Quantifying Building Engineering Demand Parameters in Seismic Events

H.N. Dantanarayana, G.A. MacRae, R. P. Dhakal & T.Z. Yeow
University of Canterbury, Christchurch, New Zealand

S.R. Uma
GNS Science, Wellington, New Zealand

SUMMARY:
Engineering demand parameters (EDPs), such as inter-storey drift or floor acceleration, can be correlated to structural, non-structural and content damage within a structure. While current code provisions exist to estimate EDPs for design of components within a structure, their accuracy has not been rigorously quantified. This paper describes a robust and comprehensive study on 180 frame and wall type structural configurations using dynamic inelastic time history analysis with a suite of ground motion records to quantify drift and acceleration related EDPs. Parameters investigated included number of stories, design ductility and design target drift. It is shown that the current New Zealand code conservatively estimates median demands and the 84th percentile acceleration demands in most cases. However, the 84th percentile drift demands were often significantly greater than the code values implying that the code protects more against the possibility of damage due to acceleration, rather than drift, demands.

Keywords: *Engineering demand parameters, non-linear analysis, inter-storey drift, total floor acceleration*

1. INTRODUCTION

As a part of probabilistic based seismic design, it is essential that Engineering Demand Parameters (EDP), which are often used to estimate the amount of damage (structural, non-structural and content), can be quantified for a particular level of shaking. In order to carry out a comprehensive study a broad range of structures should be considered and the analysis model should be computationally efficient. This paper seeks to address this need by answering the following questions.

1. How does varying various structural parameters, such as structural system, building height and design drift/ductility affect drift and acceleration demands?
2. Are estimation techniques used in current codes adequate?

2. BACKGROUND

Damage to different components (structural, non-structural and contents) in buildings is generally related to the total accelerations or to interstorey drift (e.g. Mitrani-Reiser (2007), Aslani (2005)). Therefore, many studies have been conducted to determine the likely storey drifts and floor accelerations for structures of various types under different levels of seismic excitation. The results from such studies have been incorporated in many design codes. However, most studies have looked at only a relatively limited range of structures. A literature summary of these is given by Uma et al. (2010).

The current New Zealand Loadings Standard for earthquake actions, NZS 1170.5 (Standards New Zealand 2004), specifies that the maximum allowable inter-storey drift is 2.5% under design level shaking. Acceleration demands are specified by a floor height coefficient which is shown in Figure 1.

These coefficients are multiplied by the peak ground acceleration (PGA) to obtain the accelerations at higher floors in the structure.

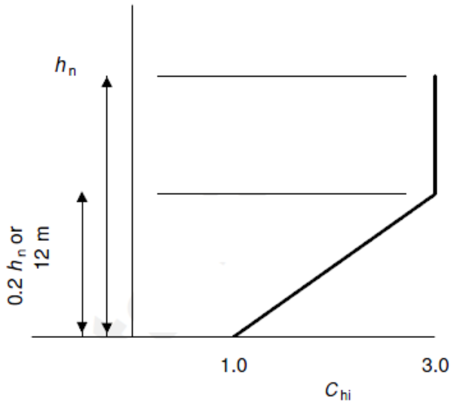


Figure 1. Floor Height Coefficient

In the past, shear type structures have been modelled using a combination of a vertical shear beam and a vertical flexural beam (e.g. Taghavi and Miranda 2004). Tagawa et al. (2004, 2006) showed that a shear-flexural-beam (SFB) model can represent the overall behaviour of frames well. This model uses the shear-beam model to resist the majority of the lateral forces, and the flexural beam, which is pinned at the base, models the column continuity effects over the height. Also, the range of column stiffnesses, both considering and neglecting the gravity and out-of-plane seismic columns, was characterised for realistic building. As the flexural beam stiffness approaches zero, each storey behaves as an independent single-degree-of-freedom (SDOF) system. This can result in large inter-storey drift concentrations due to soft storey mechanisms for structures with low post-elastic stiffness (Sadashiva et al (2009)).

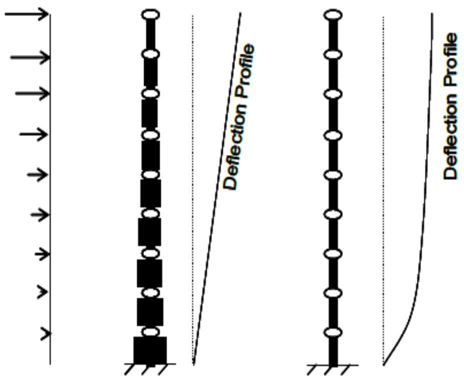


Figure 2: Deformed shape for different structural configurations

Rapid modelling techniques have been used by Sadashiva et al. (2009) for two extreme structural configurations of regular shear-type structures representing different types of frame system. One method is the Constant Inter-Storey Drift Ratio method (CISDR) shown in Figure 2a, where the member sizes decrease with height and the deflection profile is approximately linear. A target drift is set and then an iterative procedure is used to obtain the stiffness of each floor. The other method, shown in Figure 2b, is the Constant Stiffness method (CS), where member sizes are kept constant. Using the CS method, the peak inter-storey drift of each floor decreases with increasing floor height. It is expected that realistic shear type structures will have characteristics between those of these two extreme forms.

3. METHODOLOGY

3.1. Design Approach: Equivalent Static Method

Structures of 3, 9 and 15 storeys were designed for Wellington, New Zealand, using the NZS 1170.5 equivalent static method. P-Delta effects were included in design as per Method A in NZS 1170.5. The study incorporated structural ductility factors (equivalent to lateral force reduction factors, *R*) varying from 1-6, and the structures were designed to target drifts of 0.5%-2.5%. The NZS 1170.5 structural performance factor was assumed to be equal to unity in the design and analyses.

3.2. Structural Models

Three types of structures were developed. These were:

- Shear frames designed with constant stiffness over the height (CS)
- Shear frames designed with a constant interstorey drift ratio over the height (CISDR)
- Flexural wall designed with constant stiffness over the height

For all structures, an iterative procedure was used on the stiffness of each floor until the desired interstorey drift at the critical level was reached. For shear type structures, the critical level (i.e. that with the maximum drift) was at the bottom floor, while for the wall structural structures it was at the top floor.

The methodology used to evaluate floor acceleration and inter-storey drift demands was as follows.

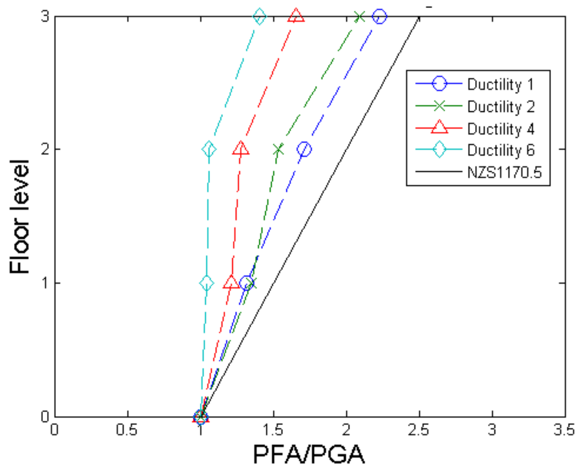
1. Select the structure (i.e. number of storeys, design ductility, target drift, and form (e.g. wall, CS frame, or CISDR frame).
2. Using MATLAB the structure is designed according to NZS1170.5 for the input parameters selected. The resulting model is a fixed base beam for the wall structures and a SFB model for frame structures. The flexural beam stiffness is the minimum found in realistic structures (Tagawa, 2006). This design was carried out using an iterative procedure on the stiffness of the elements.
3. Conduct an inelastic dynamic time-history analysis using the 20 SAC LA 10in50 ground motion records scaled to the Wellington seismicity. The finite element analysis software RUAUMOKO was used (Carr, 2005) with 5% constant model damping. The hysteresis model that was used is the bi-linear hysteresis loop with a post-elastic stiffness ratio of 1%.
4. For each ground motion record, the peak total acceleration demand and inter-storey drift for each floor is extracted. The 20 sets of data are then used to find the median and 84th percentile demands using a lognormal distribution, which is then plotted as a function of the height along the structure.

A base design case was selected in order to facilitate comparison of the behaviour. This is a steel structure with 3 metre storey height, floor mass of 20,000kg, 2.0% target drift, bi-linear hysteretic model and a 5% constant modal damping.

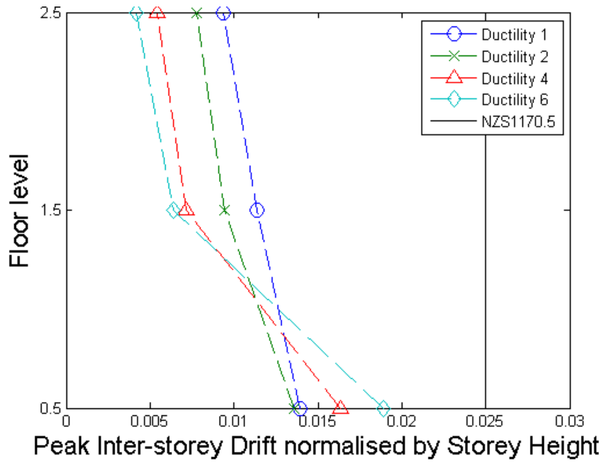
4. SEISMIC BEHAVIOUR

4.1. Shear type structures: CISDR method

Figures 3 and 4 show the median acceleration and drift demands for a 3-storey and 9-storey structure designed for 2.0% constant inter-storey drift. The acceleration demands become more uniform as the height of the structure increases so the effect of design ductility is reduced. Figures 3a and 4a show that increasing the design ductility has the effect of decreasing the acceleration demands as yielding occurs in the lower stories providing an isolation effect on the upper stories. Therefore, the structure tends to filter the high frequency content of ground motion resulting in a deamplification of total floor accelerations up the height of the structure.

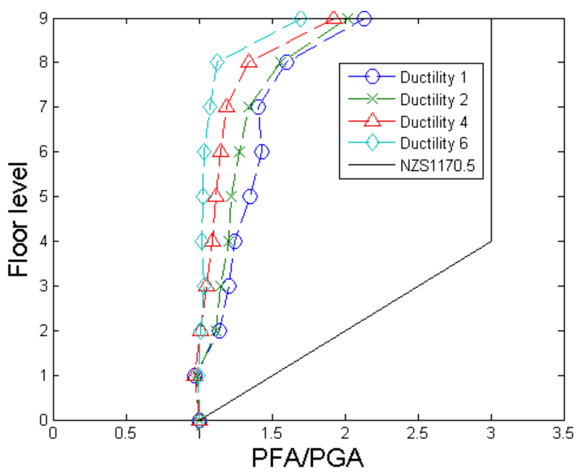


(a) Peak floor acceleration demand normalised by peak ground acceleration

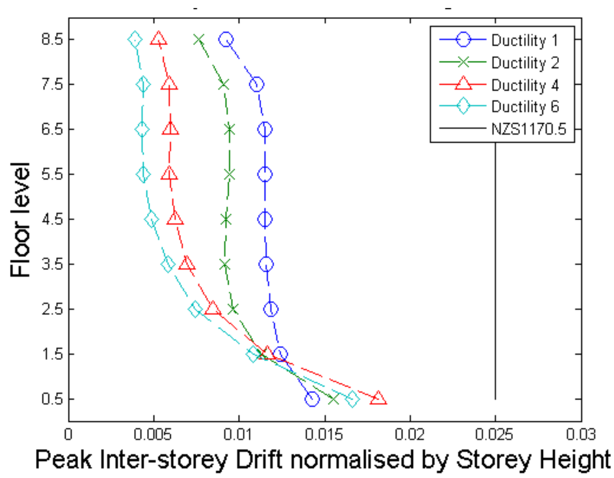


(b) Peak inter-storey drift demand normalised by storey height

Figure 3. Median demands for a 3-storey shear-type structure designed for 2.0% target drift using CISDR method



a) Peak floor acceleration normalised by peak ground acceleration



(b) Peak inter-storey drift demand normalised by storey height

Figure 4. Median demands for a 9-storey shear-type structure designed to 2.0% target drift using the CISDR method

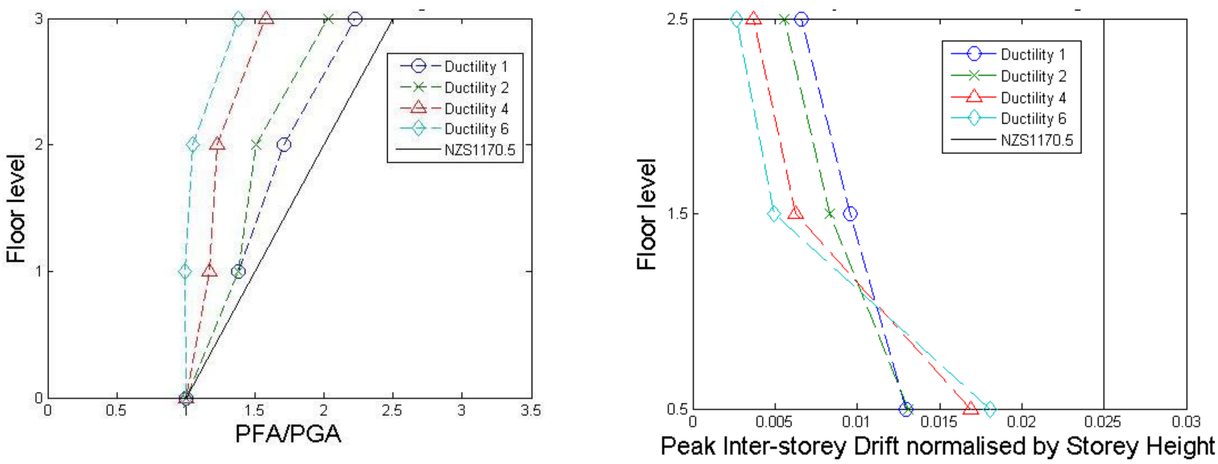
It can be seen that the spectral shape factor specified by NZS1170.5 shows a good approximation of acceleration demands for 3-storey shear structures designed using the CISDR method. However, Figure 4a shows that as the number of stories increases to 9, the acceleration demands become more uniform, and the spectral shape factor significantly overestimates acceleration demands for these structures. This effect was also observed for 15-storey shear type structures.

Figures 3b and 4b show the drift demands on 3-storey and 9-storey structures respectively. The drift demands at the base of the structure increase with increasing design ductility. This is caused by yielding of the columns at the base of the structure resulting in large inelastic first floor deformations. Structures with a higher design ductility have a lower yield moment and therefore undergo greater inelastic behaviour due to yielding occurring earlier. Because the lower storey yielding causes the higher floors to be essentially base isolated, this significantly reduces the inter-storey drift demands on these floors. Figure 4b shows that the effect of the base isolation on the upper floors increases with increasing ductility.

4.2. Shear type structures: CS method

Figures 5 and 6 show acceleration and drift demands for shear type structures designed to 2.0% target drift using the CS method. These frames have elements of the same size over their height.

The median total acceleration demands are shown in Figures 5a and 6a. The acceleration demands show the same trend as for the CISDR method with increasing design ductility resulting in decreased acceleration demands.

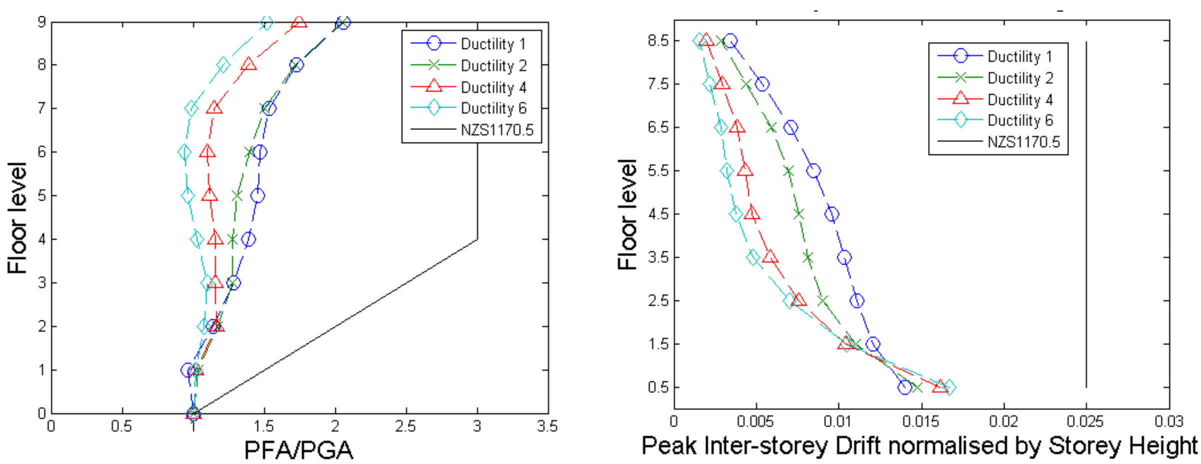


(a) Peak floor acceleration normalised by peak ground acceleration

(b) Peak inter-storey drift demand normalised by storey height

Figure 5. Median demands for a 9-storey shear type structure designed for 2.0% target drift using CS method

Comparing Figure 4b to Figure 6b, the drift demands for structures designed using the CS method tend to continue to decrease at higher levels, whereas with the CISDR method the drift demands for the higher floors are relatively constant. This is in accordance with expectations from the design methods used as shown in Figure 2.



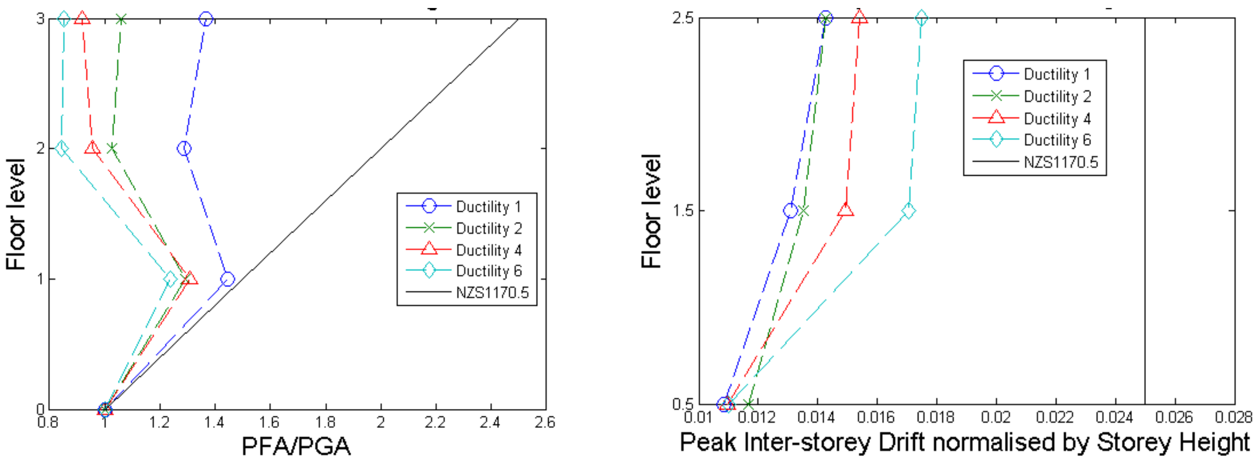
(a) Peak floor acceleration normalised by peak ground acceleration

(b) Peak inter-storey drift demand normalised by storey height

Figure 6. Median demands for a 9-storey shear type structure designed for 2.0% target drift using CS method

4.3. Flexural (Wall) type structures

Figures 7 and 8 show the median normalised acceleration and drift demands for wall type structures designed to 2.0% target drift. Figures 7a and 8a show that acceleration demands on a flexural type structure peaks at the first floor. Beyond the first floor, acceleration demands tend to decrease along the height of the structure. The increase in acceleration at the first floor is modelled well by the spectral shape factor from NZS1170.5. However, the shape factor significantly over estimates the acceleration demands beyond the first floor.

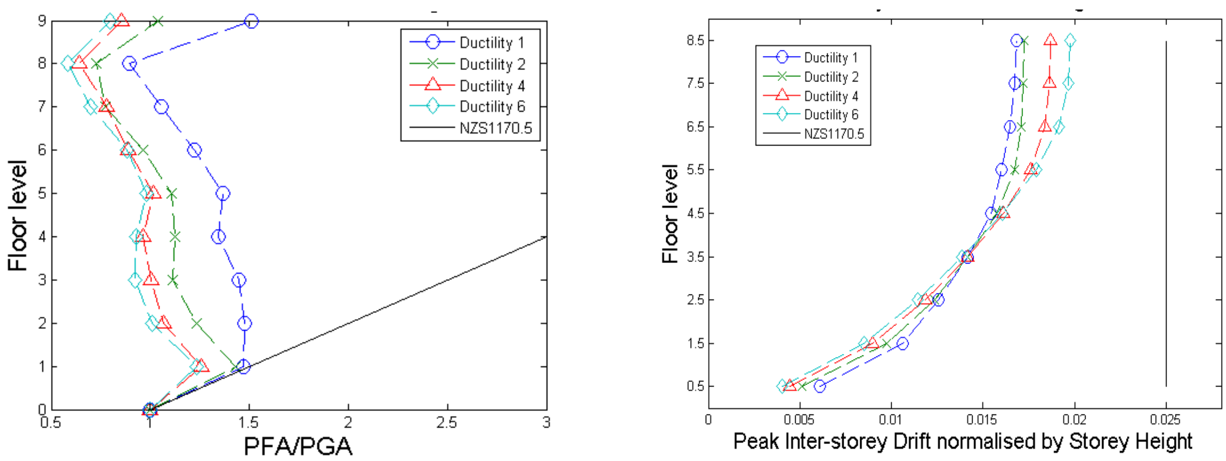


(a) Peak floor acceleration demand normalised by gravity

(b) Peak inter-storey drift demand normalised by storey height

Figure 7. Median EDP demands for a 3-storey flexural type structure designed for 2.0% target drift using CS method

The inter-storey drift profile for wall (flexural type) structures shows that the maximum inter-storey drift occurs at the top level of the structure. This is different for shear-type structures where the peak drift occurs at the base. Both types of structure were designed for a target drift ratio of 2%, and the median drift ratio demands were generally less than this value.



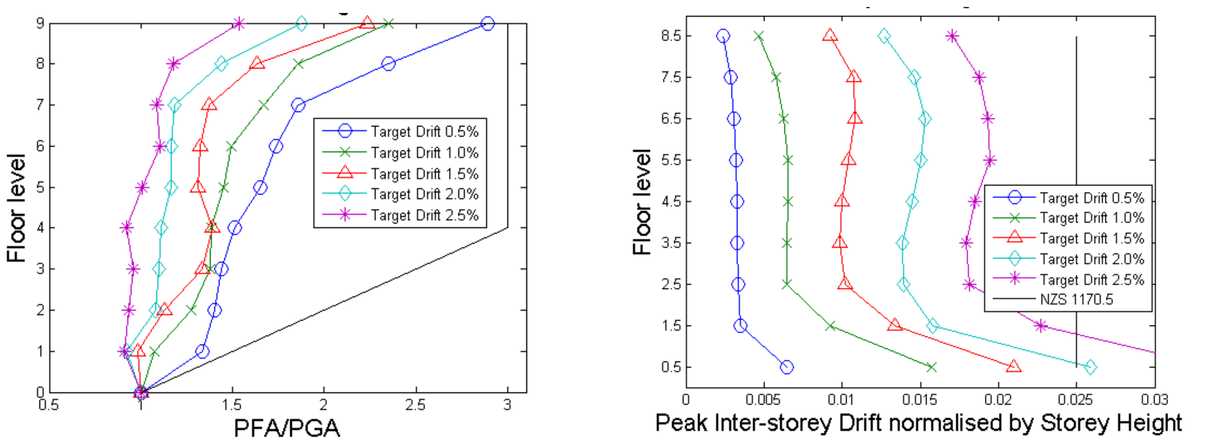
(a) Peak floor acceleration demand normalised by peak ground acceleration

(b) Peak inter-storey drift demand normalised by storey height

Figure 8. Median EDP demands for a 9-storey flexural type structure designed for 2.0% target drift using CS method

4.4. Effect of Design Inter-storey drift

Figures 9 and 10 show the 84th percentile drift and acceleration demands on structures designed to various target drift limits. The values shown in the figures are the maximum 84th percentile values for structures with design ductilities of 1, 2, 4 and 6.

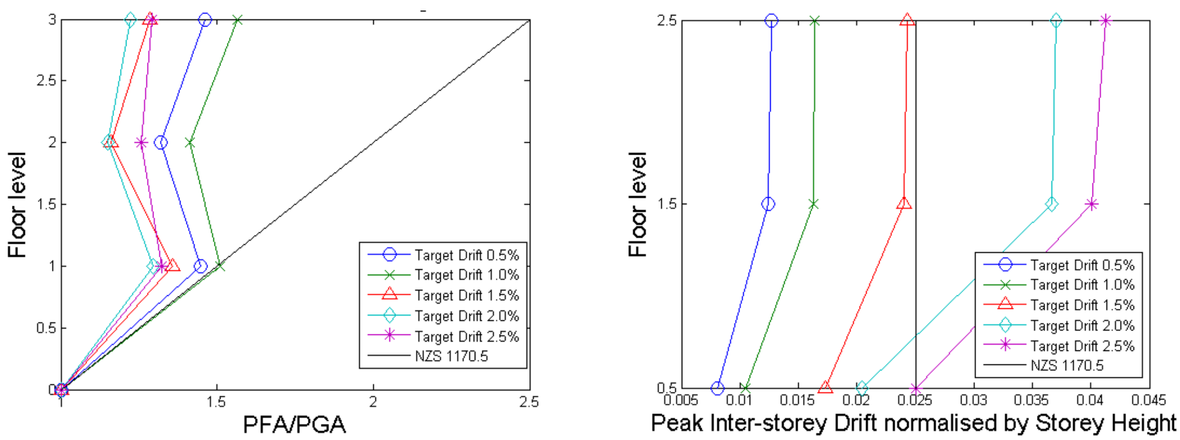


(a) Peak floor acceleration normalised by peak ground acceleration **(b)** Peak inter-storey drift demand normalised by storey height

Figure 9. The maximum 84th percentile EDP demands for design ductilities of 1, 2, 4, and 6 for a 9-storey CISDR shear type structure considering various design target drifts

Figure 9a shows that increasing the design target drift limit decreases the acceleration demands on the structure. This is because increasing the design target drift results in a lower stiffness, longer period structure which attracts lower acceleration demands. Structures designed using the CS method showed similar trends to those designed using the CISDR method. In both cases, the code design acceleration was greater than the 84th percentile demands. Figure 9b shows that for a shear type structure designed using the CISDR method, the peak inter-storey drift occurs between the ground floor and the first floor. Also the 84th percentile drifts are often more than 25% greater than the target drift.

Figure 10 shows the acceleration and drift demands on a 3-storey flexural type structure under varying design target drift. Again, target drift demands were significantly exceeded. Also, the 84th percentile acceleration demands were less that the code design level. This raises the question, "Why are we designing to protect our structures more against damage related to acceleration demands than against drift demands?"



(a) Peak floor acceleration normalised by peak ground acceleration **(b)** Peak inter-storey drift demand normalised by storey height

Figure 10. The maximum 84th percentile EDP demands for design ductilities of 1, 2, 4, and 6 for a 3-storey CISDR shear type structure considering various design target drifts

5. CONCLUSION

A comprehensive analytical study of a large range of different frame and wall type structural configurations was conducted to examine the effect different structural parameters, such as building height or type of structural system, can have on building engineering demand parameters. It was found from this study that:

1. Frame structures were observed to have a maximum interstorey drift at the base of the structure, whereas for wall structures this occurred at the top level of the structure. In both cases the maximum interstorey drift increased with increasing design ductility. Acceleration demands were found to decease with increasing design target drift and ductility. This is due to the reduction in stiffness as the structure undergoes larger displacements, which results in the attraction of lower floor accelerations. Floor accelerations were found to become more uniform as the height of the structure increases.

2. The current code provisions (considering a structural performance factor of unity) are adequate to represent the median demands. Also, the 84^{th} percentile total accelerations were less than the code design recommendations. However, the 84^{th} percentile drift demands may be more than the 2.5% code target design drifts. Discussion is required regarding whether or not more protection is required against large accelerations than against large drifts.

ACKNOWLEDGEMENTS
The authors wish to thank Dr. Vinod Sadashiva for his help with MATLAB and RUAUMOKO as well as Brett Miranda and Richard English for their continued support. A first draft of this paper was included in the 2012 NZSEE conference proceedings.

REFERENCES

Aslani, H. (2005). Probabilistic earthquake loss estimation and loss disaggregation in buildings, Stanford University, Stanford, CA.

Carr, A. J. (2010). Ruaumoko2N: Dynamic Analysis of 2 Dimensional Inelastic Structures. Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand.

Dantanarayana, H.N., MacRae, G.A., Dhakal, R., Uma, S.R., Yeow, T.Z. (2012). Quantifying Building Engineering Demand Parameters in Seismic Events. *NZSEE Conference*, Christchurch, New Zealand April 13-15.

MacRae, G.A. (2010). The Development and use of the Continuous Column Concept. *5th International Conference on Earthquake Engineering*, Tokyo, Japan, March 3-5.

Mitrani-Reiser, J. (2007). An Ounce of Prevention: Probabilistic Loss Estimation for Performance-based Earthquake Engineering, California Institute of Technology, Pasedena.

Sadashiva, V.K., G.A. MacRae, and B.L. Deam. (2009). Determination of Structural Irregularity Limits – Mass Irregularity Example, Bulletin of the New Zealand Society for Earthquake Engineering, **42:4**, 291 - 293.

Singh, J., G. A. MacRae, R. P. Dhakal, S. Pampanin. (2011). Building seismic ceiling fragility using spectral acceleration. *Ninth Pacific Conference on Earthquake Engineering*, Auckland, New Zealand, 14-16 April.

Standards New Zealand. (2004). NZS1170.5:2004 – Structural Design Actions Part 5: Earthquake actions.

Tagawa H., MacRae G., and Lowes L. (2004). Evaluations of 1D Simple Structural Models for 2D Steel Frame Structures. *13th World Conference on Earthquake Engineering*, Vancouver, August 2004.

Tagawa, H., MacRae, G. A. and Lowes, L. N. (2006). Evaluation of simplification of 2D moment frame to 1D MDOF coupled shear-flexural-beam model. *Journal of Structural & Constructional Engineering. (Transactions of AIG)*, No. 609.

Taghavi, S., and E. Miranda. (2004). Estimation of Seismic Acceleration Demands in Building Components. *13th World Conference on Earthquake Engineering*, Vancouver, Canada, August 1-6.

The MathWork , Inc. (2010). MatlabR2010b

Uma, S.R., J.X. Zhao, and A.B. King. (2010). Seismic Actions on Acceleration Sensitive Non-Structural Components in Ductile Frames, Bulletin of the New Zealand Society for Earthquake Engineering, **43:2**, 110 – 124.