DISTRIBUTED MASS EFFECTS ON BUILDING POUNDING ANALYSIS

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ABSTRACT

This paper challenges the view that building pounding can be adequately modelled with rigid diaphragms at each floor. Two existing low rise RC frame buildings located in Wellington, New Zealand are subjected to an abridged El Centro record. Non linear time history simulations are undertaken with both lumped mass (rigid diaphragm) and distributed mass (flexible diaphragm) assumptions. Multiple building configurations are modelled to allow floor-to-floor and floor-to-column contact to occur at different points on the two structures. Building displacements are found to be sensitive to diaphragm flexibility only in specific circumstances. However, significant sensitivity is shown in the shears of columns that come in contact with adjacent floors, with shear results differing by up to 18 %. The consequences of pounding on the two low rise structures are also presented, and show critical element failures as a result of floor-to-column pounding.

Introduction

While building pounding is commonly reported after earthquakes, scientific understanding of the phenomenon and its consequences is very limited. Many researchers have used numerical modeling of pounding to gain further insight into the process. Typically the modeling is similar to that shown in Figure 1 (Anagnostopoulos 1988; Maison and Kasai 1992; Jankowski 2006). A contact element is placed between two buildings at each floor, with the floors modeled as a single lumped mass. Alternatively the buildings' frames may be explicitly modeled, but the floors' diaphragms are rigidly slaved together so no diaphragm oscillation or mass distribution effects can occur. The specifics of the collision element vary but it typically comprises of a very large stiffness being activated once a specified gap has closed. Modeling of this type does not usually include allowances for floor-to-column pounding.

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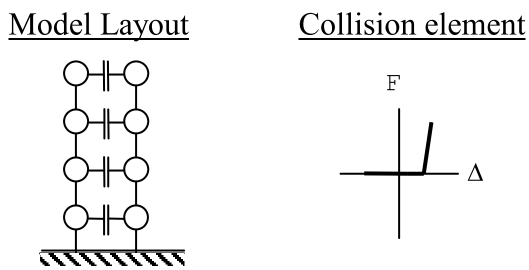

Figure 1. Typical pounding numerical modeling configuration

An alternative method investigated by the authors includes at least three lumped masses distributed over each diaphragm to allow the modeling of diaphragm mass distribution effects. Previous investigations have demonstrated that this method can produce displacement results that vary significantly from the method described in Figure 1 for buildings with all floors aligned (Cole et al 2009). Furthermore, the relative magnitude of the difference in displacements can be qualitatively predicted by comparing the values of α, a property that is dependent on the diaphragm modeling method (Cole et al 2009b). The work presented herein extends this investigation to look at the performance of two real buildings with floors of different heights. Analyses are run with both axially flexible and rigid diaphragms for three different pounding configurations. A rigid diaphragm causes all floor mass to act immediately upon a floor collision, thus the diaphragm acts as a lumped mass. If a flexible diaphragm is used instead, the masses lumped at each node only interact with a collision once the stress wave propagates through the adjacent diaphragm element. Thus, provided at least three lumped masses are present in the diaphragm, the response is very similar to that of a distributed mass. The effect of diaphragm mass distribution on building response from floor-to-column contact is hence investigated.

Model Setup

Building Configuration

Two existing buildings from Wellington, New Zealand were selected for pounding study. The buildings are not actually situated next to each other; however the configuration represents a common scenario in New Zealand. Both buildings were selected because their details were readily accessible. Figure 2 shows the overall layout of the buildings Floors are labeled first by building number (left to right), followed by floor number. For example, B2F1 refers to building 2, floor 1.

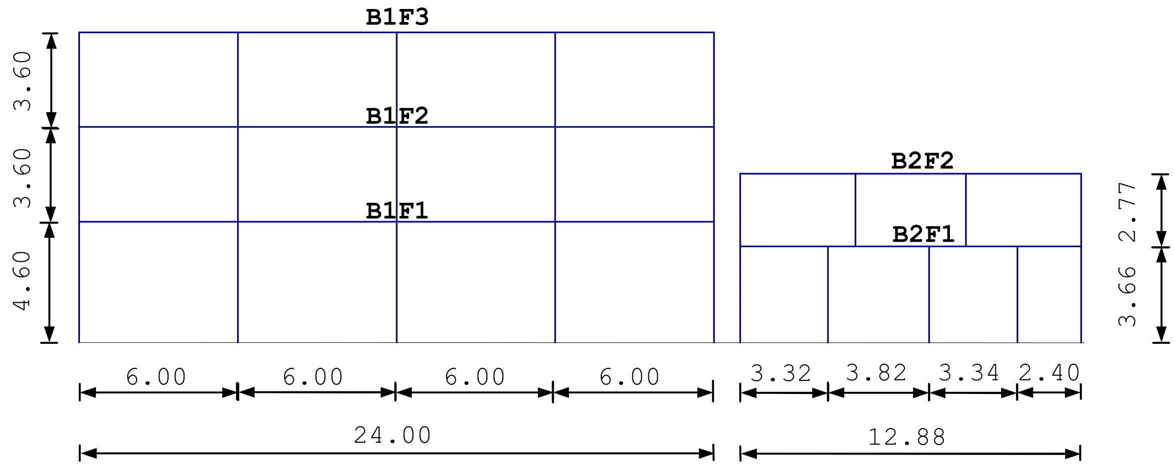

Figure 2. Building layout (floors are labeled first by building number followed by floor number)

Building 1 (shown on the left) was constructed in 1958 while building 2 was constructed in 1961 and both are currently in use as offices. Both buildings have been modeled using the guidelines produced by the New Zealand Society of Earthquake Engineers (NZSEE 2006). Element sections and floor seismic mass are presented in Figure 3 and Table 1, respectively.

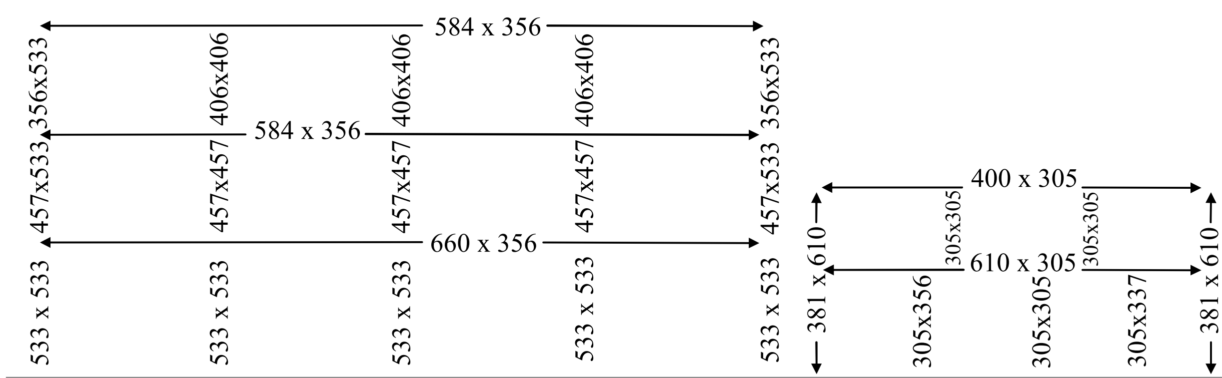

Figure 3. Member section size

Table 1. Floor seismic mass

Floor	Seismic mass (kN)	Floor	Seismic mass (kN)
B1F3	910	-	-
B1F2	1080	B2F2	67
B1F1	1080	B2F1	206

Three building configurations are investigated; buildings aligned at ground level, at the first floor, and at the second floor, respectively. The floor alignment is achieved by raising the entire second building (Figure 4). Each configuration was run twice, once with all floors modeled as lumped masses and once with floors as distributed masses. All analyses had a nominal building separation of 0.01 m. Two analyses with no building contact were also run for reference (once with each mass assumption).

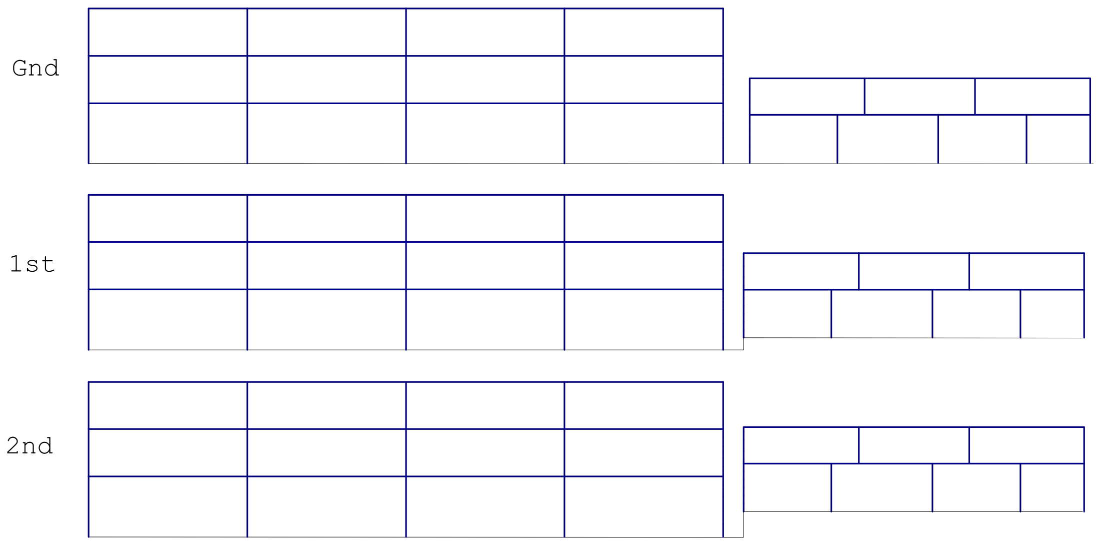

Figure 4. Building configuration allowing alignment of stated floor

Contact element properties

The contact elements between the adjacent buildings have been calibrated following the recommendations of Watanabe and Kawashima (2004). Collision elements have stiffness equal to the greater axial element stiffness of adjacent diaphragms. Collision elements are modeled as completely elastic.

Excitation

The first twelve seconds of the El Centro record, scaled as required by the relevant New Zealand standard (NZS1170.5; 2004), was used in all cases. The total record was scaled to an annual probability of exceedance of 1/500. The first twelve seconds then selected as it contained a portion of moderate excitation and also restricted the computation time to an acceptable duration. A time step of 0.00001 seconds was required to avoid excessive energy losses in the modeling. All modeling was undertaken using Ruaumoko, a non linear time history program developed at the University of Canterbury (Carr 2007).

Column mass distribution

The distribution of mass in a column that undergoes contact may also make a significant difference to results. While column mass distribution is not likely to affect the global performance of the buildings, the local shears and moments could potentially be affected. As research on this particular topic is currently ongoing by the authors, five column elements have been used to model each column that undergoes collision to ensure realistic performance.

Predicted Performance

The significance of the different diaphragm models can be qualitatively predicted by the method presented in the authors' previous works (Cole et al 2009b). The parameter α appears in the formulae that predict diaphragms' velocity after a single floor-to-floor impact (Equation 1). The lumped mass version of this formula is commonly known as stereo mechanics.

$$v_1' = v_1 - 2\alpha_1(v_1 - v_2) \qquad (1)$$

Where and the subscripts '1' refers to the diaphragm with the shortest axial period and '2' refers to the remaining diaphragm. V is diaphragm velocity immediately before collision and v' is the velocity immediately after collision. The calculation of α is dependent upon the mass distribution and whether diaphragm has the shorter or the longer axial period (Table 2).

Table 2. Calculation of α

	Lumped mass	**Distributed mass**
α_1	$\frac{1}{1+\frac{m_1}{m_2}}$	$\frac{1}{1+\frac{m_1 T_2}{m_2 T_1}}$
α_2	$\frac{1}{1+\frac{m_2}{m_1}}$	$\frac{1}{\frac{T_2}{T_1}+\frac{m_2}{m_1}}$

Where T is the diaphragm axial period and m is the diaphragm mass. Thus, the greater the change in the value of α between mass assumptions, the larger the resulting differences in displacement (by Equation 1). Note the results can only be obtained for the collision of two diaphragms and therefore are not useful when floor-to-column collisions occur. For further information the reader is directed to the reference stated above. Figure 5 details the values of α for the cases where floor-to-floor collisions occur.

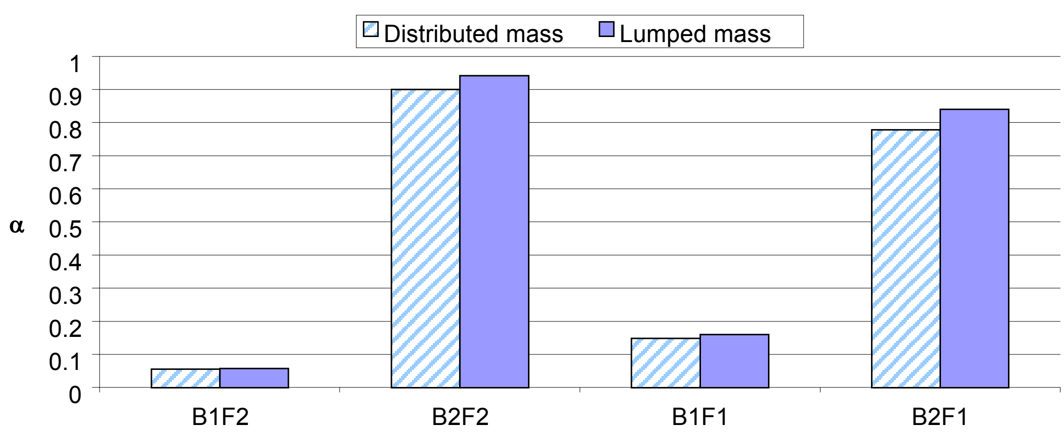

Figure 5. Qualitative prediction of the effect of the mass distribution. Note the values for B1F2 and B2F2 are only valid when the second floors are aligned, and B1F1 and B2F1 are only valid when the first floor is aligned (as this is when floor-to-floor contact occurs)

Thus very little displacement difference is predicted for building one as a result of floor-to-floor collisions. This is a result of its much larger mass, which contains the majority of the system's momentum. Floor 1 of building 2 is likely to be the most affected by the diaphragm models, while floor 2 of building 2 should also show some change in displacement.

Results

Figure 6 shows the positive (right) envelope displacements for each building configuration including no building contact. Eight series are shown; which identifies the four building configurations, for both the lumped mass (shown as LM) and distributed mass models. 'No' identifies the no contact case. 'Gnd', '1st' and '2nd' identify which floors are aligned in each configuration (as shown in Figure 4). Floor labels are shown on Figure 2.

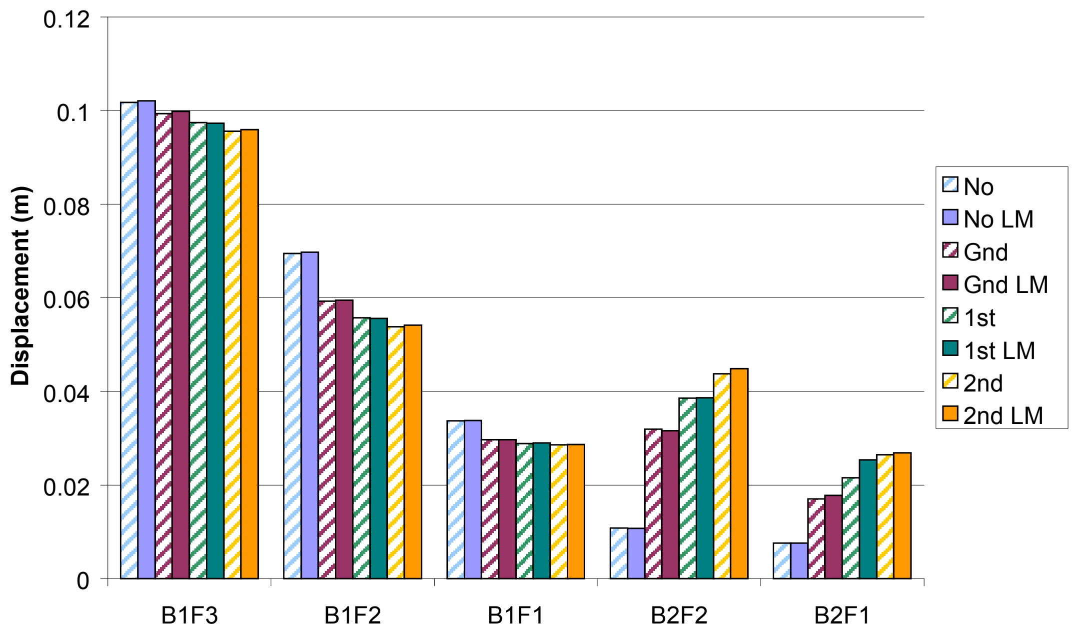

Figure 6. Positive (right) displacement envelopes. LM denotes Lumped Mass

As predicted, the largest difference between the different mass assumptions is found in floor one of building 2, when the first floors are aligned. The only other notable difference occurs at floor 2 of building 2 when the second floors are aligned. Both these differences are in the order of 5 – 10 mm. The effects of building contact can be seen by comparing the no contact (labeled as 'No') with the other results. Building 2 is clearly much more affected than building 1.

The negative (left) displacement envelope is presented in Figure 7. The negative envelope results are almost completely unaffected by pounding, regardless of the height of building 2. This is because of the large mass difference between the two buildings; even when building 1 collides with building 2 (moving to the left), the momentum transfer is so small that it has almost no affect on building 2. In contrast, when building 1 hits building 2 (moving to the right), building 1 has to effectively push building 2 in order to displace further. This results in a more 'forced' momentum transfer. B1F3 is the only floor that shows any sensitivity to the location of pounding and even that is small. This increase in sensitivity can be attributed to 'fling over' effects. Fling over occurs when the top part of one structure continues to move over the top of the second structure while its lower storeys have been slowed due to collision. Large increases in shear can result from this phenomenon, particularly in tall buildings.

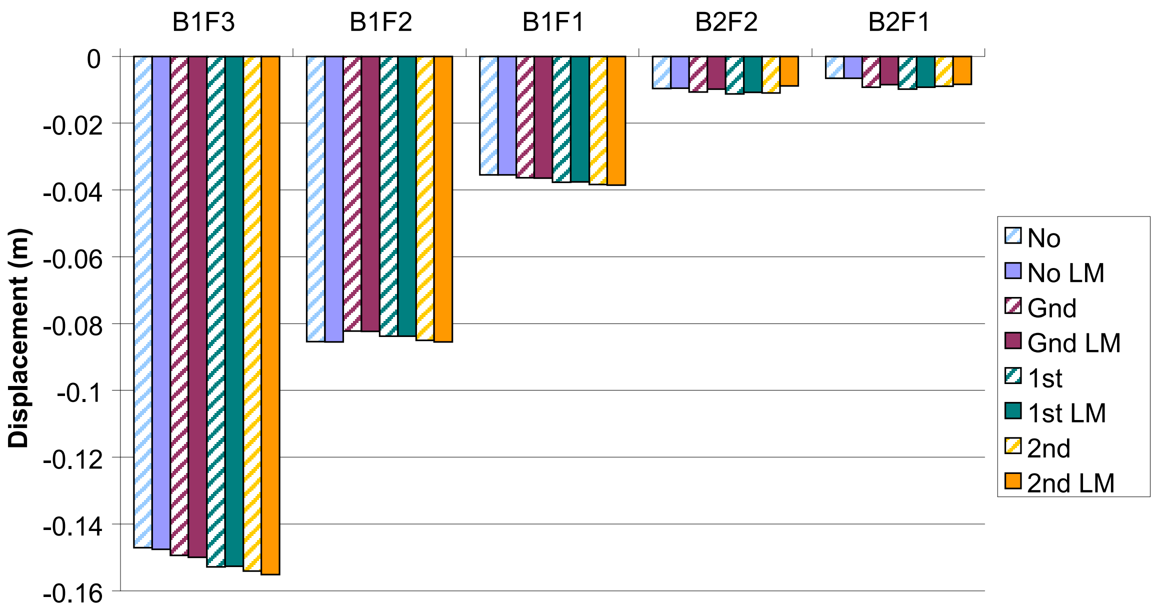

Figure 7. Negative (left) displacement envelopes. LM denotes Lumped Mass

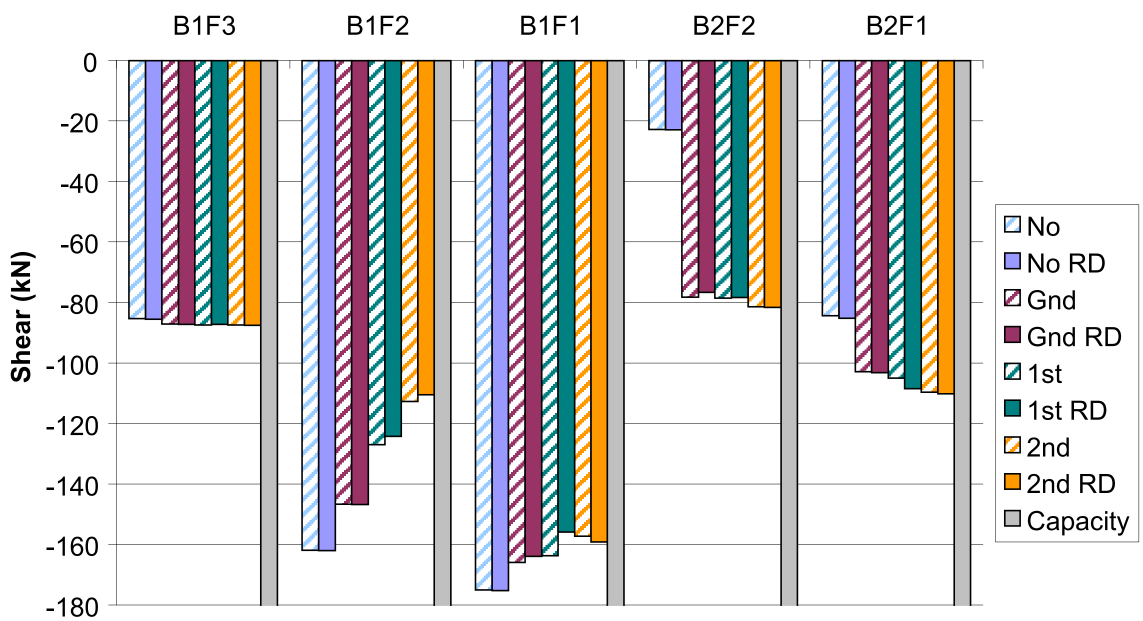

Figure 8. Negative interstorey shear envelope (corresponding to the right displacement envelope)

Figure 8 illustrates the global interstorey shears. The shear values shown are taken from the external columns (located at the end of the floor not undergoing collision). Columns are identified by the floor immediately above their location. Pounding has greatly increased the shear force in building 2, particularly at the top floor. Shear loading generally drops in building 1.

These results further illustrate the momentum and energy transfer that results from pounding interaction (in this case transferring from building 1 to building 2). Once again almost no dependence on mass distribution is noted. The shear capacity of each column is also shown and no capacity is exceeded. Positive shear results show very little sensitivity to pounding and mass distribution.

Figure 9 shows the local shear in the columns that endure collisions. Note many of these columns only suffer a column collision in some configurations. For example, when the first floors are aligned, the only mid column collision occurs in the column under B1F2 (refer Figure 4). Only column B1F2 has collisions in all configurations. Each column now has two shear loadings; a shear below the point of impact (shown as '-') and a different shear above the point of impact (shown as '+'). The columns' capacities are exceeded in all configurations except when the second floors of the two buildings are aligned. The worst results are found when the ground floors are aligned. This is because column collision is the only means of momentum transfer between the two buildings. It is likely that both the ground floor and first floor alignment would thus result in at least one building collapse due to column shear failure. As columns are almost always critical elements within a structure, local shear failure is likely to cause global collapse. The shear loading also shows a surprisingly high dependence on mass distribution when compared to other results. For B1F1-, the distributed mass model predicts shear failure while the lumped mass does not. This difference would potentially change the retrofit recommendations by an engineer undertaking a pounding analysis. However, in this particular case, the result would not have been critical because B1F1+ also exceeds capacity and thus the column between the ground and floor one is predicted to fail anyway.

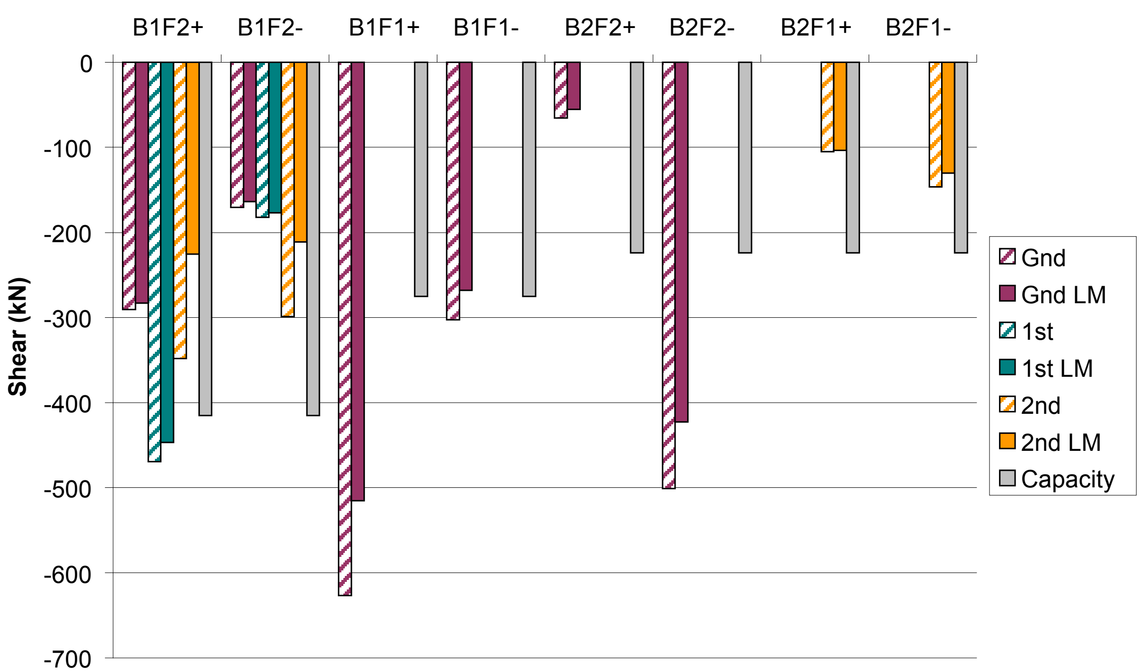

Figure 9. Negative shear on columns subject to impact

Conclusions

Base on the results of the analytical investigation conducted in this study, the following key points are noted;

1. Two real buildings undergoing pounding are modeled for a moderate earthquake excitation. Pounding is shown to significantly affect the two buildings when compared to the same excitation without pounding. Building 1's displacements are generally reduced while building 2's displacements increase.
2. The qualitative prediction of displacement sensitivity was successfully achieved using the method outlined in previous papers by the authors (Cole 2009b). The largest displacement dependence on diaphragm flexibility was accurately predicted. However, this prediction can not be accurately extrapolated to other building properties, such as shear force.
3. For the analyzed building configuration, both global shear and displacement results were generally found to be insensitive to mass distribution. However, shear loadings on columns that undergo collision can be significantly affected. In the examples shown the local shears differed by up to 18 %.
4. For the given excitation, the two analyzed buildings are predicted to survive if there was a sufficient gap to prevent pounding. However if pounding does occur as modeled, both buildings are likely to collapse due to column shear failure. Column pounding is thus a critical factor to consider when retrofitting existing buildings

Based on the above work, distributed mass diaphragms are recommended when modeling either floor-to-floor or floor-to-column pounding if local shearing actions are required. It is noted that the building configurations presented above are not optimized to cause diaphragm oscillation; thus other building configurations may show significantly more dependence on mass distribution. Research is ongoing into other building configurations and their sensitivity to mass distribution.

Acknowledgments

The first author would like to acknowledge the Tertiary Education Commission and Beca, Carter, Hollings and Ferner Ltd for personal financial assistance to conduct this research.

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