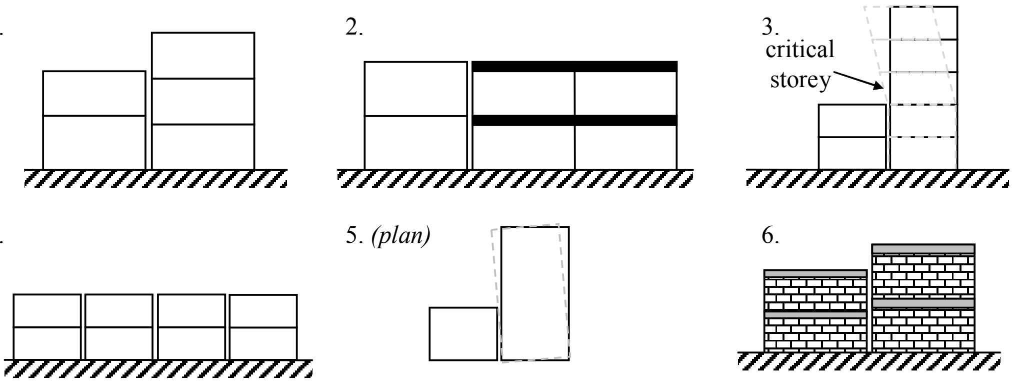

Figure 7.1 Critical pounding configurations

Most floor-to-column analyses have been undertaken with modern building designs, and with collisions occurring near the mid-height of the column (Karayannis and Favvata 2005). The affected columns fail in shear. Adjacent buildings that have floor heights just offset from one another (such as the second floors of configuration 1 in

Figure 7.1) will greatly amplify the column shear demand. This finding is at odds with the IEP process which treats floors of near alignment as better performers than floors of greatly differing alignment (NZSEE 1996).

Buildings that are prone to pounding but do not meet any of the above criteria are significantly more likely to survive during an earthquake. However, pounding creates large acceleration demands on any floors directly involved in collision, which may cause significant damage to contents and endanger human lives. Thus care must be taken with all buildings that may suffer pounding.

In terms of generic building performance, no numerical results have been reported in this paper. This is because very few consistent trends are found between researchers. Even simple properties such as the effect of increasing the separation between buildings does not seem to have consensus (ULIEGE 2007). In particular, many researchers have attempted to categorise which building type is affected more; the stiffer building or the more flexible building. Many contradictory conclusions have been made from this assessment. A recent study using dimensional analysis provides one explanation for this conflict (Dimitrakpoulos 2009). It is found that the displacement amplification is dependent on the 'characteristic' excitation frequency of the record. Thus building may either be amplified or deampilified depending on the excitation. Similarly, characterising buildings by relative mass is also difficult. At this stage few other useful generalisations regarding pounding structures can be made.

8 EXPERIMENTAL POUNDING DATA

Due to the cost of destructive experiments, few major experiments have been performed. Even when experiments are performed, their form are often restricted so that the specimens can be preserved. Space restraints of this paper prevent a detailed overview of experimental data. Further information may be found in previous state of the arts papers (ULIEGE 2007; Anagnostopoulos 1995).

9 CONCLUSIONS

Based on the above works, the following conclusions are drawn;

- Six building configurations are identified as being critically vulnerable to building pounding. They are; floor-to-column pounding, pounding of buildings with greatly differing mass, pounding of buildings of greatly differing total height, pounding inducing building torsion, and pounding of buildings comprised of brittle elements.

- The inelastic time history is the only modelling method for evaluating floor-to-floor contact that is available to design engineers. No floor-to-column modelling methods are available for design engineers.
- Separation distances required to prevent pounding are most appropriately modelled by SRSS.
- Three types of mitigation methods are available; providing redundant systems, reducing deflections to avoid pounding, and linking buildings to reduce contact. Linking buildings can provide beneficial results but requires detailed modelling and can significantly change both buildings dynamic behaviour.

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