NEW ZEALAND SOCIETY FOR EARTHQUAKE ENGINEERING

Low damage solution for a biomass boiler structure by a new three-dimensional seismic isolation

M. Pourmasoud, A. Park
Low Damage Design, Hamilton.
S. Mosaferi, I. Brown
Stiles and Hooker ltd, Hamilton.

ABSTRACT

The February 2011 Christchurch earthquake caused significant property damage within Christchurch city. Since this devastating event, there has been a shift in engineering practice to Performance Based Design (PBD), to limit property losses, by setting acceptable acceleration thresholds from structural modelling. Low Damage Design (LDD) solutions look beyond code compliance (life safety) and address property protection, focussing on immediate occupancy after a moderate to large seismic event. Seismic isolation in New Zealand has become more commonplace; however, industrial buildings (dairy factories) are far behind to embrace this state-of-the-art. In addition to structures such as buildings and bridges, the seismic isolation can be used for specific applications, including transformers, tanks, and refineries. Industrial buildings have a variety of elements and equipment that can be damaged. This paper compares an analytical modelling of a biomass boiler using three structural systems. Firstly, a traditional Fixed Based design (FB) secondly a Conventional Seismic Isolated (CSI) solution and finally a 3-Dimensional Seismic Isolation (3DSI) solution. The analytical results are compared against the accelerations' thresholds defined by seismic requirements. The results show that the significant stiffness of the FB structure magnifies the imposed acceleration and cause extensive non-structural damage. On the other hand, the CSI system reduces the horizontal accelerations up to 80% but do not reduce high

vertical accelerations associated with Near Fault effects. The 3DSI system restrict the coupled horizontal-vertical responses to less than recommended thresholds.

1 INTRODUCTION

The February 2011 Christchurch earthquake resulted in significant and widespread damage to property in the Canterbury region. The recorded peak ground acceleration (PGA) from this event at Heathcote Valley (HVSC), approximately 2km from the epicentre was 2.2g and 1.7g in vertical and horizontal directions, respectively. In Christchurch City Center, although accelerations recorded were reduced, however the PGA was still 0.8 g vertically and 0.7 g horizontally (Kaiser et al. 2012). Both would result in moderate to extensive damage according to the FEMA acceleration thresholds and clearly caused significant property damage.

The thresholds for vertical accelerations are suggested by researchers through the full-scale shaking table tests. The conducted test’s results at the E-Defence facility in Japan show that the freestanding objects start jumping once the vertical floor acceleration exceeds 1.0 g (Furukawa et al. 2013). in addition, damage to appliances and equipment happens when the vertical floor acceleration goes beyond 2.0 g. Guzman Pujols & Ryan (2018) studied the effects of two- directional and three- directional excitations on a fixed base and seismic isolation buildings by a series of shaking table tests at the E-Defence facility in the US. The results demonstrated that coupling of horizontal and vertical components affects the building's functionality depends on the magnitude of vertical acceleration. Indeed, the slight damage to non-structural elements emerges for the floor vertical acceleration between 2 and 3 g. vertical accelerations between 3 and 5 g cause moderate damage. When it reaches up to 5 g, the damage will be extensive. Generally, in order to provide a low damage design, the horizontal and vertical accelerations shall be restricted to 0.30 g and 2.0 g, respectively.

Normally, the performance of structural elements depends on the applied forces and stories’ drifts, while the functionality of non-structural elements and contents (which are the most valuable part of buildings) are reliant on the imposed accelerations. It is vital to address the horizontal-vertical coupling effects to determine the performance of the building (Ryan et al. 2016; Soroushian et al. 2016).

Table 1 sets the damage thresholds for floor acceleration in the horizontal direction as given in FEMA 2003. Moderate to extensive damage is expected once the imposed floor acceleration exceeds 0.6 g and 1.2 g, respectively. The PGA within Christchurch City Centre were within this range. Accelerations beyond 2.40 g cause complete damage to acceleration sensitive elements.

Table 1: Peak floor accelerations to define damage to non-structural acceleration-sensitive components.

Seismic Design Level	Floor Acceleration at the Threshold of Non-structural Damage (g)			
	Slight	Moderate	Extensive	Complete
High-Code	0.30	0.60	1.20	2.40
Moderate-Code	0.25	0.5	1.00	2.00
Low-Code	0.20	0.40	0.80	1.60
Pre-Code	0.20	0.40	0.80	1.60

Performance based design and the application of bae isolation solution has become widely used on commercial buildings, however, industrial buildings (generally with low occupancy) such as dairy factories or biomass boilers have limited application of PBD solutions (Whittaker 2019). To date, only one dairy factory in New Zealand is built on the seismic isolation system.

Partial damage from a moderate seismic event of critical equipment may lead to temporary closure an entire production line, or in the worst case close the entire factory, until replacement parts or repairs can be completed. Downtime and repairs/replacement could be significant, and in many cases are preventable through LDD solutions.

This paper reviews two low damage solutions for a Biomass Boiler structure. The analytical results of the pre-designed Fixed Base (FB) structure is compared with the Conventional Seismic Isolated (CSI). Finally, a 3 Dimensional Seismic Isolation (3DSI) is reviewed to assess the resulting accelerations (both horizontal and vertical). The 3DSI system includes vertical flexibility and damping (Pourmasoud et al, 2020). A typical sample of 3DSIs is shown in Figure 1.

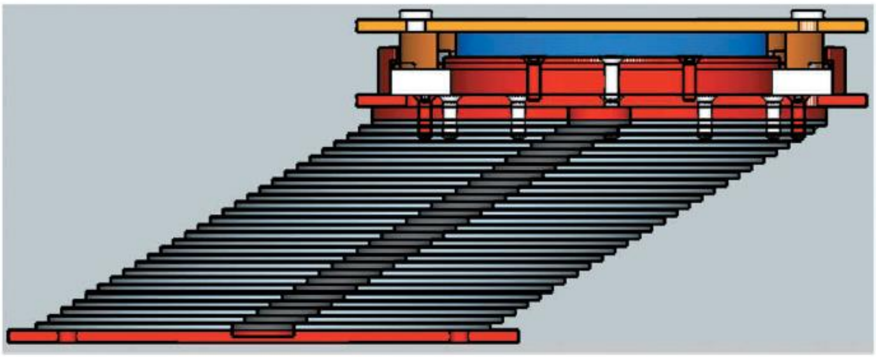


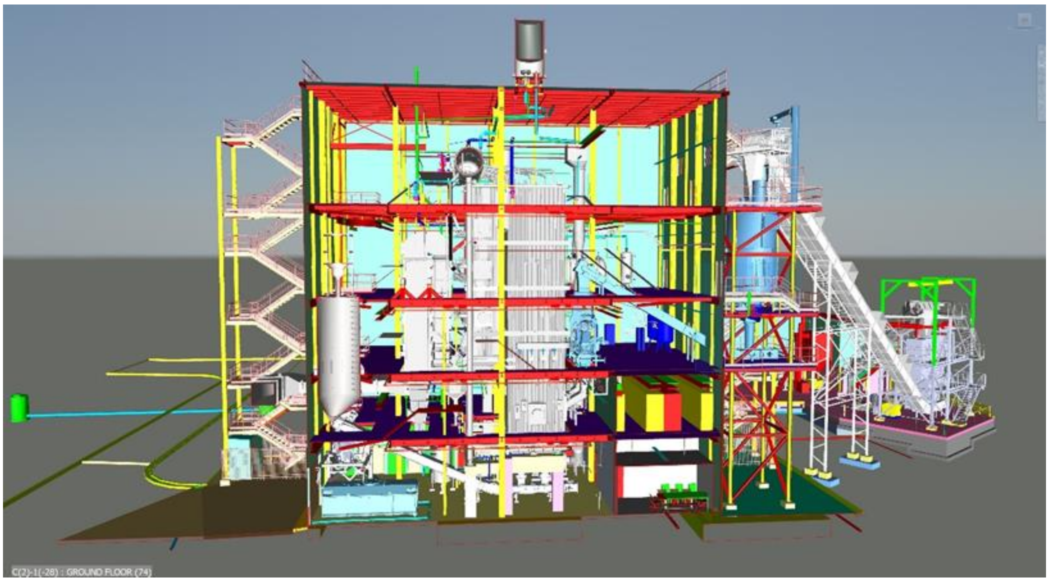
Figure 1. A 3DSI under lateral displacement.

2 BIOMASS BOILER DESIGN AND MODELLING

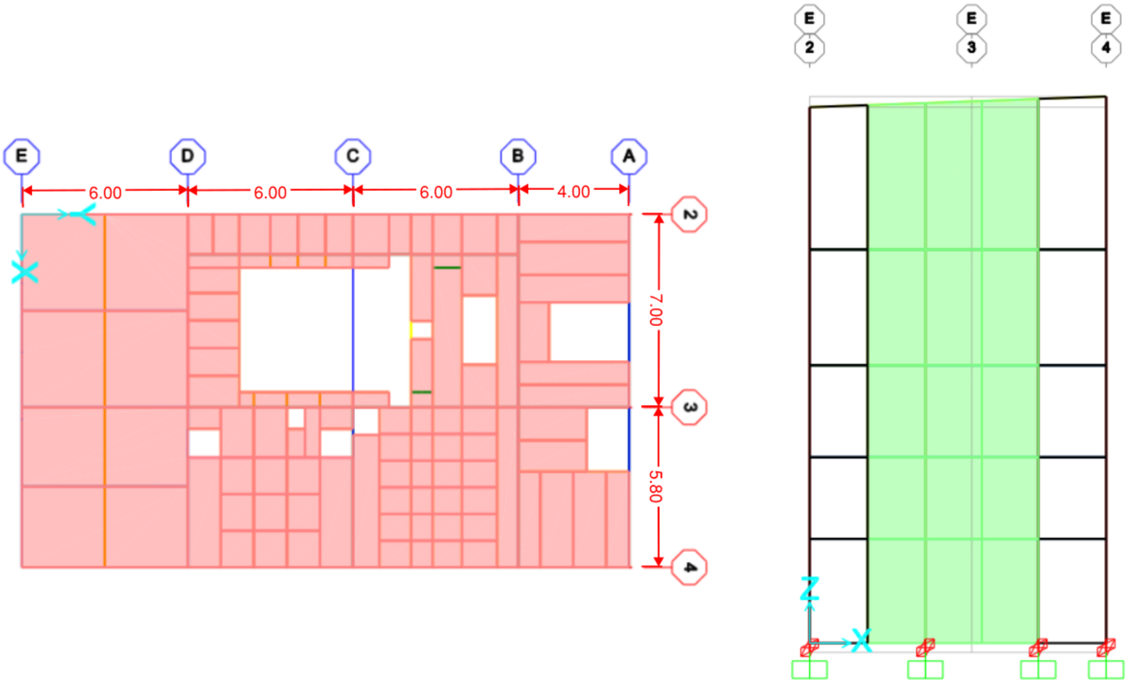
The Biomass Boiler is an existing design that is to be located within the Canterbury region. The building structure is industrial and is relatively low cost by comparison with the significantly more expensive internal machinery. The major investment in this case is in the mechanical plant that makes up this plant, and this paper looks at the effects of each of the NLTHA records when applied to the model. The 3D analysis models for the biomass boiler were developed in SAP 2000 using the design that was completed under NZS 1170.5:2004 – for a traditional fixed base structure. Figure 2 shows the basic plan and elevations of model as well as the location of the CIS for the LDD solutions.

The structure consists of a steel frame with lightweight cladding, with the primary lateral load path being concrete shear walls. The floors are concrete slab and make up working platforms for access around the mechanical plant within the building. The internal floor heights vary between 3.5m and 6m. The steel columns and beams within the building are a mixture of universal columns and Universal beams (UC – UB).

Three identical models were created with the only variation being that CSI and 3DSI were included. NLTHA was then run on each of the models, using actual earthquake records, refer to section 3.

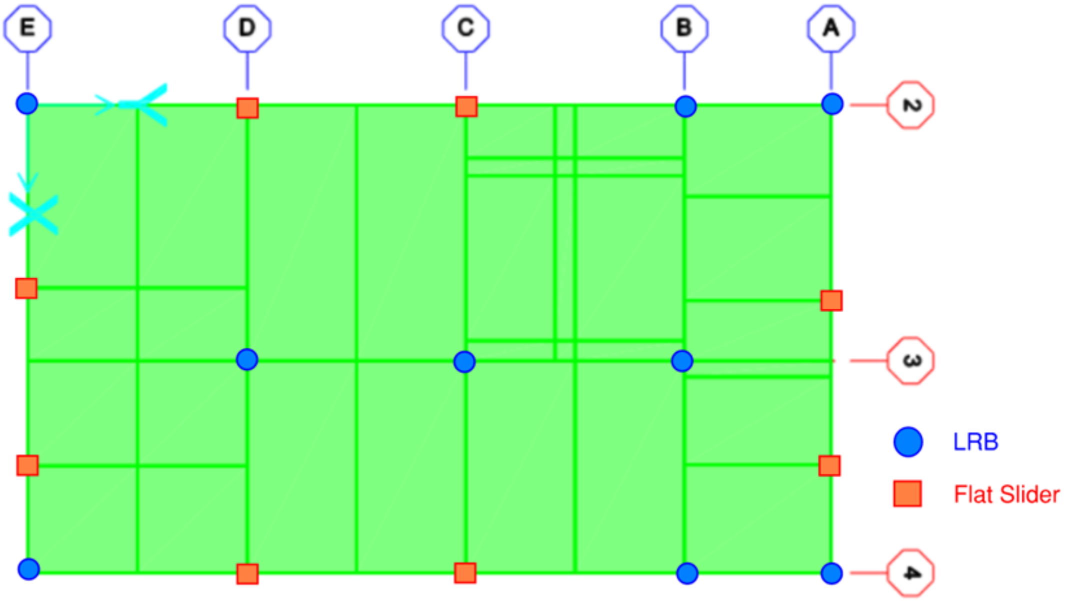


a) T*he biomass boiler structure's contents.*



b) *The model Plan.*

c) *The model elevation.*



d) *Base isolators' location in Biomass Boiler model.*

Figure 2: The specifications of biomass boiler structure

3 EARTHQUAKE RECORDS SELECTED FOR NLTHA

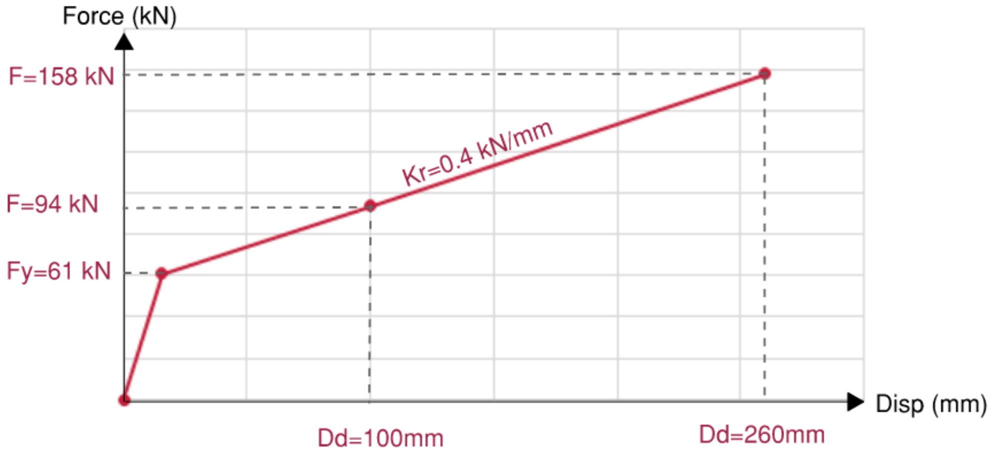
Seven strong near field earthquake records were selected from the Pacific Earthquake Engineering Research Center to compare structural performance of the systems. Four of seven records are from the February 2011 Christchurch stations. Also, at least the magnitude in one direction (horizontal or vertical) was required to be greater than 0.80g. Non-scaled records were run individually thorough the analysis and the review of the output have been completed from each event. Our objective in this review was to look at how the Biomass Boiler performed in a moderate to strong event.

Table 2: Specification of seven selected earthquake records (PEER 2018)

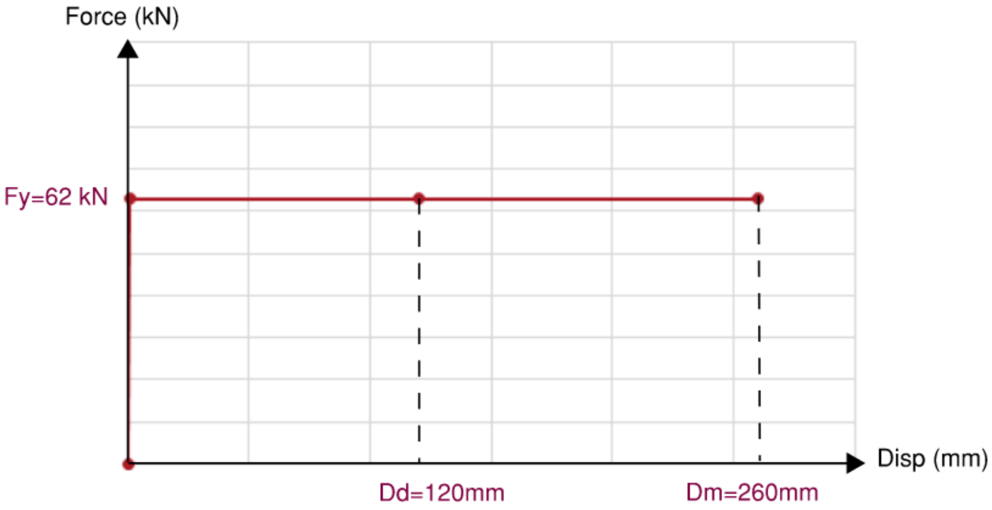
No.	Records	Station	Peak acceleration in H-direction (g)	Peak acceleration in V-direction (g)	Magnitude
Eq.1	Christchurch 2011	Heathcote Valley Primary School	1.7	2.2	6.2
Eq.2	Christchurch 2011	Cashmere High school	0.4	0.97	6.2
Eq.3	Christchurch 2011	Cathedral	0.38	0.8	6.2
Eq.4	Christchurch 2011	Hospital	0.35	0.6	6.2
Eq.5	Kobe 1995	JMA	0.83	0.34	6.9
Eq.6	Landers 1992	Lucerne	0.79	0.82	7.3
Eq.7	Northridge 1994	Rinaldi	0.87	0.96	6.7

4 LOW DAMAGE DESIGN SOLUTIONS

The application of a CSI and/or a 3DSI has a significant effect on accelerations within the building. To compare the analytical results, the FB option is compared against the two seismic isolated structures, and the resulting accelerations and their corresponding damage levels reviewed. The CSI consists of Lead Rubber Bearings (LRB) and POT Sliders. Figure 3 represents the mechanical specifications of the LRB isolator and the POT sliders.



a) Mechanical specification of LRBs



b) Mechanical specification of Flat Sliders

Figure 3: Bilinear force-deformation diagram of isolation system

5 REVIEW OF ANALYSIS RESULTS.

5.1 Accelerations

The tables presented below compare the NLTHA output between the FB, CSI and 3DSI models.

Table 3 to Table 5 present the horizontally transited acceleration across the floors for each system. The white and blue cells indicate the accelerations less than 0.3 g and 0.6 g, which reflect none to slight non-structural damages. The green and orange cells represent moderate and extensive damage for accelerations more than 0.6 g and 1.2 g, respectively. The accelerations greater than 2.4 g lead to complete non-structural damage and are highlighted in red. The first two levels of the FB structure were affected by moderate to extensive damage as accelerations vary between 0.6 g to 1.35 g. the range of horizontal acceleration at upper floors is between 1.3 g to 2.6 g and imply extensive to complete non-structural damage. For CSI and 3DSI systems, the extracted accelerations are quite close as the isolators' horizontal specifications are similar. All accelerations are degraded significantly, and the damage level is attenuated to none to slight. It worth mentioning that the average of records indicates about 60% reduction in accelerations while the response spectrum offers up to 80%.

Table 3: Floor acceleration (g) – fixed base structure – horizontal direction.

	Cashmere	Cathedral	CH CH Hospital	HVSCS	Kobe	Landers	Northridge	Response Spectrum	Average of Records
ROOF	2.02	2.09	1.99	2.09	2.00	1.22	2.11	2.21	1.93
LEVEL 4	1.70	2.24	1.54	1.86	1.70	0.74	1.66	1.65	1.64
LEVEL 3	1.61	1.80	1.28	1.98	1.70	0.67	1.79	2.58	1.55
LEVEL 2	0.77	1.00	0.91	0.67	0.94	0.65	1.07	1.35	0.86
LEVEL 1	0.78	1.00	0.74	0.70	0.96	0.58	1.10	1.35	0.84

Total Average: 1.36

Table 4: Floor acceleration (g) – CSI Structure – horizontal direction.

	Cashmere	Cathedral	CH CH Hospital	HVSCS	Kobe	Landers	Northridge	Response Spectrum	Average of Records
ROOF	0.97	1.07	0.84	1.22	0.74	0.49	0.68	0.26	0.86
LEVEL 4	0.62	0.48	0.46	0.51	0.43	0.19	0.41	0.22	0.44
LEVEL 3	0.43	0.54	0.35	0.42	0.53	0.16	0.66	0.20	0.44
LEVEL 2	0.38	0.42	0.47	0.39	0.29	0.21	0.61	0.19	0.40
LEVEL 1	0.30	0.52	0.40	0.49	0.36	0.29	0.31	0.70	0.38

Total Average: 0.50

Table 5: Floor acceleration (g) – 3DSI Structure – horizontal direction.

	Cashmere	Cathedral	CH CH Hospital	HVSCS	Kobe	Landers	Northridge	Response Spectrum	Average of Records
ROOF	1.07	1.01	0.76	1.10	1.00	0.36	0.82	0.29	0.87
LEVEL 4	0.59	0.50	0.50	0.62	0.56	0.25	0.56	0.23	0.51
LEVEL 3	0.63	0.60	0.38	0.81	0.57	0.37	0.58	0.20	0.56
LEVEL 2	0.45	0.35	0.35	0.46	0.40	0.16	0.32	0.19	0.36
LEVEL 1	0.58	0.54	0.34	0.49	0.57	0.21	0.30	0.58	0.43

Total Average:	0.55

It is remarkable that even for Cashmere and HVSCS stations (with high peak accelerations), the damage levels are considerably reduced by using seismic isolation systems, and imposed accelerations are reduced from about 1.7 g to 0.4 g (75% reduction).

Figure 4 represents the trend of horizontal accelerations along the height. The FB trend is irregular, and acceleration escalated along with the height, while the isolated seismic options offer an almost uniform trend and have controlled the imposed acceleration along with the height and the damage level correspondingly.

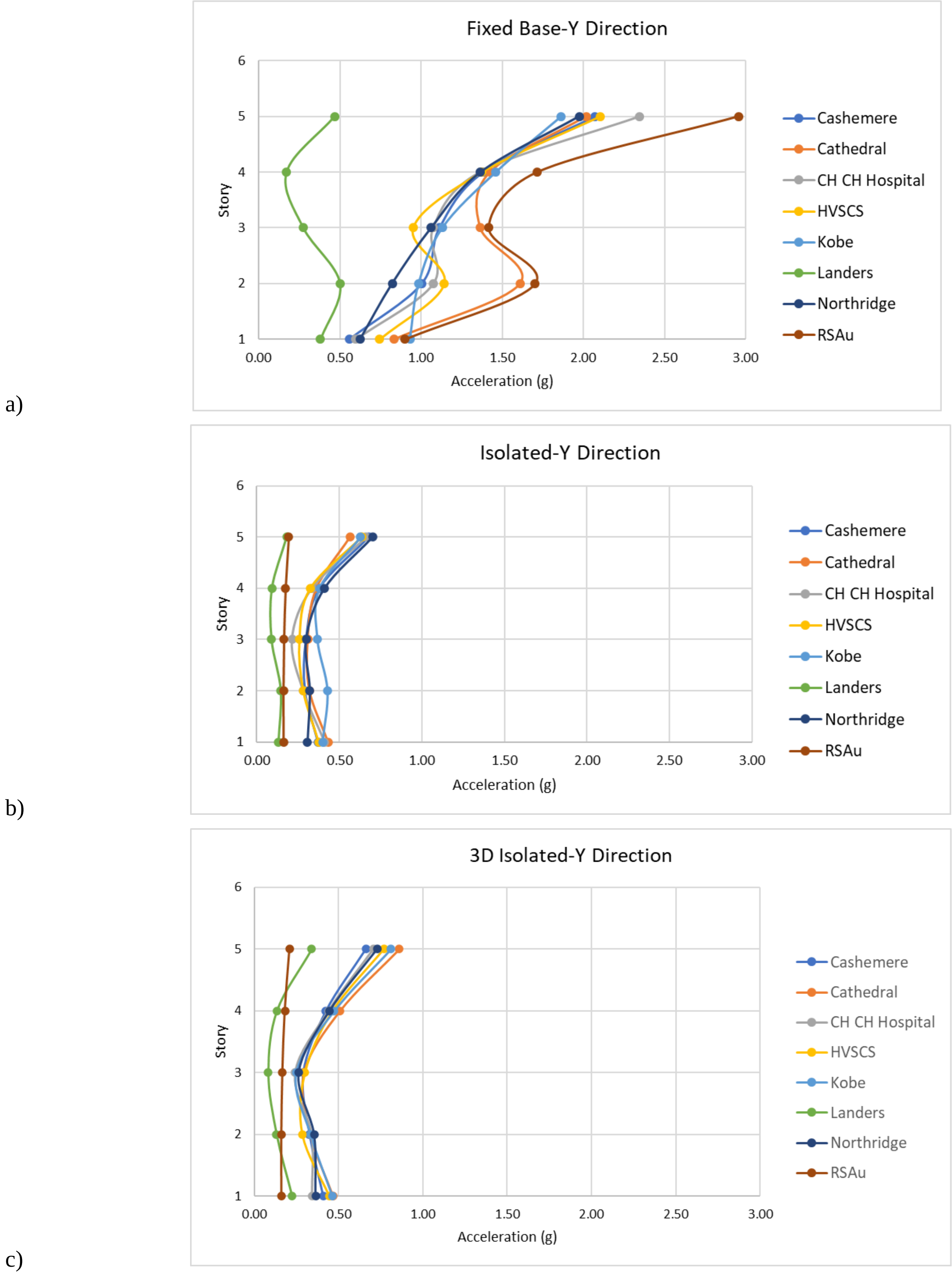


Figure 4: The distributed horizontal accelerations along the height. a) Fixed Base, b) CSI, c) 3DSI.

For a better insight, Figure 5 shows the average of accelerations from all records for all systems. Almost for all stories, the horizontal acceleration of the seismic isolated structures are about one-third of the fixed base option.

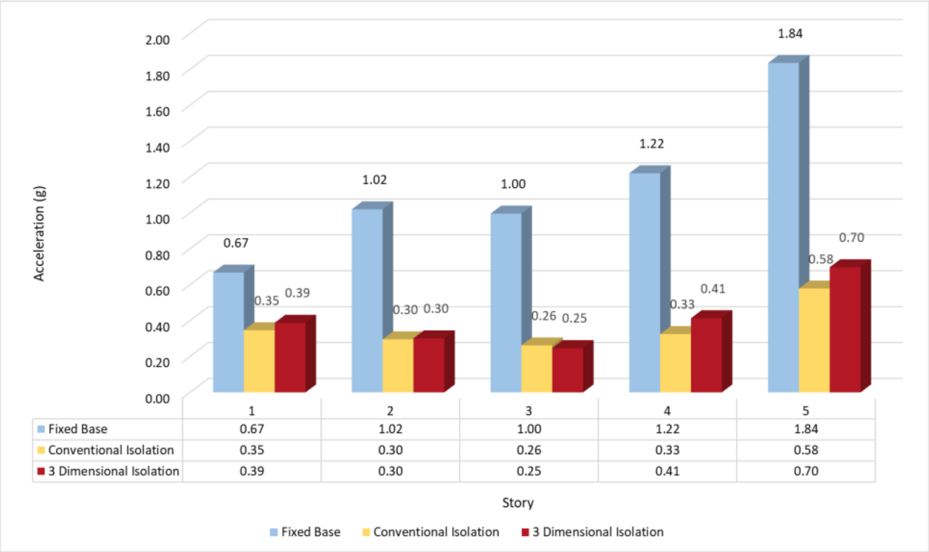


Figure 5: Average of horizontal accelerations taken from different systems.

The performance of structural elements has a direct relationship with horizontal responses; however, the vertical responses shall be addressed to ensure the functionality of fixtures and fittings as well. Vertical accelerations can suffer most buildings' contents such as mechanical and electrical pipelines, equipment (particularly the acceleration sensitive ones), and ceilings. Indeed, the coupling of horizontal and vertical responses define the performance of the structures. Figure 6 illustrates the distributed vertical accelerations along with the height. Even for the conventional seismic isolated structures (particularly in the near fields), the vertical accelerations are magnified, and the trend is similar to the FB option. This phenomenon happens because of the low vertical flexibility of conventional isolators that cause a partial escalation in the vertical direction. 3DSIs solved this issue as the isolator's vertical specifications are independent of horizontal specifications, and the appropriate flexibility is attainable without affecting other features. Unlike the FB and CSI, the trend of 3DSI is almost uniform (Figure 6c), and the vertical accelerations are attenuated significantly.

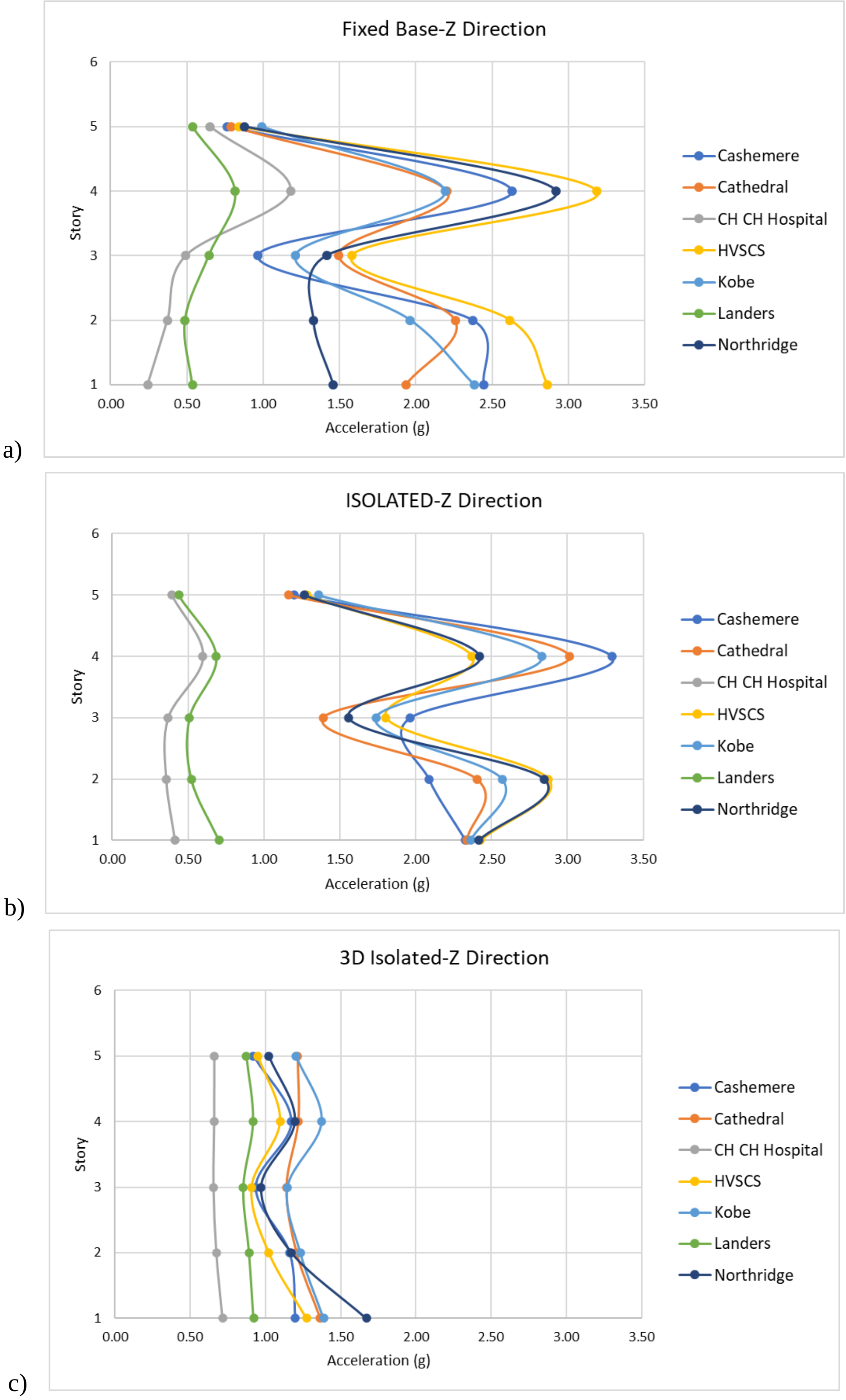


Figure 6: The distributed vertical accelerations along the height. a) Fixed Base, b) CSI, c) 3DSI.

Table 6 and Table 7 demonstrate the vertical accelerations for FB and CSI structures. The accelerations greater and less than 1.5 g are shown in red and green colure, respectively. The majority of cells are filled in by accelerations even more than 2.0 g, which implies serious damage to non-structural elements.

Table 6: Floor acceleration (g) – fixed base structure – vertical direction.

	Cashmere	Cathedral	CH CH Hospital	HVSCS	Kobe	Landers	Northridge
ROOF	0.76	0.79	0.65	0.84	0.99	0.54	0.88
LEVEL 4	2.63	2.21	1.18	3.19	2.19	0.82	2.92
LEVEL 3	0.97	1.50	0.49	1.58	1.21	0.64	1.42
LEVEL 2	2.37	2.26	0.37	2.62	1.96	0.49	1.33
LEVEL 1	2.45	1.94	0.24	2.86	2.38	0.54	1.46

Table 7: Floor acceleration (g) – CSI structure – vertical direction.

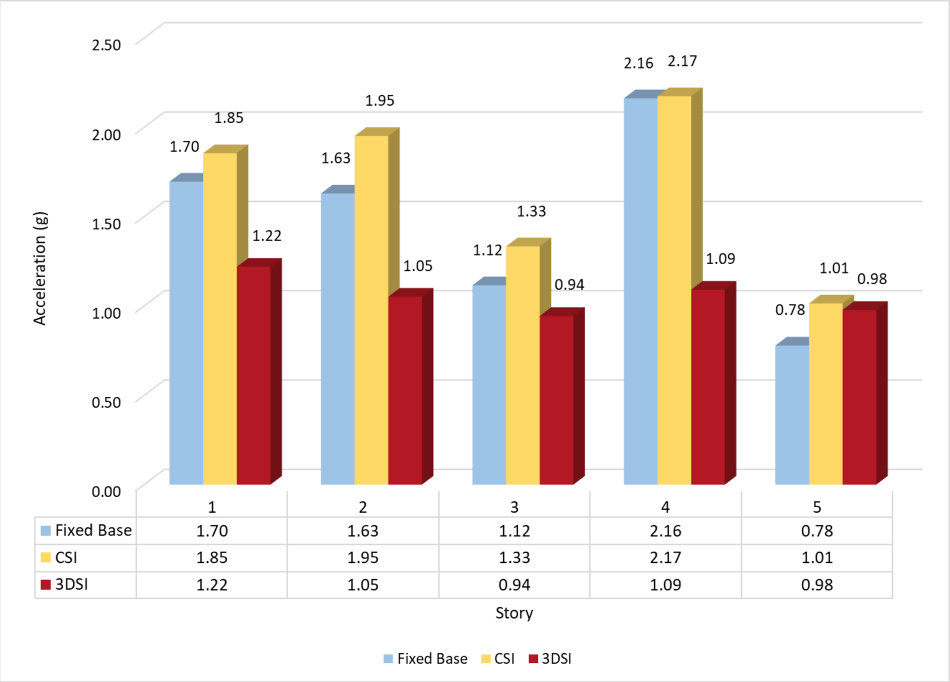
	Cashmere	Cathedral	CH CH Hospital	HVSCS	Kobe	Landers	Northridge
ROOF	1.20	1.16	0.39	1.28	1.36	0.44	1.26
LEVEL 4	3.29	3.01	0.60	2.37	2.83	0.69	2.42
LEVEL 3	1.96	1.39	0.37	1.80	1.74	0.51	1.56
LEVEL 2	2.09	2.40	0.35	2.87	2.57	0.52	2.85
LEVEL 1	2.33	2.34	0.41	2.42	2.36	0.70	2.41

Table 8: Floor acceleration (g) – 3DSI structure – vertical direction.

	Cashmere	Cathedral	CH CH Hospital	HVSCS	Kobe	Landers	Northridge
ROOF	0.92	1.21	0.66	0.95	1.20	0.87	1.02
LEVEL 4	1.17	1.22	0.66	1.10	1.38	0.92	1.20
LEVEL 3	0.93	1.14	0.66	0.91	1.15	0.85	0.97
LEVEL 2	1.16	1.21	0.67	1.02	1.23	0.89	1.17
LEVEL 1	1.20	1.36	0.72	1.27	1.39	0.92	1.67

Table 8 points out the vertical accelerations for the 3DSI system. A large number of accelerations are about 1.0g that may entail shaking of unsecured objects. It is notable that even for strong near field records such as Cashmere and HVSCS, the peak vertical accelerations are significantly degraded from

2.20 g to about 1.0 g. For further insight, the average of all records in different levels is compared in Figure 7. It shows that 3DSI obtains an average of up to 50% vertical acceleration degradation.



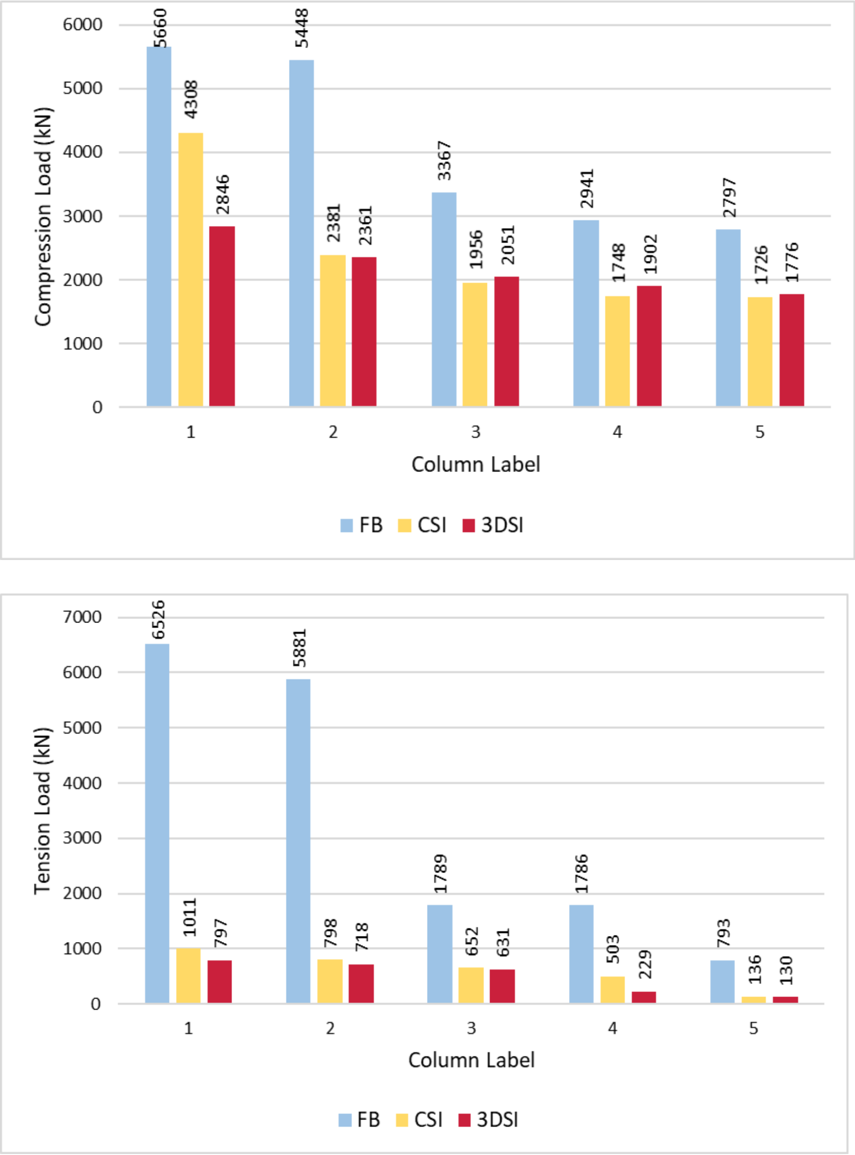
	1	2	3	4	5
Fixed Base	1.70	1.63	1.12	2.16	0.78
CSI	1.85	1.95	1.33	2.17	1.01
3DSI	1.22	1.05	0.94	1.09	0.98

Figure 7. Average of accelerations taken from different systems.

5.2 Axial Loads

Although this paper aims to compare the functionality of building by investigating the imposed acceleration, however, as the magnitude of applied axial loads is more tangible for most engineers, it has been addressed in this section. Figure 8a present the five highest axial loads under compression and tension have arisen from the Cashmere three-directional excitation. The maximum compression load on the first floor is degraded from more than 5500 kN to 4300 kN by CSI and 2800 kN by 3DSI. It may cause more flexibility for structural designers to choose the appropriate structural elements and make a partial structural saving compared to the FB option.

The maximum tension load is also significantly decreased from more than 6000 kN to about 1000 kN and 800 kN for CSI and 3DSI options, respectively (Figure 8b). It is because of the low vertical stiffness of isolators under the tension load which leads to minimizing the uplift loads and is quite helpful for executive detailing.



a)

b)

Figure 8. Five highest columns' axial loads. a) compression. b) tension.

6 COST ANALYSIS

Figure 9 illustrates that in most common commercial buildings, the largest capital investment belongs to non-structural elements and contents. In other words, the functionality of the most valuable parts of buildings (about 85%) depends on the less valuable part (15%). So, it is vital to provide a functional structural performance to minimize damage to valuable contents (FEMA E-74, 2012). The first three columns from the left-hand side are taken from FEMA's estimation, and the fourth column is according to the consultant experiences. Also, the approximate seismic isolation cost (±5% to ±10% of the structural part) is added to the diagram that conservatively leads to less than 2.0% of the total project cost. For the biomass boiler structure, the designed seismic isolation system roughly costs less than 1.0% of the total price. It instead positively affects the structural elements specifications and also facilitates other executive details during construction.

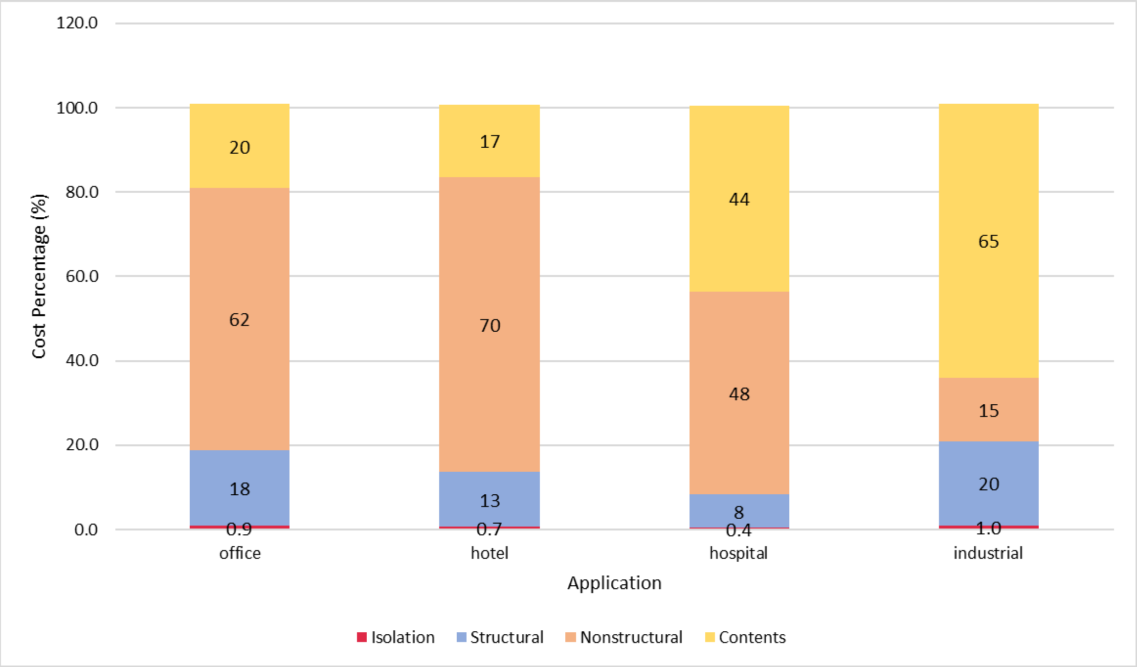


Figure 9. Capital investment on most commercial buildings including industrial structures

Conclusion

Based on the analysis' results, the following conclusions can be drawn:

- The transferred horizontal acceleration in high seismic regions such as Cashmere and HVSCS have experienced up to 75% degradation by using the CSI system. Almost similar trends were observed for 3DSI, which cause a considerable undermining damage level from extensive non-structural damage to slight damage.
- CSI systems magnify the vertical excitations along with the height. Their trend is similar to FB structures and can affect fixtures and fittings' functionality when the imposed vertical acceleration reaches out to about 2.0 g. 3DSI attenuates the vertical accelerations up to 50% and restricts the objects' vertical responses from jumping and throwing to vibration.
- Seismic isolation systems decrease the structural elements' internal actions significantly and cause flexibility for designers. Seismic isolation systems decrease the structural elements'

internal actions significantly and cause flexibility for designers. It is important for structural designers can manage the numbers and size of structural elements, especially when facing complex buildings such as biomass boiler structures.

The Biomass boiler building structure is industrial and is relatively low cost by comparison with the significantly more expensive internal machinery. The major investment in this case is in the mechanical plant and protecting this investment from damage using CSI is shown to be a very cost effective solution.

The CSI systems are an extremely effective way of reducing accelerations exerted onto the building to below the FEAM thresholds, protecting the investment, and ensuring continued functionality during and after a moderate to large seismic event.

ACKNOWLEDGMENTS

Special thanks to those who have assisted in this research, in particular, KPA Unicon company for sharing the structural design documents.

REFERENCES

Kaiser, A., Holden, C., Beavan, J., Beetham, D. 2012. The Mw 6.2 Christchurch earthquake of February 2011: preliminary report, *New Zealand Journal of Geology and Geophysics*, 55:1, 67-90, DOI: 10.1080/00288306.2011.641182.

FEMA. 2003. *Multi-hazard loss estimation methodology - earthquake model*. *HAZUS-MH MR4 Technical Manual.* Washington: Federal Emergency Management Agency.

FEMA E-74. 2012. *Reducing the risk of non-structural earthquake damage – a practice guide*. Washington: Federal Emergency Management Agency.

Furukawa, S., E. Sato, Y. Shi, Y. Becker, and M. Nakashima. 2013. Full-scale shaking table test of a base-isolated medical facility subjected to vertical motions. *Earthquake Engineering & Structural Dynamics* 42 (13): 1931–49. doi: 10.1002/eqe.2305.

Guzman Pujols, J. C., and K. L. Ryan. 2018. Computational simulation of slab vibration and horizontal-vertical coupling in a full-scale test bed subjected to 3D shaking at E-defence. *Earthquake Engineering & Structural Dynamics* 47 (2): 438–59. doi: 10.1002/eqe. v47.2.

NZS 1170:2004, *Structural Design Actions, Part 5, Earthquake design actions*.

Pacific Earthquake Engineering Research Center (PEER). 2018. PEER ground motion database. Accessed April 27, 2018. http://peer.berkeley.edu/smcat/search.html.

Pourmasoud, M. M., Lim, J. P., Hajirasouliha, I., and McCrum, D. 2020. Multi-directional base isolation system for coupled horizontal and vertical seismic excitations. *Journal of Earthquake Engineering*, doi: 10.1080/13632469.2020.1713925.

Ryan, K. L., S. Soroushian, E. M. Maragakis, E. Sato, T. Sasaki, and T. Okazaki. 2016. Seismic simulation of an integrated ceiling-partition wall-piping system at E-defense. I: Three-dimensional structural response and base isolation. *Journal of Structural Engineering* 142 (2): 04015130. doi: 10.1061/(ASCE)ST.1943-541X.0001384.

SAP2000NL software. 2014. *Structural Analysis Programs-Theoretical and User's Manual*. Berkeley, CA: Computer and Structures Inc.

Soroushian, S., K. L. Ryan, E. Sato, T. Sasaki, T. Okazaki, and G. Mosqueda. 2016. Seismic simulation of an integrated ceiling-partition wall-piping system at E-defense. II: Evaluation of JOURNAL OF EARTHQUAKE ENGINEERING 25 nonstructural damage and fragilities. *Journal of Structural Engineering* 142 (2): 04015131. doi: 10.1061/(ASCE)ST.1943-541X.0001385.

Whittaker, D. 2019. Recent developments in New Zealand in seismic isolation, energy dissipation and vibration control of structures. Proceedings of the 16th World Conference on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures, St. Petersburg, Russia, 1-6 July.