Investigation of modelling methods for buildings with non-structural elements

C.E. Kerr

Opus New Zealand Ltd, Queenstown.

D.G. Proudfoot

Aurecon New Zealand Ltd, Christchurch.

C-L. Lee

Department of Civil Engineering, University of Canterbury, Christchurch.

2017 NZSEE Conference

ABSTRACT: The modelling of non-structural elements is becoming increasingly important. It has been found that during seismic events modern buildings can incur significant downtime due to the damage of contents, even when the building is performing well structurally. This report details an investigation into the validity of the cascade modelling method for the design of buildings with non-structural elements. The cascade method is a way of modelling a building without using specific details of non-structural elements, and then later performing a separate analysis in order to design the contents. It was found that the cascade method may be an appropriate method for modelling non-structural elements. However, as the non-structural mass increases, the error becomes more significant. Currently, most cascade modelling considers only translational motions. Rotational motion, if present and relevant, should be considered as part of the modelling input.

1 INTRODUCTION

The performance harmony of structural and non-structural elements is vital. It is often found post-earthquake that the non-structural elements have lowered the performance level and functionality of the building system (Filiatrault & Sullivan, 2014). This is because damage can occur to non-structural elements at lower intensities than that required to cause structural damage.

In many recent earthquakes, the value of losses from damage to non-structural elements has far exceeded the losses from structural damage in affected buildings (Filiatrault & Sullivan, 2014). This is because even if the structural elements have performed well enough to support immediate occupancy, failure of non-structural elements can result in the closure of structures for a long period of time. Moreover, fallen non-structural elements may cause injury, or hinder the movement of building occupants and rescuers following a seismic event.

In a typical multi-storey building, the non-structural elements can make up approximately $82 - 92\%$ of the system's monetary investment (Miranda & Taghavi, 2003). With this in mind, it is, therefore, surprising that there is limited specific guidance, or research, toward the design of non-structural elements. This is a result of the empirical nature of current seismic practice (Filiatrault & Sullivan, 2014). Further research in this area is necessary in order to increase the ability of engineers to design safer, more cost effective structures.

1.1 Problems

Non-structural elements are commonly neglected in the design of building systems. Instead, the mass of the elements is accounted for as part of the live load acting on the building. In some cases, the structural mass will be specifically accounted for. However, this is only done for significant elements e.g. water towers or air conditioning units. The problem with this is that the result does not account for the interaction between structural and non-structural responses.

Recently, effort has been devoted to developing rational methods for conducting the seismic analysis

of non-structural elements. These methods have so far not been accepted into the industry standards (Filiatrault & Sullivan, 2014). Contributing reasons for this are:

- There is a difference between damping ratios for the structural and non-structural elements. Most software does not allow the modelling of multiple damping regions.

- The non-structural elements are often unknown at the time of structural design. It is, therefore, difficult to perform a combined analysis from a scheduling point of view.

- The range of frequencies in a combined model often requires a very small time step in order to capture the response. For large models, this may be too time consuming.

1.2 Objectives

When the response of a non-structural element is deemed important, the current modelling options available to an engineer are very limited. The objective of this paper is to investigate the accuracy of a modelling method currently being researched for use with non-structural elements. The method considered throughout this paper is known as the cascade method. By completing this investigation, it is expected that the accuracy of the cascade method will be better understood. Moreover, the results of this research will make it possible to comment on how non-structural modelling could proceed in future design of building systems.

1.3 Scope & limitations

The study was only performed on a single type of structure. Furthermore, the investigation was only carried out for simple single-degree-of-freedom (SDOF) non-structural elements. As such, any conclusions drawn from the analysis are of limited value when considering the wide range of variables present in real world designs. Further investigation is required in order to strengthen the conclusions made in this paper.

2 CASCADE METHOD

The cascade method of modelling involves the attempted separation of 'insignificant' elements during earthquake modelling. This is done based on the assumption that elements, not designed for structural purpose, are affected by the building's seismic response, but do not affect the building's response significantly.

To perform the cascade method, a simple building frame is subjected to an earthquake, and the full time history response at each floor is recorded. In the model, the estimated weight of the non-structural elements is simply added to the mass of each floor. This first modelling step is assumed to be sufficiently accurate for the design of the structure.

The recorded floor acceleration is then applied to a simple SDOF model. In doing so, the drift demand of the non-structural element can be estimated for design purposes. This method is outlined in Figure 1 (Filiatrault & Sullivan, 2014).
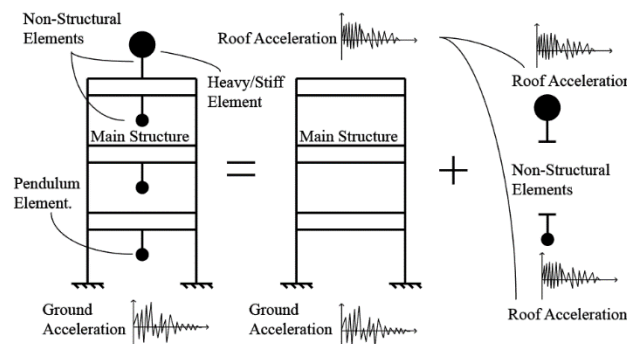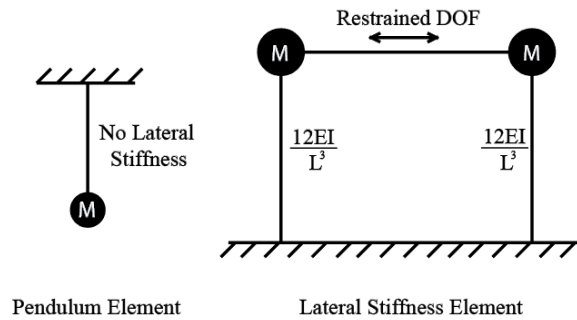

Figure 1. Illustration of the cascade method used to analyse the response of non-structural element.

3 METHODOLOGY

Initially, a model was developed for the complete building system including non-structural elements. The building model was based on a typical six story, two bay, steel moment frame e.g. an office building. The mass per floor was 60 tonnes and the assumed damping ratio was 5%. Without any non-structural elements, the period of the structure was 0.63 seconds. The non-structural elements included in this model were able to be changed independently of the primary structure. The mass, period and damping ratios of the elements were varied depending on the desired analysis.

A second model of the building was developed containing only the primary structure with both structural and non-structural masses lumped together. This model was used as part of the cascade analysis. Two separate SDOF models were then developed to represent non-structural elements (Figure 2). The two non-structural elements considered in this investigation were: a pendulum element, in order to represent a fully-floating ceiling system; and a column element, in order to represent a heavy, stiff, component such as a water tank or machinery.

**Figure 2. Illustration of the SDOF non-structural components used to examine the cascade method.**

For some sections of the comparison, a third building model was considered. This model was similar to the full model described. However, the model used a 5% damping ratio for all of the structural and non-structural elements. It is anticipated that this method would be a common modelling method for those wishing to improve upon cascade modelling. Most software is easily able to support the addition of non-structural elements. However, it is relatively rare to perform analysis with damping ratios specified for each individual element. This means that modelling of a full structure is often performed with a single 5% damping ratio throughout the building.

The effect of non-linear modelling was also investigated. For stiff non-structural elements this involved the p-delta effect, while the pendulum type elements were investigated for their dependence on small-displacement pendulum approximations. If a pendulums angle of inclination becomes greater than 22°, the period estimated by the simple pendulum equation becomes inaccurate (Beléndez et al., 2009). If this is the case, the period of the pendulum will be approximated by equation (1), instead of the simple pendulum period, and so the displacement will become affected.

$$T = 2\pi\sqrt{\frac{L}{g}}[1 + \frac{1}{16}\theta_0^2 + \frac{11}{3072}\theta_0^4 + \cdots] \qquad (1)$$

The ground motions were selected based on the New Zealand design code NZS1170.5. Twenty motions were selected that closely match the elastic design spectra for a 1 in 500-year event in the Christchurch region using post 2011 earthquake zone factors. The period range for spectral matching was 0.5 to 3.0 seconds and the scaling factors were limited to between 0.4 and 2.5.

Responses were analysed and recorded for the selected ground motion set (shown in Figure 3) and the difference between the full and alternative modelling methods was evaluated. The relative error between the models was investigated by looking at the estimated peak building displacement, and the peak non-structural drift demand. The error was only compared for non-structural elements at the roof of the building. It was a key assumption in the analysis that the full model was considered to be entirely correct and the error calculated is therefore relative to this model.
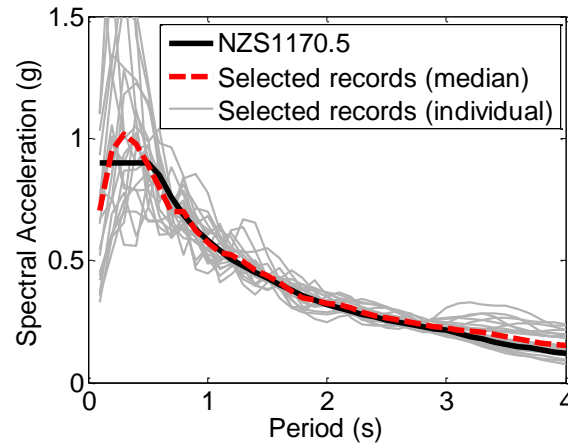
Figure 3. Ground motion record set selected based on post 2011 Christchurch earthquake factors.

Open System for Earthquake Engineering Simulation (OpenSees) (Version 2.5.0; McKenna et al., 1999) was used to complete the analysis due to it having a range of features applicable to the investigation. This includes non-linear modelling methods and the ability to apply different damping ratios to elements within the same structure.

3.1 Non-structural element specifications

The pendulum non-structural elements were added on every floor as would be expected of a hanging ceiling system. The pendulums were implemented with a one-meter length and 1% damping, although this was modified for some analyses. The damping ratio was chosen based on the research of Pourali et al. (2015). Using simple pendulum theory, the period of the hanging ceilings was 1.4 seconds.

The element with lateral stiffness was modelled only on the roof of the building. This would be expected of a heavy non-structural element such as a water tower.. The element was roughly designed to mimic a typical water tower. The damping ratio of the element was estimated as 3%. This is based on the assumption that the simple SDOF element would be damped less than the building, although this is difficult to verify. The period of the stiffness based member ranged from 0.06 to 0.63 seconds. This range was dependant on the elements mass and second moment of inertia. These values were varied during the investigations. The rotational inertia was not included for this investigation.

4 RESULTS & DISCUSSIONS

### 4.1 Inclusion of advanced modelling techniques

4.1.1 *Large displacement effect on pendulum element*

The results of the analysis showed that the pendulum model never exceeded an angle of 22°. The maximum horizontal displacement recorded was 0.142 m which resulted in an angle of approximately 8° using a 1 m pendulum cable length. A similar displacement was recorded for a pendulum with a cable length of 0.5 m, and this resulted in an angle of 17°. This finding suggests that the pendulum modelling is unlikely to be significantly affected by large displacement and therefore the simple pendulum period was used for the remainder of analysis. The effect of pendulum displacement on the oscillating period can be seen in Figure 4.

4.1.2 *Additional cascade inputs*

Initially, analysis results showed that the maximum drift recorded for stiffness elements was significantly underestimated by the cascade method. This error was not observed when modelling the pendulum element. An investigation of this error found that applying the total horizontal roof acceleration to the non-structural element was not sufficient. The element also required the application of the building's nodal rotations in order to provide a relevant estimation (Figure 5). It was observed that performing this additional step in the cascade method led to much more appropriate results, and was therefore a relatively simple way of improving the cascade analysis. This was verified by

4

recording the acceleration and nodal rotations for the full model and applying them to the non-structural element model. This result was then compared to the full model result. The error found from the verification process was less than 1% and therefore the addition of nodal rotations was considered an appropriate addition to the cascade method. The pendulum model was not affected by this since it does not have any dependence on nodal rotations. The improved cascade method was used for the rest of the analyses.
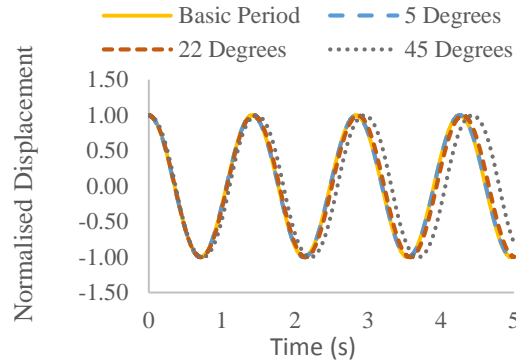
Figure 4. Effect of a pendulums inclination angle on its oscillating period.
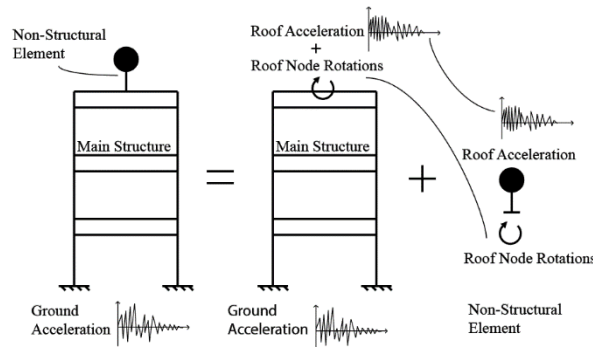
**Figure 5. Proposed improvement of the cascade analysis for elements with lateral stiffness.**

4.2 Effect of non-structural damping ratio

The effect of damping ratio on the cascade modelling method was investigated. Figure 6 shows the effect of different non-structural damping ratios on the error associated with cascade modelling.

Note the error bars displayed in the following figures represent one standard deviation above and below the mean. Also note that the non-structural mass percentage is relative to the mass of one floor in the building. A positive error indicates that the cascade method is conservative and gives a larger drift than the full model.

Increasing the non-structural damping ratio appears to slightly increase the accuracy of cascade modelling for pendulum type elements. Moreover, the variance in drift error is significantly decreased with higher non-structural damping. Generally, non-structural elements have a low damping ratio as they are simple structures that do not dissipate significant amounts of energy, particularly in the case of pendulum elements. This means typically the cascade modelling method will be used in situations where there is a higher degree of error and uncertainty.

The damping ratio appears to have no significant effect on the error or uncertainty associated with the cascade modelling of laterally stiff elements. This could be because the element experienced significantly less drift than the pendulum elements, and therefore did not experience considerable response changes due to damping.
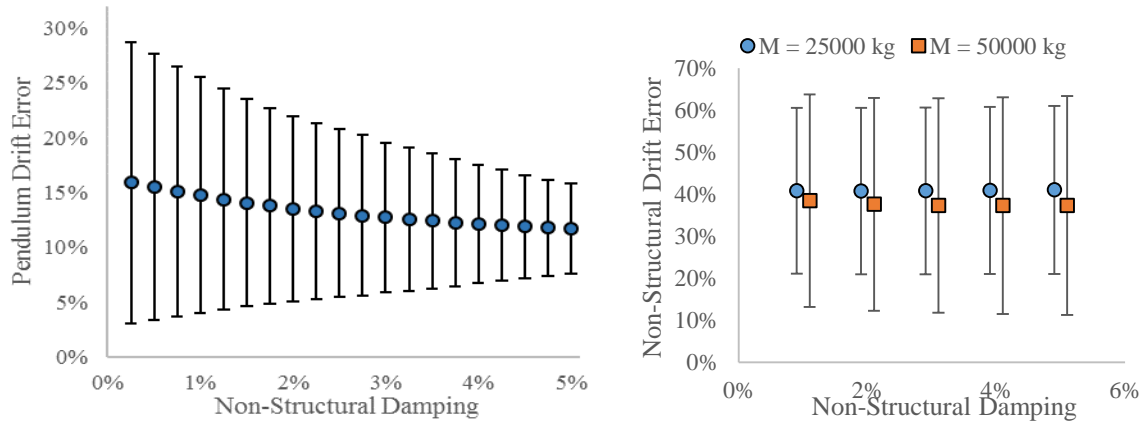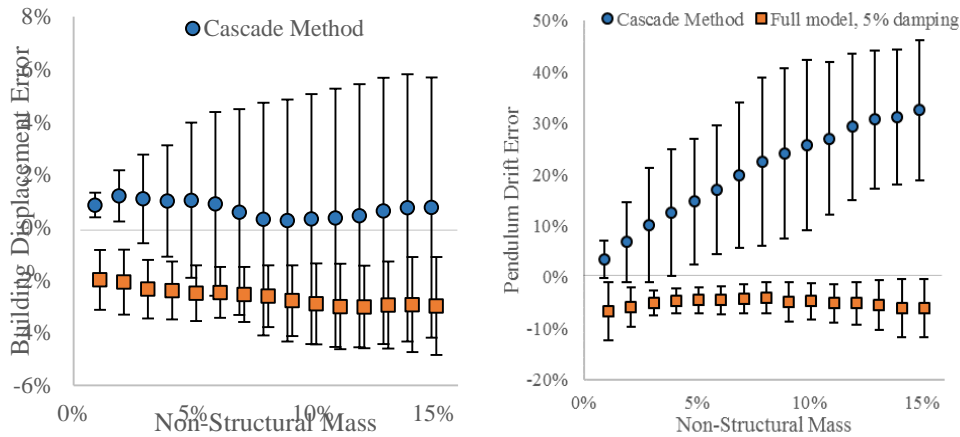
Figure 6. Error in drift of non-structural elements for varying non-structural element damping ratios. (Left) Pendulum element with mass defined as 5% of the building weight. (Right) Laterally stiff element with mass defined as seen in Figure.

4.3 Effect of non-structural mass

4.3.1 *Pendulum element*

Figures 7 displays the effect of non-structural mass on the effectiveness of alternative modelling methods for pendulum type non-structural elements.

Figure 7. Error in building displacement (left), and error in drift demand (right), for varying non-structural pendulum mass.

The previous graphs show that, as the non-structural mass increases, the associated cascade method error also increases. This is true for both the building displacement and non-structural drift.

The cascade model tends to provide conservative estimations of the drift demand, although it is not systematically conservative. This is interesting to note as it significantly affects the safety of the design method. It can be seen that the building displacement estimation is relatively accurate regardless of the mass of the pendulums.

The full model, with global damping, provides a more accurate and precise estimation of the drift demand for the non-structural pendulum type elements. The estimations are, however, non-conservative. For this method to be suitable for design, an additional safety factor of approximately 15% may be required. This also applies to the estimated building displacement as it is also more accurate and precise than the cascade method, but again is non-conservative.

4.3.2 *Stiffness based element*

The stiffness based element displays similar trends to the pendulum element (Fig. 8). However, it can also be seen that the full model, with a global damping ratio, has an increased precision as the non-

structural mass increases. Again, the full model, with a global damping ratio, provides non-conservative results. A safety factor appropriate for the stiffness based element design is approximately 10%. This safety factor could be applied to both the building displacement and non-structural element drift to provide acceptable design demand.
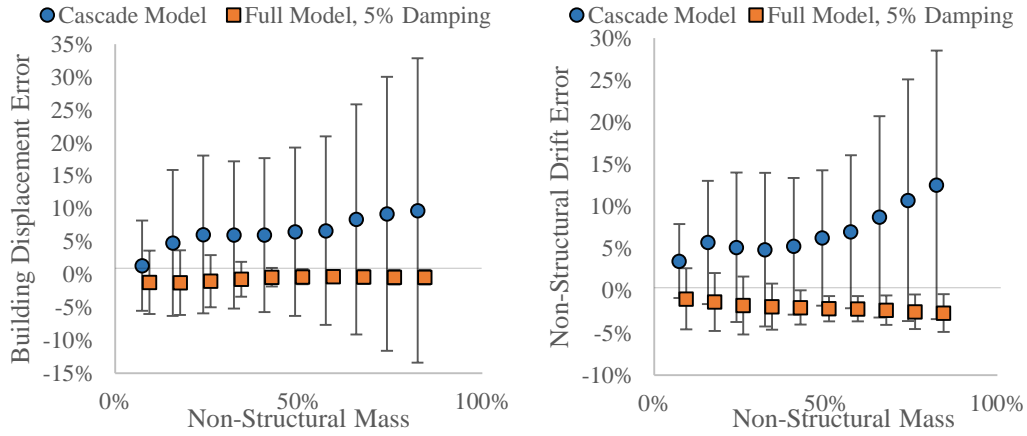

Figure 8. Effect of non-structural mass variation on the building displacement error (left), and the drift demand error (right). Non-structural element period ranges from 0.20 – 0.63 s.

4.3.3 *Unknown non-structural elements case*

Currently, structural and non-structural components are not designed simultaneously. Generally, the primary structure is designed, and the contents are specified at a much later stage. In this case, the mass of the non-structural components is unknown and so an estimation of the mass is used for cascade modelling. This estimation may be inaccurate, so it is important to consider the effects of this on the accuracy of the cascade modelling method. For this reason, an analysis was run for the cascade model in which the non-structural mass was completely excluded from the original building simulation.

Figure 9 displays the results of the analysis performed while excluding the non-structural mass from the first step in the cascade analysis. For stiff elements (T < 0.2 s), the building's roof displacement was up to 10% less conservative than the standard cascade method. It should be noted that the building displacements for this case were constant due to the exclusion of non-structural mass. Both methods have high levels of uncertainty and can return non-conservative estimates of both structural and non-structural element displacements. By excluding the non-structural mass from the original model, it was found that the error increased more rapidly with increasing mass.
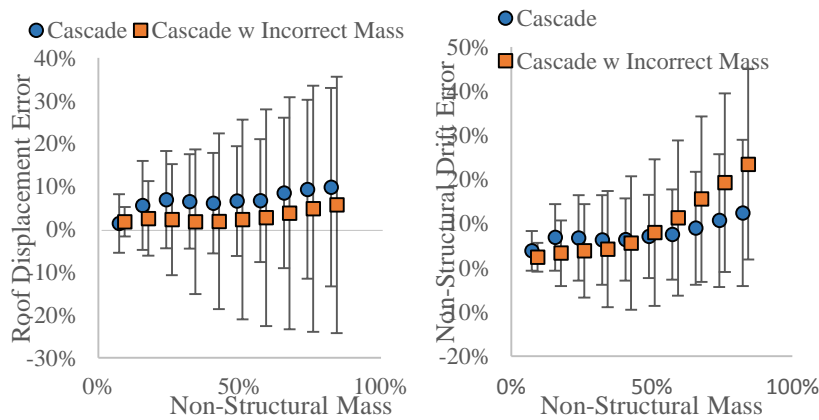
Figure 9. Comparison of building displacement errors (left), and drift demand errors (right), between the common cascade method and a variation.

The average drift recorded from this method was similar to that for the standard cascade method. It did, however, become less accurate for larger amounts of non-structural mass. At lower masses the method was more accurate, though this relationship does not necessarily hold true for other types of structure. These findings suggest that the cascade analysis can become quite inaccurate if a poor estimation of the non-structural mass is made, though for small variations in mass the error may be acceptable.

5 CONCLUSIONS

Overall it can be seen that the cascade method may provide an acceptable estimation of the drift demand for structures with non-structural pendulum elements. The cascade analysis is generally conservative in the estimation of the drift demand. The period of pendulums had no significant relationship to the error of the cascade analysis, however increased non-structural damping ratios result in the cascade analysis becoming more accurate.

The cascade method is generally very accurate in predicting the building response, and there is much lower variation associated with building displacement estimation than the non-structural drift.

For stiffness based non-structural elements, the cascade method provided similar errors to those seen for the pendulum element. However, the results were only acquired by modifying the current cascade method. The modification required the recording and application of nodal rotations in order to achieve sensible results. Further analysis may indicate whether this modification should be adopted.

Using a full modelling system with only a single damping ratio for all elements provided a much more accurate estimate with much lower variation for both pendulum and stiffness based elements, although the estimate is non-conservative so a factor of safety around 10 - 15% would need to be considered in order to use this method for design. It is, expected that the full model design method would not be utilized as it requires design of the main structure and non-structural elements simultaneously, while also having a significantly higher computational demand.

The results presented in this report are based on a very limited range of investigations, and further investigation is required in order to be confident enough to use the cascade analysis method for the design of any real-world structures, or their contents.

6 ACKNOWLEDGEMENTS

7 REFERENCES

Beléndez, A., Rodes, J., Beléndez, T. & Hernández, A. (2009). Approximation for a large-angle simple pendulum period. *European Journal of Physics, 30*(2), L25.

Filiatrault, A. & Sullivan, T. (2014). Performance-based seismic design of nonstructural building components: The next frontier of earthquake engineering. *Earthquake Engineering and Engineering Vibration, 13*(1), 17-46. doi:10.1007/s11803-014-0238-9

McKenna, F., Fenves, G., Filippou, F. & Mazzoni, S. (1999). Open System for Earthquake Engineering Simulation (Version 2.5.0) (Software). http://opensees.berkeley.edu/OpenSees/user/download.php.

Miranda, E. & Taghavi, S. (2003). *Estimation of seismic demands on acceleration-sensitive nonstructural components in critical facilities.* Paper presented at the Proceedings of the Seminar on Seismic Design, Performance, and Retrofit of Nonstructural Components in Critical Facilities.

Pourali, A., Dhakal, R., MacRae, G. & Tasligedik, A. (2015). Fully-Floating Suspended Ceiling System: Experimental Evaluation of Structural Feasibility & Challenges.