Vertical spectral demands on building elements induced by earthquake excitation.

T.C. Francis & B.C. Hendry

Beca Ltd & Department of Civil Engineering, University of Canterbury, Christchurch.

T.J. Sullivan

Department of Civil Engineering, University of Canterbury, Christchurch.

2017 NZSEE Conference

ABSTRACT: Certain building elements are sensitive to vertical acceleration demands imposed by earthquakes. In many countries and building design codes it is common practice to make simplistic estimations to determine vertical design spectra based on site specific horizontal spectra. Previously in the New Zealand Standard (NZS1170.5), a scaling factor of 0.7 was applied to the horizontal spectral acceleration to determine the vertical design spectrum. This value is used due to past research efforts indicating the vertical to horizontal acceleration ratio is around 2/3. The vertical spectrum at the base of the building is then applied at all levels without consideration of possible filtering and dynamic amplification effects. This paper investigates the effects of filtering and amplification of the vertical spectral demands by modelling and subjecting a four storey reinforced concrete wall building to a number of non-linear time history analyses. Vertical spectral acceleration demands are determined in various locations up the height of the building including in wall and beam sections. The ratio of vertical acceleration found at these locations to the input vertical acceleration of the ground indicate amplification factors greater than seven may be possible. Sensitivity studies were conducted indicating the results are applicable to a range of structural properties and modelling assumptions. Further research should investigate methods for predicting vertical amplification effects in a range of building typologies. Ultimately, it is desired that a method for predicting vertical demands throughout the height of a structure be implemented in the code.

1 BACKGROUND AND OBJECTIVES

During an earthquake buildings are subjected to movement in all three Cartesian directions with the horizontal components typically being attributed to causing the most structural damage. Hence, buildings have been developed principally to resist horizontal earthquake loading. However, the effect of the vertical component of ground motions is only briefly considered, with most countries simply adopting a 'scale factor' approach which reduces the horizontal acceleration demands for use in the vertical direction.

Three modern design codes were investigated to determine various approaches for dealing with vertical acceleration, (i) EUROCODE 8 (2004) (ii) American Society of Civil Engineers Standard (2010) (iii) NZS1170.5 (2004). All codes use a scaling approach for determining vertical design spectra. The New Zealand Earthquake Structural Design Actions code (NZS1170.5) previously stated that a scale factor of 0.7 shall be applied to the horizontal spectrum to determine the acceleration spectrum for vertical design[1]. The scaling factor is based on the work by Newmark (1973) where 14 strong ground motions were analysed finding that *"the acceleration ground value for a given site for the vertical spectrum should be based on an acceleration of roughly 2/3 that for the horizontal motion"*. Review of a number of documents relating the horizontal and vertical components of ground

[1] Determination of the site hazard spectra for vertical loading has been updated to include the effect of the soil class, period length, and source to site distance.

motions indicate the broad use of this scale factor is outdated and inaccurate. Previous studies from Bozorgnia & Campbell (2004) suggest that the ratio of vertical to horizontal ground accelerations (V/H) is strongly sensitive to the period, with short periods showing larger ratios than longer periods. Also, studies on near source regions suggest that V/H spectral ratios can exceed 1.8 at short periods and short distances whereas at long periods this ratio is generally less than 0.5 (Lee et al, 2013). This has important implications for the spectral accelerations experienced at different levels of a building. If international codes are currently under predicting the vertical site demand, then it is likely the demands within the building itself are not accurately represented. Therefore, the purpose of this research will be to indicate the behaviour of vertical accelerations in different building elements in an effort to implement improved demand predictions in the code.

The vertical spectrum at any level can be computed from acceleration response histories at various stories as shown in Figure 1. These spectra may differ significantly at each level due to filtering and amplification of ground accelerations.

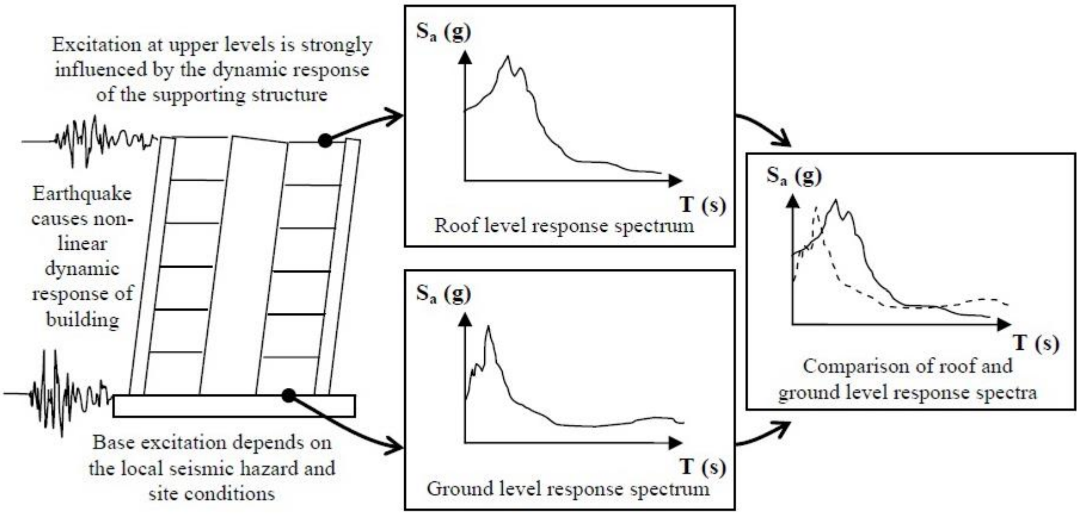

Figure 1. Schematic indicating the filtering and possible amplification of vertical ground motions through the height of a building from Sullivan et al. (2013).

Recent research has shown that the vertical acceleration demand increases with height of a building. Simplified modelling methods from Moschen et al. (2015) indicated the peak floor acceleration of a "stick model" can increase by a factor of four for buildings between 3 and 24 stories tall. Given this, an objective of this paper will be to expand on this research by examining vertical acceleration demands and associated spectra in beam and floor slab elements of a four storey building subject to accelerations imposed in the Christchurch earthquake sequence, known for its particularly high levels of vertical acceleration. The effect of amplification will be documented by determining ratios between vertical spectra at different locations in a building and the peak vertical ground acceleration (PGA_v). The effect of low and high intensity earthquakes on the amplification of vertical spectra throughout the model will be measured and compared.

Furthermore, a special study was undertaken to determine whether or not the vertical acceleration component varies with earthquake intensity (intensity taken as PGA). This will give some indication on when the vertical effects are likely to be more significant.

2 METHODOLOGY

Ruaumoko (Carr, 2016) has been used to analyse the response of various building elements to ground motions in both the horizontal and vertical directions. A simple four-storey two dimensional building model was designed and depicts a simple concrete structural wall type building seen across New Zealand. The model consists of a central 4 m wide structural concrete wall with 8 metre long beams

spanning from the wall to perimeter gravity columns. The layout of the Ruaumoko model can be seen in Figure 2.

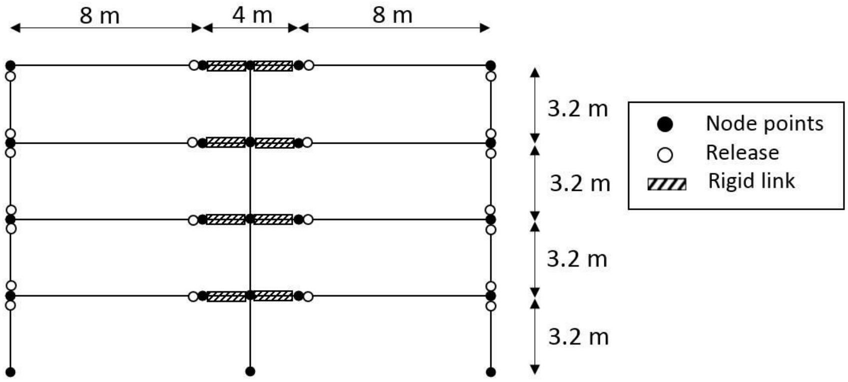

Figure 2. Ruaumoko building model to examine vertical spectral demands with a set of NLTH analyses.

Beam elements were used with cracked section properties and lumped masses along its length. The wall section was also modelled using a reduced (effective) stiffness. Lumped masses were placed at each level up the wall. The reduced stiffness of the wall was initially modelled at 30% of the gross stiffness which agrees with NZS3101 (2006) recommendations.

Weights on the structure were calculated through tributary widths and areas of the wall, beams and perimeter column of the model. To capture the response of the level 1 and level 4 beams in the model, each beam was subdivided into numerous elements. Weights were then assigned to the subdivided elements. This meant that modal shapes and fundamental periods of the model elements could be retrieved from the Ruaumoko output.

Numerous dynamic non-linear time history analyses (NLTHA) using the Newmark Constant acceleration method were run in Ruaumoko (Carr, 2016). The analysis was carried out using an integration time step of 0.001 seconds where large displacement effects were considered. Damping of the structure was modelled using Rayleigh damping with a tangent stiffness matrix used to produce the secant damping matrix with 2% damping imposed on the first mode of vibration and 5% on the second mode. The wall was considered to carry all of the lateral resistance in the horizontal direction. The potential plastic hinge region of the wall was in line with recommendations from Priestley (1996).

The spectral demands throughout various locations of the building were predicted for 20 different ground motions. 10 of these ground motions were chosen from the February 2011 Christchurch earthquake (M_L 6.2) to represent high intensity ground accelerations. A further 10 records from the June 2011 Christchurch aftershock (M_L 6.0) were chosen to represent low intensity ground shaking. For the purpose of this study, a cut off value of 0.1 g (PGA) in the vertical direction was used to differentiate between high and low intensity. All ground motions chosen from the February 2011 event had peak accelerations significantly higher than 0.1 g with most exceeding 0.6 g in both vertical and horizontal components. The largest PGA was 2.2 g in the vertical direction measured at Heathcote Valley Primary School.

To determine the vertical spectra at various points in the structure, nodal accelerogram time histories were extracted from DYNAPLOT (Carr, 2016). The vertical spectral acceleration was then plotted and the peak amplification ratio (denoted ω) between the response of elements within the building and the vertical ground spectra could be found. The peak response was determined for the fundamental period of the element of interest as this generally resulted in the largest amplifications. The fundamental period in the vertical direction could be determined from the modal outputs of the analysis.

The damping characteristics of the model were changed to determine the sensitivity of the results obtained from the NLTH analysis. By comparing outputs from various damping models it could be determined how dependant the amplification of the ground motion in the building was on the damping model used. Additionally, the weights and inertia modelled in the structural wall were changed to further analyse whether the results obtained were sensitive to the stiffness and period of the wall.

Therefore determining whether the model was applicable to a range of building typologies with varying stiffnesses, mass and periods.

The maximum vertical to horizontal acceleration ratio was then computed for each recorded ground motion of the Christchurch sequence. The RotD100 acceleration value, which is the maximum PGA value obtained after rotating the horizontal components of the ground motion record through all angles, was used for normalising the peak vertical demand to produce the vertical to horizontal ratio (PGA_v/PGA_h). This ratio was plotted against the PGA_h to determine whether the V/H ratio varies with earthquake intensity.

2.1 Results

2.1.1 *Vertical Spectral Demands for Beam Members*

Vertical spectral demands were determined for the mid-section of the wall and mid-span of the beam element at the first and top floor levels. In Figure 3a the comparison between the vertical acceleration spectrum and the peak vertical ground acceleration are shown. A significant peak in vertical acceleration can be seen at the mid-span of the beams at both the roof and first level. This peak corresponds to a fundamental period of the first storey and roof beams of 0.220 seconds and 0.209 seconds respectively. An amplification ratio between the roof storey beam and the ground acceleration for the same period was determined to be approximately 7.44 and 7.78 for level one and level four respectively. These demands are significantly higher than what was predicted by Moschen et al. (2015) who proposed an amplification of four for peak floor accelerations.

(a) (b)

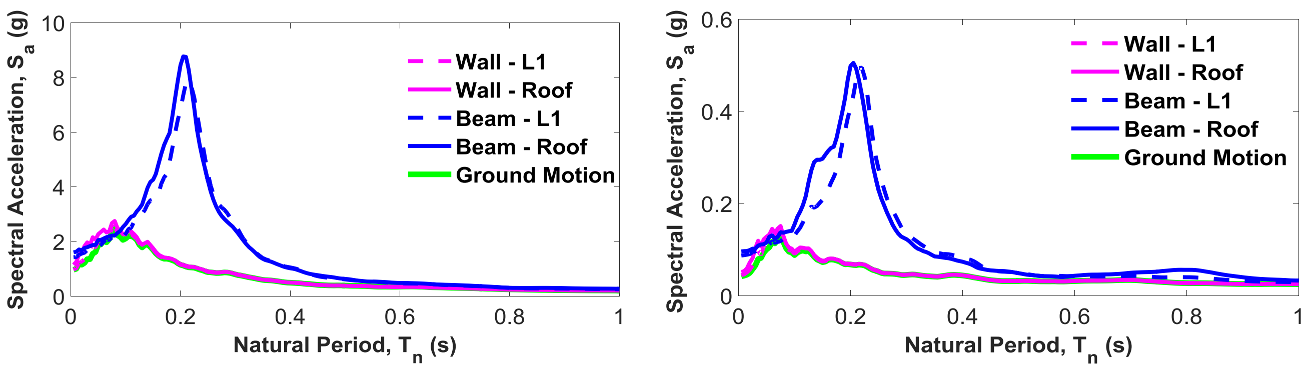

Figure 3. Mean vertical acceleration spectra for various model locations compiled using 10 different ground motions. (a) For high intensity ground motions and (b) for low intensity ground motions. A cut off intensity of 0.1 g in the vertical direction was used to differentiate between high and low intensity.

In reference to NZS1170.5 and the design of elements based on the scaled vertical spectrum, the actual demand will be significantly higher than required for design. In particular, Figure 3a shows components with fundamental periods between 0.1 and 0.3 seconds will be vulnerable to these amplified spectral demands. The current code may therefore be inadequate and grossly under predict the actual spectral response.

In Figure 3b the response of the model to low intensity ground motions is shown. The response to these ground motions was similar to that shown in Figure 3a. The roof storey beam shows a similar amplification ratio to the beam model of 7.29.

Comparing the response from high and low intensity ground motions in Table 1 shows that there is little effect on the amplification of the vertical acceleration with differing intensity earthquakes. This means even for locations with low seismicity and lower design demands, the vertical component of shaking is still likely to be significantly amplified for short period elements and should be considered.

Table 1. Comparison of the spectral amplification ratio (ω) when the analysis is run for low and high intensity Christchurch ground motions.

	High		Low	
	T_v	ω	T_v (s)	ω
Wall (Level 1)	0.02	1.11	0.0298	1.0
Wall (roof)	0.02	1.50	0.0298	1.0
Beams (Level	0.22	7.44	0.220	7.2
Beam (roof)	0.20	7.78	0.209	6.9

2.1.2 *Vertical Spectral Demands for Floor Slabs*

Figure 4 shows the vertical acceleration spectrum at various locations throughout the building with a floor slab in place of the beam elements. This was done by reducing the inertia of the beam elements in the model to resemble the inertia of a typical hollow core floor slab used in New Zealand.

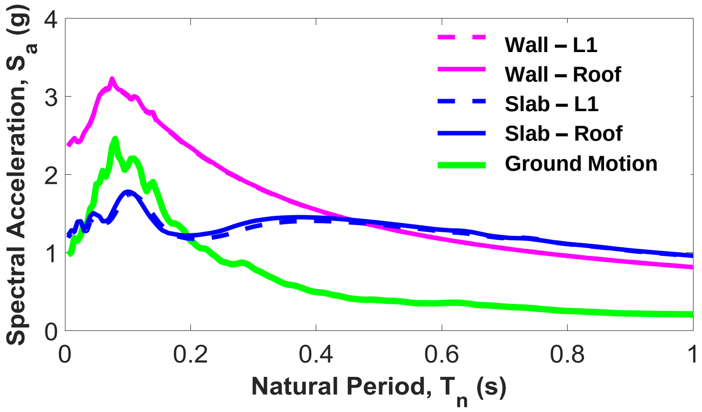

Figure 4. Mean vertical acceleration spectra when modelling floor slabs.

When a hollow floor slab was modelled in Ruaumoko no apparent peak in vertical spectral floor acceleration was evident. However, the amplification ratio of the wall at its first vertical mode increased compared to the model with beam elements (1.99 compared to 1.02 at roof level). This may have been due to the effects of higher modes in the floor although further research should be completed in order to fully determine the cause of effects observed.

2.2 Model Uncertainty and Sensitivity Study

To assess the impact of the assumed damping model, various values of damping were altered and the analysis repeated to compare differences in the response. The percentage damping coefficient was altered for three cases which were then run against the ground motion measured at Christchurch City Hospital from the February 2011 Earthquake. This was representative of moderately large accelerations in the February 2011 event. Table 2 shows the damping models considered. The values of percentage damping were applied to the first two modes (horizontal first mode of the wall and vertical first mode of the lower beam) of the structure in which the damping on further modes is calculated based on a Rayleigh damping model.

Table 2. Different damping models used on the Ruaumoko model.

Damping model	1	2	3
% Damping on 1st mode	2	2	5
% Damping on 2nd mode	5	2	5

In Figure 5 the response of the top floor beam is shown and compared between the three damping models. The legend shown in the figure indicates the percentage damping on the first two modes of the beam element (M1 and M2) as determined by the first two modes of the global structure. As expected, when the damping ratios are changed the period of elements in the building remain similar. The three models also give similar spectral shapes of the vertical response. However, the change in damping alters the peak vertical spectral accelerations of the beam. With less damping the acceleration is greater and therefore the amplification ratio of elements within the building will be greater. The increase in amplification is therefore proportional to the damping ratio corresponding to a particular mode of vibration.

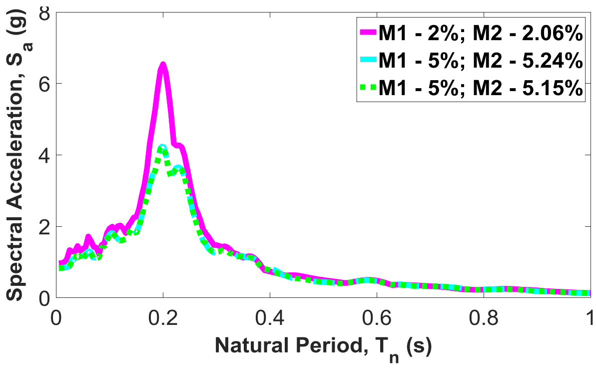

Figure 5. Impact of damping assumption on the top floor beam vertical acceleration spectrum.

Additional sensitivity of the model was checked by changing the mass and stiffness combinations of the wall section with four different models. The vertical weights in Ruaumoko were kept constant across the four models and the weights in the horizontal direction were altered. Two different inertias were also used; the effective inertia used in the previous analyses and a gross inertia of the wall in order to increase lateral stiffness. Each model therefore gave a different overall period for the structure. In Table 3 the mass and stiffness of the wall in the four models is shown along with the corresponding fundamental period of the structure.

Table 3. Period of building models with varying mass on each floor and inertia of the concrete wall.

	Weight per floor (kN)	I (m^4)	T_1 (s)
Model 1	2500	0.48	0.823
Model 2	2500	1.60	0.613
Model 3	1250	0.48	0.582
Model 4	1250	1.60	0.433

The plot on Figure 6 shows the vertical spectra for the roof beam in the structure. The spectral response is relatively similar over the four models showing a similar period and amplitude of spectral acceleration.

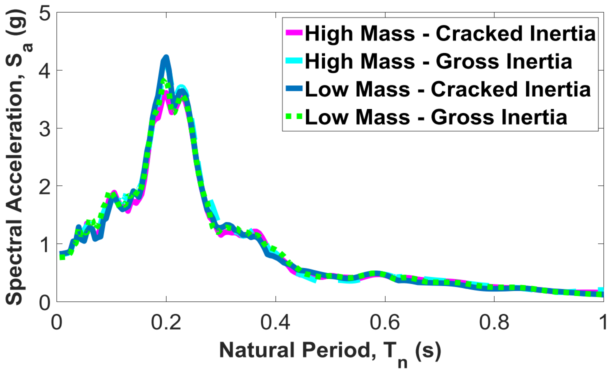

Figure 6. Sensitivity of the building model to weights and inertia on the structural wall.

Spectral amplification was shown not to change significantly with the properties considered. The amplification of the beam elements can therefore be considered as independent of the fundamental period of the structure. This is an important finding as it implies the research presented in this paper may be applied to other structural systems and similar spectral amplification phenomena can still be expected.

2.3 The Effect of Earthquake Intensity on the V/H Ratio

Figure 7 shows the vertical to horizontal ratio against peak ground acceleration for the two Christchurch earthquakes considered. Peak horizontal accelerations were computed using the RotD100 method. These were plotted on a log scale to aid interpretation of data given there are significantly fewer high intensity records compared to low intensity records.

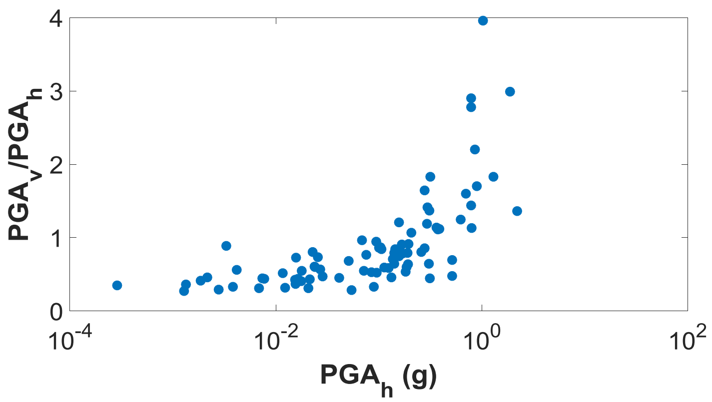

Figure 7. V/H ratio as a function of the peak RotD100 horizontal acceleration for the Christchurch sequence.

The clear trend from the Christchurch sequence indicates the V/H ratio increases with horizontal intensity. This is an important implication as it means there is a disproportionate increase in the total vertical and horizontal demand as the horizontal demand increases. Furthermore, this indicates that for particularly strong ground motions there will usually be a significant vertical component that requires careful consideration for design. In particular, for near source sites and high levels of vertical acceleration demand, damage in beam and floor slab elements may be highly under predicted.

3 CONCLUSIONS

Current building codes only briefly consider vertical accelerations by using broad approximations to determine the vertical spectral demand. NZS1170.5 recently used a scaling factor of 0.7 applied to the horizontal spectrum to determine the vertical spectrum. This factor was based on work by Newmark (1973) who stated the vertical acceleration component was approximately 2/3 of the horizontal component. The V/H ratio was computed for two recorded events in the Christchurch sequence and was shown to increase as the earthquake intensity increases. This means the likelihood of experiencing larger vertical accelerations is related to the horizontal intensity, meaning for large ground motions there will usually be a significant vertical component that requires careful consideration for design. There is potential for further research to be carried out to determine similar relationships for different seismic regions to compare trends.

A building model was subjected to a NLTH analysis for a number of high and low intensity ground motions from the Christchurch earthquake sequence. Vertical spectral demands were produced for the beam and wall on the first and fourth storey. The spectral amplification factor, ω, was computed which is the ratio of the peak vertical spectral demand at these locations to the input peak vertical ground motion spectrum. The wall element is relatively rigid in the vertical direction which meant the vertical spectra were not significantly amplified for either low or high intensity earthquakes resulting in relatively low spectral amplification factors (<2). The beam elements were significantly amplified for

both low and high intensity cases with amplification ratios greater than 6 with a maximum predicted of 7.78. Although NZS1170.5 now considers higher vertical to horizontal ratios for various periods, soil classes, and source to site distances, amplification of vertical accelerations in certain building elements and locations are still not currently considered by the code. Further research will be required to determine appropriate recommendations to account for this in future standards. In addition, further research may be undertaken to determine what types of building elements may be susceptible to these amplified spectral accelerations.

When a typical hollow floor slab element was modelled no apparent peak in the spectral acceleration was shown. However, the top of the structural wall showed slightly higher amplification compared to the beam model. This may have been due to the effects of higher modes in the floor although further research should be completed in order to fully determine the effects observed.

The effect of damping on the first and second mode periods of the top beam was also determined. Results indicated that a higher critical damping on the first mode of vibration for the top floor beam element reduced the amplification of the ground motion. The decrease in amplification, as expected, was proportional to the amount of damping on the element of interest.

Finally, the seismic mass and lateral stiffness of the central wall were altered to determine if the vertical spectra of the beam elements were dependant on the translational behaviour of the building. A plot of vertical spectra produced with different mass/stiffness combinations and different periods indicated the change in vertical response was minimal. This finding suggests similar results regarding the amplification of vertical spectra, particularly in long beam elements, will be applicable to a range of structures.

4 REFERENCES

ASCE/SEI 7-10. (2010). Minimum Design Loads for Buildings and Other Structures. American Society of Civil Engineers.

Bozorgnia, Y., & Campbell, K. (2004). The Vertical-to-Horizontal Response Specra Ratio and Tentative Procedures for Developing Simplified V/H and Verical dsign Spectra. Journal of Earthquake Engineering, 8(2), 175-207.

Calvi, P. M., & Sullivan, T. J. (2014). Estimating Floor Spectra in Multiple Degree of Freedom Systems. Earthquakes and Structures, 6(7), 17-38.

Carr, A. J. (2016). Ruaumoko3D - A Program for Inelastic Time-History Analysis. New Zealand: Department of Civil Engineering, University of Canterbury.

CEN EC8 . (2004). Eurocode 8 - Design Provisions for Earthquake Resistant Structures, EN-1998-1:2004. Brussels, Belgium: E, Comite Europeen de Normalization.

Lee, R. L., Franklin, M. J., & Bradley, B. A. (2013). Characteristics of Vertical Ground Motions in Canterbury Earthquakes. 2013 NZSEE Conference, (pp. 1-8). Christchurch.

Moschen, L., Medina, R. A., & Adam, C. (2015). Vertical Acceleration Demands on Nonstructural Components in Buildings. Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering.

Newmark, N. M. (1973). A Study of Vertical and Horizontal Earthquake Spectra. Washington D.C.

NZS1170.5; 2004. (2004). Structural Design Acions, Part 5: Earthquake Actions - New Zealand. Standards Council of New Zealand.

NZS3101; 2006. (2006). Concrete Structures Standard. Standards Council of New Zealand.

Priestley, M. (1996). Displacement-Based Seismic Assessment of Existing Reinforced Concrete Buildings. Bulletin of the New Zealand National Society for Earthquake Engineering, 29(4), 256-272.

Ryan, K. L. (2016). Lessons Learned from 3D Shake Table Testing of a Full-Scale Seismically-Isolated Building. New Zealand. Retrieved 6 15, 2016, from http://www.nzsee.org.nz/wp-content/uploads/2016/09

Sullivan, T. J., Calvi, P., & Nascimbene, R. (2013). Towards Improved Floor Spectra Estimates for Seismic Design. Earthquakes and Structures, 109-132.