PERFORMANCE BASED DESIGN OF BUILDINGS TO ASSESS DAMAGE AND DOWNTIME AND IMPLEMENT A RATING SYSTEM

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ABSTRACT

The Christchurch earthquakes have highlighted the mismatch in expectations between the engineering profession and society regarding the seismic performance of buildings. While most modern buildings performed as expected, many buildings have been, or are to be, demolished. The ownership, occupancy, and societal costs of only targeting life-safety as the accepted performance standard for building design are now apparent in New Zealand.

While the structural system has a significant effect on the seismic performance of the entire building, including the contents, it is only about 20% of the total building cost. Hence, structural engineers should view the seismic performance in a wider context, looking at all the systems of the building rather than just the damage to structural items and life-safety.

The next generation of performance-based seismic design procedures, outlined in the FEMA P-58 document, provide engineers with the tools to express the seismic performance of the entire building in terms of the future life loss, facility repair cost and repair time. This paper will outline the FEMA P-58 procedure and present the results of a comparative study of six different structural systems for a three storey commercial and laboratory building: moment frame; buckling restrained braced frame; viscously damped moment frame; Pres-Lam timber coupled-walls; cast-in-place reinforced concrete shear wall; and base isolated braced frame. Each system was analysed as a fully non-linear structure and the calculated drifts and floor accelerations were input into the FEMA P-58 PACT tool to evaluate the overall building performance. The PACT tool performs loss calculations for the expected casualties, repair cost, and repair time from which a QuakeStar or SEAONC rating for the building can be obtained.

1 INTRODUCTION

1.1 General

Conveying the value of higher-performance seismic design to clients, building users and the general public has always been a difficult task. The design philosophy of current building codes, as given in their commentary, state the code provisions are intended to provide a degree of reliability and minimize risk against major failures and loss of life, NOT to limit damage, maintain functions, or provide for easy repairs. This often comes as a surprise to many building owners, who believe they are getting an "earthquake proof" building when they hire a competent structural engineer to design a code conforming building. Some proposed grading systems for the seismic performance of buildings, for example the approach proposed in the NZSEE guidelines (NZSEE 2012) and supported by the Canterbury Earthquake Royal Commission (CERC 2012), focus on life safety issues only, which will further increase this misleading perception.

As we have painfully learned in many recent disasters ($30b (US) in 1994 Northridge, $170b (US) in 1995 Kobe, $20b Eastern Japan earthquakes), the major economic issues relate not only to the direct cost of earthquake damage, but also to the business disruption costs associated with the loss of one or more buildings for significant periods of time. These include loss of production or operations, loss of sales or services and loss of on-going research and development in some industries (e.g., the biotech industry). These losses translate into major economic issues for a corporation including loss of revenue¸ loss of market share and loss of share value.

Clearly these business disruption costs overwhelm any first-cost considerations, but in too many instances, project personnel focus entirely on first-cost issues and never look at the longer-term bigger picture cost/benefit analysis.

On-going developments in performance based seismic design will permit engineers to discuss a buildings seismic performance in terms of deaths, dollars and downtime. This will revolutionize the relationship between the owner and the structural engineer and it will permit a much more rational approach to the selection of an appropriate structural system for a project. The US Federal Emergency Management

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Agency’s (FEMA) document, FEMA P-58 is used herein to compare the relative performance of six different structural systems in terms of the expected cost of earthquake damage.

Over the past several years, the Structural Engineers Association of Northern California (SEAONC) Building Ratings Subcommittee, a subcommittee of the SEAONC Existing Buildings Committee, has conceptualized and developed an Earthquake Performance Rating System (EPRS). Previous papers (SEAONC Existing Buildings Committee 2008, 2009, 2011, 2012) described the motivation for such a system, the context for which the proposed EPRS was developed, the evolution of its key features, and the feedback received from potential users through a FEMA-sponsored workshop (ATC 2010). A non-profit company, the US Resiliency Council, (USRC) has been organized to implement the rating system in the US (Reis *et al.* 2012). In New Zealand a similar EPRS system called QuakeStar (Mayes *et al.* 2012) is in the process of being developed. Both QuakeStar and the SEAONC systems use the information generated by FEMA P-58 and other engineering tools to develop a building rating.

1.2 Minimizing Structural Damage by Design

What is commonly referred to as low-damage design or damage-resistant design has attracted the interest of many engineers, researchers, building owners and tenants, especially following the recent Canterbury earthquakes. The authors have observed that when low-damage design is discussed, it’s typically being referred to as low-damage design of structural systems. Low-damage designs of structural systems generally fall under one of the following forms:

- Base isolation
- Rocking walls or frames
- Energy dissipation devices that can easily be replaced

The goal of most low damage designs is to avoid damage to the structural system that is difficult to repair after a severe earthquake. While limiting damage to the structure is an important goal, it should not be the only goal. When an engineer is considering a damage-resistant design they should consider all aspects of a building including non-structural components and fragile content (often the major cost of earthquake damage), soil condition, potential damage from adjacent buildings and repair time of both structural and non-structural elements.

There are two equally important variables that should be assessed when evaluating the seismic performance of a structural framing system. The first and almost universal variable is the inter-story drift. This is a code design parameter and is something most engineers focus upon during the design process. The other key parameter, from a performance perspective, is the floor acceleration as characterized by the floor response spectra. Structural engineers are not required by code to assess the floor accelerations and it has been rarely assessed as part of the design process because it requires a time history analysis to obtain it. Together, these two mechanisms are the primary cause of damage to the structural frame, building contents, architectural facades, partitions, piping, ductwork, ceilings, building equipment and elevators. Only when engineers go beyond the current requirements of the code and compare the realistic levels of inter-story drift and floor accelerations can intelligent comparisons be made between the performance of different structural systems. The paper will discuss the use of the calculated inter-story drifts and floor accelerations to assess damage and downtime estimates and thus make a more rational comparison on the merits of different structural systems.

2 FEMA P-58: SEISMIC PERFORMANCE ASSESSMENT OF BUILDINGS

2.1 General Discussion

The next-generation of performance-based seismic design procedures outlined in FEMA P-58 enables engineers to express the performance of buildings in terms of quantified risks that building owners or decision makers will be able to understand. In a workshop held in the early stages of the FEMA P-58 project, a representative sample of users (commercial real estate investors, insurers, lenders, attorneys, engineers, and architects) indicated their preference to define these risks in terms of the future life loss and injuries (*casualties*), facility *repair costs* and *repair time* that could result from design decisions. These risks may be expressed in a variety of formats including: expected loss for a given earthquake event, probable maximum loss over a given number of years, the probability of loss exceeding a specified value over a period of years, the net present value of future potential losses, average annualized loss, and others as best suits the needs of individual decision makers.

The technical bases for the methodologies implemented in FEMA P-58 were developed by researchers at the Pacific Earthquake Engineering Research Centre (PEER). The PEER framework applies the total probability theorem to predict earthquake consequences in terms of the probability of incurring particular outcomes including *casualties*, *repair costs*, and *repair time* (ATC 2012).

The FEMA P-58 document provides a general methodology to evaluate the probability that structural and non-structural components will be damaged by an earthquake. The performance assessment in FEMA P-58 is limited to consequences that occur within the building envelope. Currently the document does not evaluate consequences that could occur from loss of power, water, and sewage due to damaged utilities, and earthquake casualties that occur outside the building envelope due to falling debris. The document also does not consider potential impacts from adjacent buildings (pounding) and other earthquakes effects including ground fault rupture, landslide, liquefaction, lateral spreading, and tsunamis. Development of models to assess these additional variables is possible, but is not currently included in the FEMA P-58 document. Engineers conducting seismic performance assessments should at a minimum qualitatively evaluate these other effects.

2.2 FEMA P-58 Assessment Process

The FEMA P-58 assessment process can be summarized in 5 steps. The first step is to assemble the building performance model. The building performance model is a collection of data (fragility curves) used to define the building assets at risk and their exposure to seismic hazards. This includes:

- Structural components and assemblies that can be damaged by an earthquake
- Non-structural systems, components and content that do not provide significant resistance to earthquake loading but can be damaged during an earthquake
- Occupancy

The second step is to define the earthquake hazards for the site. As discussed above, the FEMA P-58 document currently addresses only the earthquake effects associated with ground shaking. The third step is to analyse the building response. Structural analysis is used to predict a building's response to earthquake shaking in the form of demands that can be associated with damage. Demands typically include peak inter-storey drift, peak floor acceleration (zero period acceleration), peak floor velocity, and residual drift ratio. It is possible to use other demand parameters if a building includes components that can better be correlated with such parameters. The fourth step is to develop a collapse fragility curve for the building. The fifth step is the performance calculation. The FEMA P-58 document provides a computer program (PACT) which performs this calculation.

2.3 Repair Time vs. Downtime

Repair time is the amount of time it would take to repair a damaged building component to its pre-earthquake or new condition assuming that the labour, equipment, and material required is available. Repair time does not include any delays which may hinder initiation of repairs.

Downtime is the time required to achieve a defined recovery state after an earthquake has occurred. There are three such states which were established by the Structural Engineers Association of Northern California (Bonowitz, 2009):

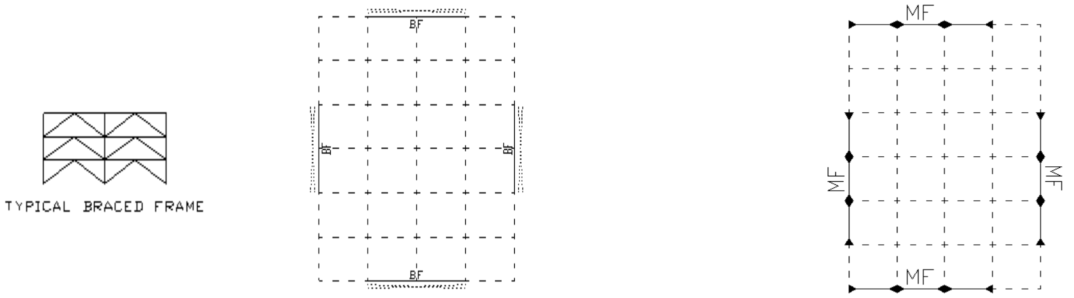
- re-occupancy of the building
- pre-earthquake functionality
- full recovery

Downtime estimates must account for the time required to complete repairs to building components plus any delays which hinder initiation of those repairs. Downtime due to delay of repair initiation may be much more significant than the repair time and would consequently increase the time required to achieve any recovery state. These delays are referred to as 'impeding factors' and include the time it takes to complete post-earthquake building inspection, gain access due to unsafe neighbouring buildings, secure financing for repairs and resolve insurance claims, mobilize engineering services, re-design damaged structural components, obtain permitting, disruption to utilities, and mobilize a contractor and necessary equipment. Development of models to assess these additional variables is possible, but is not currently included in the FEMA P-58 document.

3 DESIGN OF STRUCTURAL SYSTEMS

3.1 Three-Storey Building Configuration

A standard three-storey building configuration was used for each structural system type. The building used the same layout and floor loading as the one defined during the SAC Steel Project (SAC, 2000). The three-storey building has a 9.1 metre bay spacing, is 6x4 bays and equal storey heights of 4.0 metres. Six different structural systems were considered: moment frame (MF); buckling restrained braced frame (BRBF); viscously damped moment frame (MF); Pres-Lam timber coupled-walls (Pres-Lam CWs); cast-in-place reinforced concrete shear wall (Conc. SW); and base isolated braced frame (BI). Figure 1 shows the moment and braced frame configurations.



(a) Braced-Frame configuration

(b) Moment-resisting Frame configuration

Figure 1: Schematic representation of the three-storey frame layout of the sample building.

3.2 Design Data

The steel moment frame, cast-in-place reinforced concrete shear wall, buckling restrained braced frames, and base isolated braced frames were designed following the requirements of the 1997 Uniform Building Code (UBC) while the viscously damped frame was designed according to 2003 NEHRP requirements. The Pres-Lam coupled-walls building was designed to comply with the draft guidelines provided by the University of Canterbury (UC, 2012).

3.2.1 *Base Isolated Braced Frame*

The base isolated braced frame system was designed following the requirements of the 1997 UBC using a 2.5 second isolated system with a yield level of 0.05 times its weight.

3.2.2 *Viscously Damped Moment Frame*

The viscously damped moment frame was initially designed to meet the minimum code drift requirements (590 kN dampers) and then the system was redesigned with an almost doubling in the damping coefficient of the viscous dampers (980 kN dampers). The additional design was performed in order to study the relative performance of structural systems that could meet lower code drift limits required for essential facilities.

3.2.3 *Buckling Restrained Braced Frame*

The buckling-restrained braced frame system was designed as both a conventional building with an R-Factor of 7.0 and as an essential facility using an R-Factor of 3.5. The R-Factor is defined as the response modification coefficient and is comparable to the structural ductility factor, μ, in NZS 1170.5:2004.

3.2.4 *Moment Frame*

The moment frame system was designed with an R-Factor of 8.5 and the design was controlled by the drift requirements of the code. A reduced beam section connection was implemented for the moment frame system.

3.2.5 *Pres-Lam Coupled Shear wall*

Pres-Lam is a recently developed technique, which implements the basic principles developed previously for reinforced concrete rocking wall structures (PRESSS). The lateral resisting system of the building is defined by coupled timber walls, where walls are allowed to rock at the base. U-shaped Flexural steel Plates (UFPs) provide additional capacity and energy dissipation through coupling actions. Each wall is post-tensioned vertically which, together with external (unbonded) steel dampers at the base, provide flexural capacity together with re-centring and energy dissipation capability.

3.2.6 *Concrete Shear wall*

The cast-in-place reinforced concrete shear wall system was designed as a ductile concrete shear wall (R= 5.0). The floors are cast-in-place post tensioned reinforced concrete flat slabs with drop panels at columns. The shear wall was designed from a capacity design approach such that the predicted failure mechanism is flexure, not shear. The total vertical steel reinforcing ratio is approximately 1.0% and the horizontal steel reinforcing ratio is approximately 0.6%. Well confined boundary elements were detailed at the wall ends.

3.3 **Analysis**

All of the buildings except the Pres-Lam coupled-wall building were modelled using the 3D RAM PERFORM computer program developed by Professor Graham Powell of Berkeley and sold to CSI Inc. Non-linear time history analyses were performed on each building with the non-linear element being the actual BRB, viscous damper, isolator, brace and moment frame connections and their immediate surrounding frame as appropriate. SAP2000 was used to assess the performance of the Pres-Lam coupled-walls building.

Each of the models were analysed using a total of 15 time histories selected from those developed for Los Angeles as part of the SAC program. One set of five time histories is representative of a 50% probability of exceedance in 50 years design event (72 year return period), five time histories are representative of a 10% probability of exceedance in 50 years design event (475 year return period), and five time histories are representative of a 2% probability of exceedance in 50 years design event (2,500 year return period). Due to the space limitations, this paper focuses primarily on the 475 year design event results.

Figure *2* below shows the acceleration and displacement response spectra of the 475 year design event.

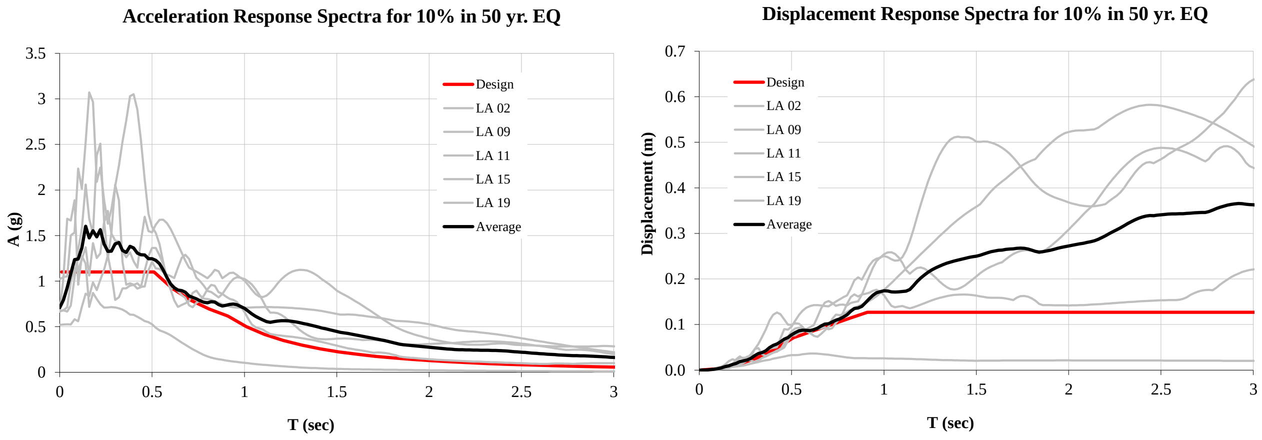


Figure 2: Response spectrum for the 10% in 50 years set of ground motions.

3.4 Drift and Acceleration Comparisons of the Structural Systems

The primary results of the non-linear analyses shown in Table 1 are the average inter-storey drifts and peak zero period floor accelerations from each of the five non-linear time history analyses for each of the three events.

Figure *3* shows a plot of the average third floor spectral acceleration (0-1.0 sec.) versus the average peak interstorey drift of the five time history analysis. Refer to section 4.2 for a discussion of floor spectral accelerations.

The base isolated braced frame has the best overall relative performance of the six systems and by a significant margin. One interesting result that was obtained from the non-linear time history analyses was the concentration of interstory drift that occurred at the 1st storey of the three-storey bucking-restrained brace building with an R= 7.0.

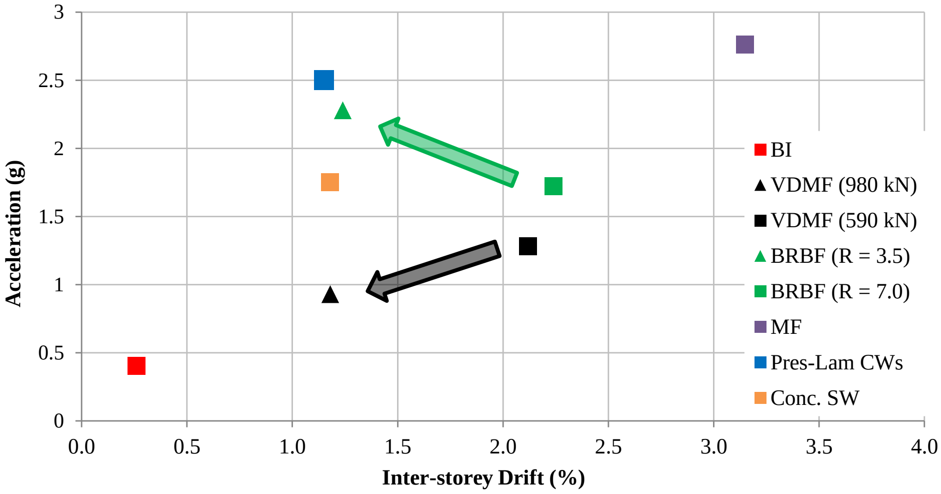


Figure 3: 10% in 50 years – Average Third Floor Spectral Acceleration (0-1.0 sec.) vs. Average Peak Interstorey Drift.

Table 1: Average Drift and Accelerations

		72 yr. return period		475 yr. return period		2,500 yr. return period	
	Floor	Drift (%)	Acc (g)	Drift (%)	Acc (g)	Drift (%)	Acc (g)
BI	3	0.13	0.15	0.22	0.24	0.22	0.25
	2	0.12	0.11	0.21	0.18	0.23	0.25
	1	0.15	0.13	0.26	0.19	0.32	0.25
VDMF (980 kN)	3	0.53	0.4	1.09	0.52	2.64	0.94
	2	0.64	0.36	1.18	0.47	2.54	0.81
	1	0.54	0.33	0.94	0.51	1.98	0.83
VDMF (590 kN)	3	1.05	0.4	2.12	0.74	4.51	1.41
	2	0.97	0.32	1.93	0.56	3.96	1.13
	1	0.7	0.31	1.36	0.55	2.89	0.98
BRBF (R = 3.5)	3	0.49	0.72	0.75	0.77	1.33	0.88
	2	0.43	0.7	0.78	0.84	1.91	1.31
	1	0.7	0.65	1.24	0.84	2.76	1.08
BRBF (R = 7.0)	3	0.62	0.43	0.95	0.51	1.98	0.65
	2	0.68	0.52	1.41	0.63	2.75	0.85
	1	1.04	0.53	2.24	0.59	4.43	0.98
MF	3	1.86	0.77	3.15	0.86	4.67	1.08
	2	1.68	1.06	2.84	1.27	3.98	1.47
	1	1.2	1.04	1.73	1.47	2.36	1.72
Pres-Lam CWs	3	0.91	0.96	1.15	1.38	3.69	2.01
	2	0.89	0.80	1.12	1.01	3.63	1.26
	1	0.78	0.65	1.00	0.91	3.44	1.15
Conc. SW	3	0.70	0.75	1.18	0.80	2.80	0.98
	2	0.66	0.76	1.13	0.80	2.76	0.93
	1	0.50	0.78	0.86	0.87	2.35	1.10

3.5 Construction Cost

A detailed structural cost take-off was performed on all the structural systems by cost estimators Hanscombe, Faith and Gould on the original designs that were performed in 2003, except for the Pres-Lam shear wall system. A cost was estimated for a typical office building so that the structural costs could be estimated as a percentage of the total building cost. In order to develop updated costs Hathaway Dinwiddie provided us with an estimated range for 2012 costs. We estimated the content costs for the laboratory facility and framing costs for the reinforced concrete shear wall and Pres-Lam coupled-walls system. These are provided in Table 2.

Table 2: Cost Summary (US$)

		MF	**BRBF R = 7.0**	**BRBF R = 3.5**	**Base Isolation**	**VDMF 590 kN Dampers**	**VDMF 980 kN Dampers**	**Pres-Lam**	**Concrete Shear wall**
Office Use	Building Cost	$3229/sm	$3218/sm	$3212/sm	$3348/sm	$3240/sm	$3245/sm	$3202/sm	$3132/sm
	Content Cost	$0/sm	$0/sm	$0/sm	$0/sm	$0/sm	$0/sm	$0/sm	$0/sm
	Total Cost	**$19.5M**	**$19.4M**	**$19.4M**	**$20.2M**	**$19.6M**	**$19.6M**	**$19.3M**	**$18.9M**
Laboratory Use	Building Cost	$3767/sm	$3757/sm	$3759/sm	$3886/sm	$3778/sm	$3784/sm	$3740/sm	$3670/sm
	Content Cost	$3229/sm	$3229/sm	$3229/sm	$3229/sm	$3229/sm	$3229/sm	$3229/sm	$3229/sm
	Total Cost	**$42.2M**	**$42.2M**	**$42.2M**	**$43.0M**	**$42.3M**	**$42.3M**	**$42.1M**	**41.7M**

4 FEMA P-58 ASSESSEMENT

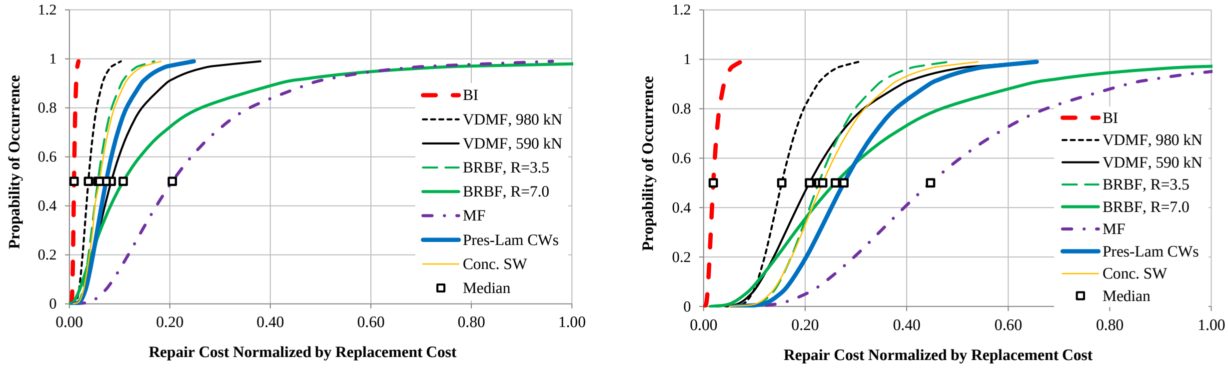
4.1 Analysis Results

All framing systems were assessed assuming the structure is an office building with no contents and a laboratory/research facility with $3,229 (US$) per square metre of contents (refer to Table 2 for a breakdown of costs). The objective of running the building both as an office building and a laboratory facility is to capture the significance of acceleration sensitive equipment to the overall loss calculation.

It should be noted the authors have not yet developed specific fragility curves for the structural components of the Pres-Lam coupled-walls building. Therefore, for this study structural damage to the Pres-Lam shear wall building components has not been accounted for. These fragilities may include drift levels at which the external dampers would need to be replaced, any potential damage to the gravity system due to imposed displacements, any repair required at the rocking base and any floor to wall connections that would need to be repaired.

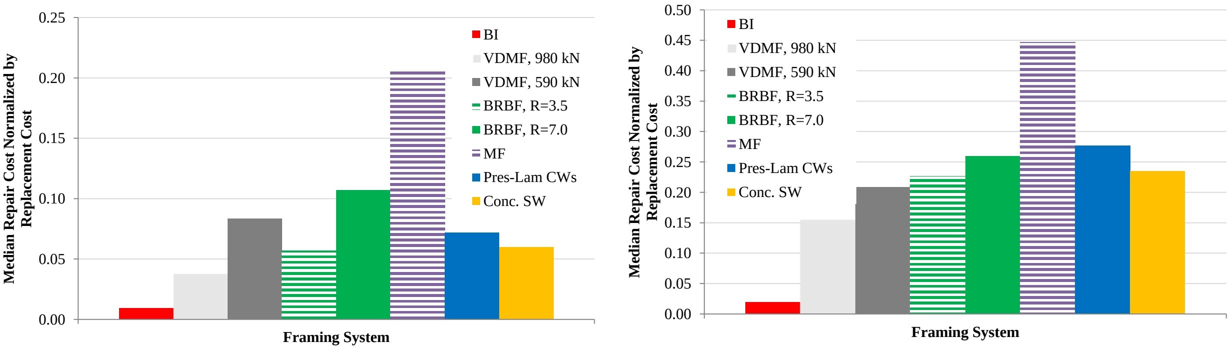
The results of the assessment are presented in Figure 4 through Figure 9. For the loss curves (Figure 4 and Figure 6), the probability that a loss will not be exceeded is plotted on the vertical axis and the loss expressed as a ratio of the replacement cost is on the horizontal axis. Thus by going to the 0.5 or 50% probability on the vertical axis the analysis indicates there is a 50% probability that the loss will not exceed the x-axis value.

Within the PACT tool there are two parameters that will trigger a complete rebuild of the structure. The two parameters are collapse and residual drift. If the analysis predicts the potential of a partial or full building collapse at a certain intensity, then PACT will consider that realisation a complete loss. Similarly, if the analysis indicates excessive residual drift within the structure, then a complete loss is triggered within the program. The FEMA P-58 documentation recommends a value of between 1% - 1.5% as the median irreparable residual drift ratio with a dispersion of 0.8, see the discussion below on residual drift. We have plotted the loss curve both with residual drift being considered (Figure 4) and without residual drift being considered in the assessment (Figure 6). For the buckling-restrained braced framed system with an R= 7.0 the analysis indicated there is a 15% probability that excessive residual drift will occur at a 475 year return period event. The estimated probability that residual drift would occur in the moment frame building was even higher than the BRBF with R= 7.0. The remaining systems have a very low estimated probability of excessive residual drift occurring for the 475 year return period event.



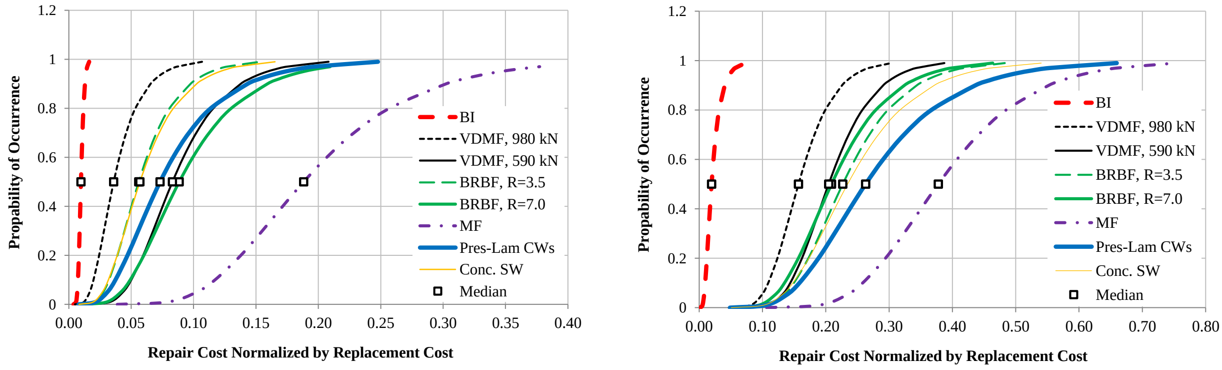
(a) Office building (b) Laboratory building

Figure 4: 10% in 50 years – Repair Cost Curves (with Residual Drift).



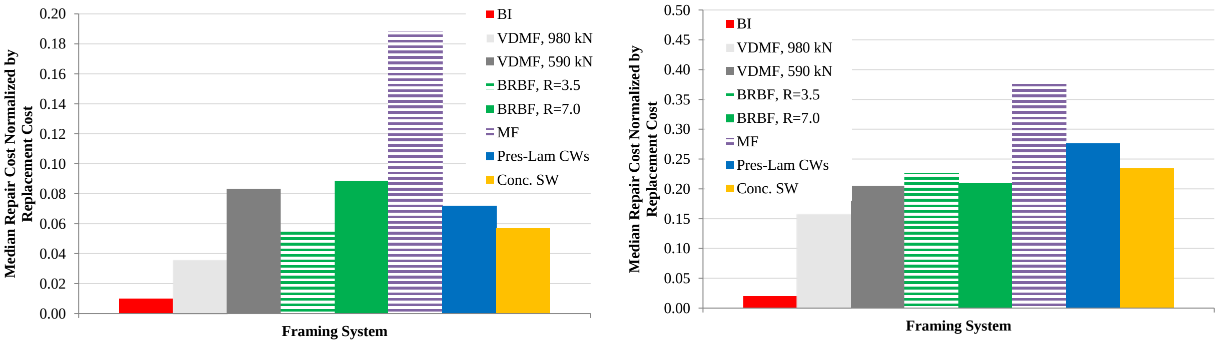
(a) Office building (b) Laboratory building

Figure 5: 10% in 50 years – Median Repair Cost (with Residual Drift) [note different scale of y-axis].



(a) Office building (b) Laboratory building

Figure 6: 10% in 50 years – Repair Cost Curves (without Residual Drift) [note different scale of x-axis].



(a) Office building (b) Laboratory building

Figure 7: 10% in 50 years – Median Repair Cost (without Residual Drift) [note different scale of y-axis].

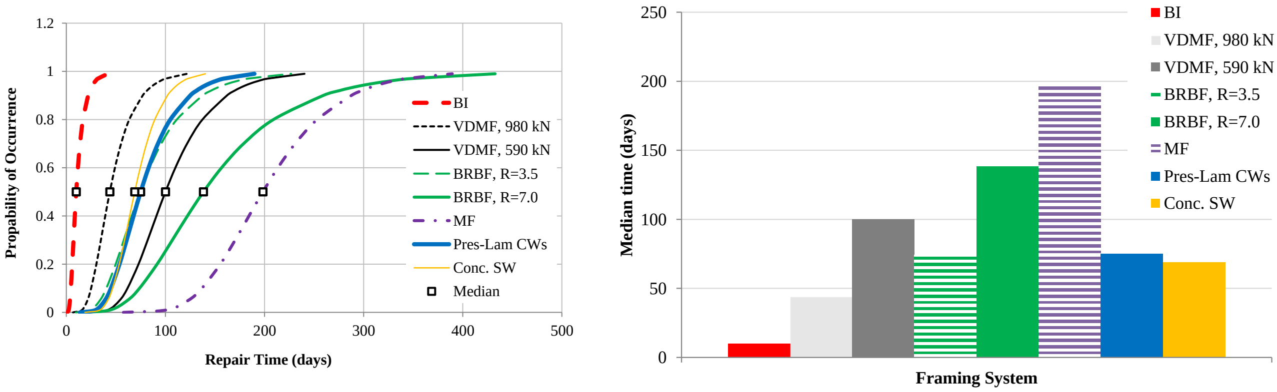
PACT provides other capabilities in addition to reporting the *repair cost* curves. It also produces cumulative probability plots for *repair time* and *casualties* as well as breakdowns for which elements (contents, partitions, structures and others) are contributing to each earthquake consequence (*cost, repair time,* or *casualties*).

Figure 8 is a plot of *repair time* for the office building at the 10% in 50 year event. As discussed in Section 2.3, the *repair time* shown below is not necessarily the estimated downtime for a building. The *repair time* estimated below is the time to repair all elements within the building envelope and does not include the time it takes to complete post-earthquake building inspection, gain access due to unsafe neighbouring buildings, secure financing for repairs, mobilize engineering services, re-design damaged structural components, obtain permitting, and mobilize a contractor and necessary equipment. Assuming there are none of the above described impeding factors, the downtime of the office building to achieve pre-earthquake functionality could be less than the *repair time* shown below. For example, repairs to components posing a life-safety hazard may require 2 months at which point the building could be re-occupied. An additional 2 months may be required to repair damaged pipes and equipment, at which point the building functionality is restored. An additional 1 month may be required to finish repairs on all damaged partitions and non-essential building components at which point full recovery is achieved. So the repair time to achieve full recovery is 5 months but the downtime to re-occupy the building is only 4 months.

It should be noted that the business disruption costs associated with the loss of one or more buildings for significant periods of time are not included in these calculations. They could be assessed by the owner once the downtime estimates have been provided. These include loss of production or operations, loss of sales or services and loss of on-going research and development in some industries (e.g., the biotech industry). These losses translate into major economic issues for a corporation including loss of revenue¸ loss of market share and loss of share value and will generally dominate discussions on the economic issues.

The authors have not provided the repair time for the Laboratory building because they do not have sufficient data to do so at this time. The time to repair fragile equipment and contents could take a significant amount of time. For example for a bio-pharmaceutical building, the time to achieve full recovery for the production of a product could take years. Especially when considering the time to procure funding and the time that would be required to re-certify equipment per USA Food and Drug Administration (FDA) regulations.

The assessment estimated a very small probability of *casualties* for all of the structural systems at the 10% in 50 year event. A partial or full collapse of a structure is the main demand parameter that triggers significant *casualties* within PACT. Another demand parameter that may trigger *casualties* within PACT is the small probability that a wall mounted piece of equipment falls due to an anchorage failure and causes an injury or a loss of life.



(a) Probability of occurrence

(b) Median repair time

Figure 8: Office 10% in 50 years – Repair Time Curves (without Residual Drift).

Figure 9 is the component breakdowns of the median *repair cost* of the laboratory and office buildings for a moment frame structure at the 10% in 50 year event and Figure 10 is the component breakdowns of the median *repair cost* for a VDMF (980 kN) structure. For the moment framed office building, the largest contributor to the median *repair cost* is structural damage and partition damage, while for the laboratory facility we see that significant *repair cost* contribution comes from the fragile laboratory equipment. As can be seen in Figure 10 for the VDMF (980 kN) structure, the viscous dampers significantly reduce the damage to the steel moment frame. This has a large benefit when considering full recovery of a building.

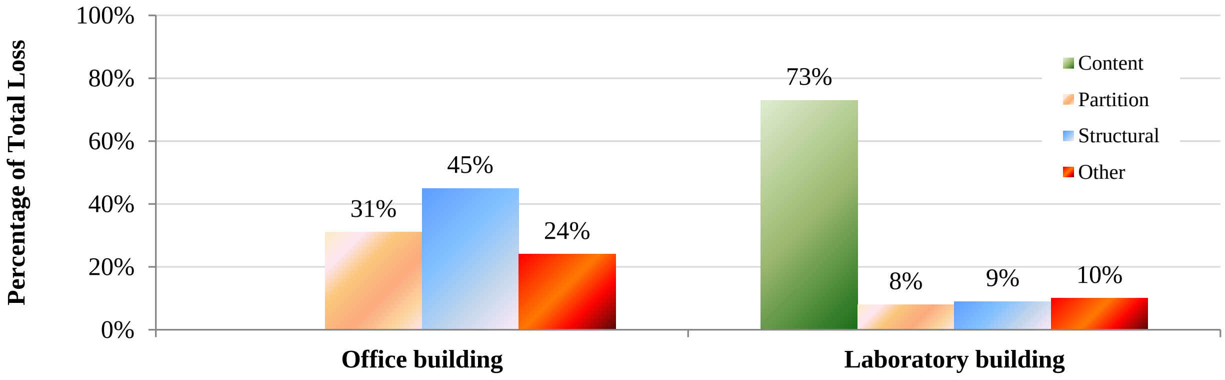


Figure 9: 10% in 50 years Moment Frame Component Breakdown of the median Repair Cost.

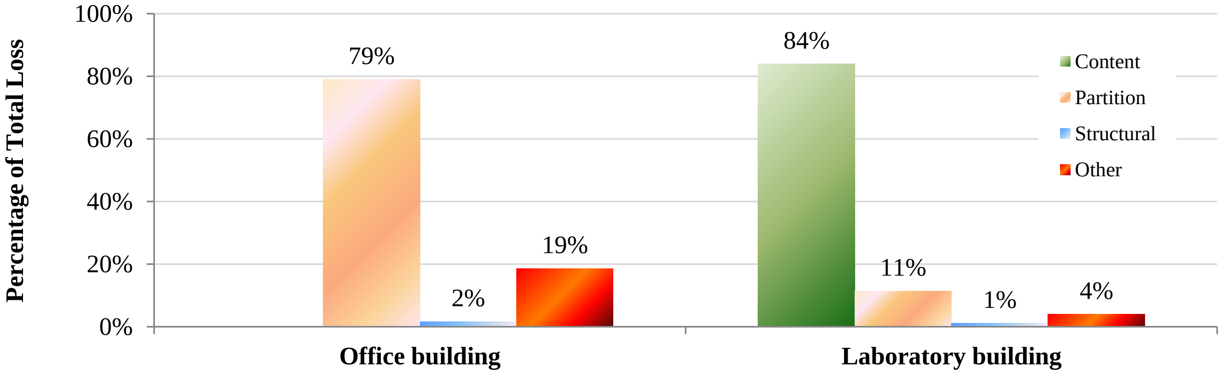


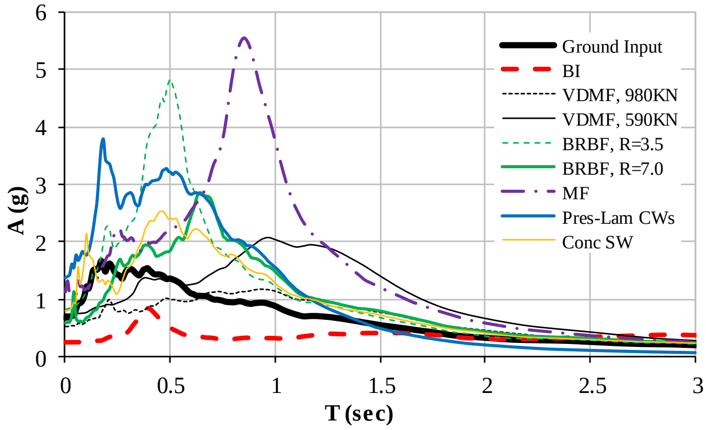
Figure 10: 10% in 50 years VDMF (980 kN) Component Breakdown of the median Repair Cost.

As can be seen in Figure 4 and Figure 6, the base isolated braced frame building performed the best overall by a significant margin for both occupancies types. The moment frame system performed the poorest for both occupancies types and in general the heavily viscously damped moment frame building performed better than the remaining structural types.

The original PACT tool and accompanying fragility curves developed by the FEMA P-58 project and published in August 2012 was utilized to develop a set of results that were published by Mayes *et.al.* (2012). The *repair costs* reported in those results were dominated by partition damage. It was recognized by the authors that the predicted contribution of damage from partitions was much higher than expected. Following the publication of the above mentioned paper, a set of revised partition fragility and damage costs were developed by the FEMA P-58 committee. The results presented in this paper include the updated partition fragility and damage costs. The main change to the partition fragilities is the cost to repair the partitions.

4.2 **Floor Response Spectra**

One of the current limitations with the PACT fragility curves for acceleration related damage is that they are tied to the Zero Period Acceleration (ZPA) at each floor level (T= 0.0 seconds). Considering only the ZPA at each floor level is somewhat akin to designing a building without regard to its fundamental dynamic period. Note the significant spectral peaks for the moment frame, Pres-Lam coupled-wall and BRBF with R = 3.5 systems in Figure 11. Furthermore the benefits of the more heavily viscously damped moment frame structure in reducing the spectral content of the floors is not fully reflected in the ZPA values. Thus the best performing structural systems in reducing the full frequency content of the floor spectra are the base isolated structure, followed by the more heavily damped viscously damped moment frame system. The worst performers, from a floor spectral acceleration perspective, are the moment frame, BRBF with R = 3.5, and Pres-Lam coupled-wall systems.



(a) Average floor acceleration response spectra

Figure 11: Third Floor Acceleration - 10% in 50 years.

At this time there is no direct way to account for these benefits in the damage estimates within the PACT Tool despite them being significant. Another way to compare these effects is to calculate the average response spectra over different period ranges (e.g. 0 – 0.5 sec, 0 – 1.0 sec, 0 – 1.5 sec, and 0 – 2.0 sec) and then divide that average value by the ZPA at that floor level. This comparison is shown in Table 3 for the 3rd floor response spectra for the 10% in 50 year event. This approach better demonstrates the relative performance of the different systems in reducing spectral floor accelerations. As the technology advances within the PACT tool, some account of the floor spectral content will be needed to address the performance of equipment and contents that are not rigid elements. It is recommended in the short term that some assessment of the floor response spectra be used when comparing different structural systems.

Table 3: Mean 3rd Floor Spectra Comparison

	BI	VDMF, 980kN	VDMF, 590kN	BRB, R=3.5	BRB, R=7.0	MF	Pres-Lam CWs	Conc SW
ZPA, g	0.24	0.52	0.74	0.83	0.59	1.1	1.3	0.78
Mean Spectra, g (0-0.5 sec)	0.44	0.77	1.03	2.38	1.33	1.73	2.66	1.67
Mean Spectra, g (0-1.0 sec)	0.40	0.93	1.28	2.28	1.72	2.76	2.50	1.75
Mean Spectra, g (0-1.5 sec)	0.39	0.93	1.43	1.82	1.48	2.50	1.96	1.47
Mean Spectra, g (0-2.0 sec)	0.39	0.85	1.38	1.49	1.25	2.09	1.54	1.24
Mean Spectra (0-0.5 sec) / ZPA	185%	149%	139%	286%	226%	158%	204%	214%
Mean Spectra (0-1.0 sec) / ZPA	167%	179%	173%	275%	291%	251%	192%	224%
Mean Spectra (0-1.5 sec) / ZPA	164%	179%	193%	219%	250%	228%	151%	189%
Mean Spectra (0-2.0 sec) / ZPA	163%	163%	187%	180%	212%	190%	120%	159%
Mean Spectra (0-0.5 sec) / Mean BI	100%	175%	232%	536%	301%	391%	599%	376%
Mean Spectra (0-1.0 sec) / Mean BI	100%	233%	320%	571%	430%	690%	526%	437%
Mean Spectra (0-1.5 sec) / Mean BI	100%	237%	362%	462%	375%	636%	499%	374%
Mean Spectra (0-2.0 sec) / Mean BI	100%	217%	353%	381%	320%	534%	397%	317%

4.3 **Residual Drift**

Residual drift is an important consideration in judging a structure's post-earthquake safety and the economic feasibility of repair. Large amounts of residual drift may require costly and difficult repairs to both structural and non-structural components and if they become large enough can jeopardize structural stability in earthquake aftershocks and render the building uneconomical to repair. Research has shown that residual drift predictions by nonlinear time history analysis are highly variable and sensitive to a number of assumed modelling parameters. Accurate statistical prediction of residual drifts requires advanced non-linear time history analyses, with a large number of ground motions and with careful consideration to cyclic hysteretic response and numerical accuracy of the solution. Since the requirements for directly calculating residual drifts are computationally complex for general implementation, the FEMA P-58 documents provides empirical equations for estimating residual drifts. The FEMA P-58 document recommends using the following equation (Eq. 1), developed in recent research studies and based on the design displacement demand (Δ) and the yield displacement (Δ_y). The FEMA P-58 document recommends using a high dispersion value of 0.8 to account for the uncertainty in accuracy of the calculated residual drift (Δ_r).

$$\begin{cases} \Delta_r = 0 & \Delta \le \Delta_y \\ \Delta_r = 0.3 \times \left(\Delta - \Delta_y\right) & \Delta_y < \Delta < 4\Delta_y \\ \Delta_r = \left(\Delta - 3\Delta_y\right) & \Delta \ge 4\Delta_y \end{cases} \qquad (1)$$

Residual drift has a significant effect on the moment frame and the BRBF with R= 7.0 system. By virtue of the post-tensioned rocking mechanism, the Pres-Lam coupled-wall system is expected to have negligible residual deformation at the 475 year return period event.

4.4 Special Considerations for Buckling Restrained Brace Frames

As mentioned above, the analysis indicates the buckling restrained braced frame systems have a concentration of inelastic drift occurring at the ground floor. This was also observed in studies by Sabelli (2001) and Fahnstock (2006 and 2007). The authors have also had discussions with researchers at the University of California, Berkeley and they too have found similar results for buildings of similar storey height (Mahin, 2012). The authors have performed a similar study as that presented in this paper on a 9-storey and 20-storey building and did not find such a significant concentration of inelastic drift occurring in the BRBF systems. The concentration of inelastic drift appears to occur in building 6-storeys and less Sabelli (2001).

To assess this issue in more detail the authors performed two different designs for the BRBF with R=7.0. Table 4 below is a table showing the brace sizes for the two different systems. For Option A we optimized the size of the braces at each floor level. In Option B we designed the first two floors with the same brace size and reduced it to a smaller sized brace at the roof. Option B was studied because the authors believe in many cases this is common practice for BRBF design. The results reported above, for the performance assessment, are for the BRBF systems with the brace sizes optimized at each floor level (Option A). Table 5 below compares the drifts and accelerations of the two options.

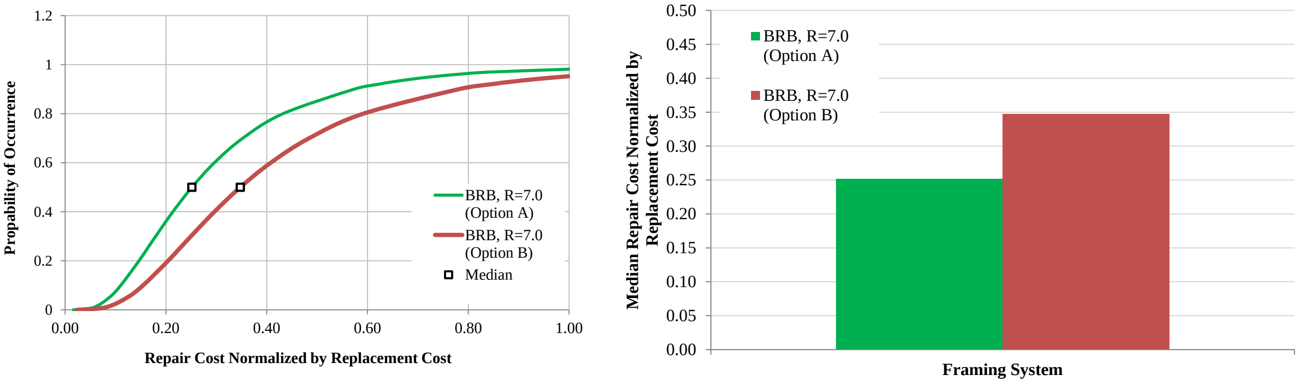
Table 4: BRBF Design Data

	Option A		**Option B**	
	T_1 = 0.58 s		T_1 = 0.57 s	
	V_{Base} = 4588 kN		V_{Base} = 4588 kN	
Storey	Brace Axial Capacity	Design Drift	Brace Axial Capacity	Design Drift
	(kN)	(2.5% limit)	(kN)	(2.5% limit)
3	600	0.79%	600	0.78%
2	905	0.85%	1050	0.75%
1	1050	0.81%	1050	0.81%

Table 5: Average BRBF R = 7.0 Drift and Accelerations

		50%-50 years		10%-50 years		2%-50 years	
	Floor	Drift (%)	Acc (g)	Drift (%)	Acc (g)	Drift (%)	Acc (g)
Option A	3	0.62	0.43	0.95	0.51	1.98	0.65
	2	0.68	0.52	1.41	0.63	2.75	0.85
	1	1.04	0.53	2.24	0.59	4.43	0.98
Option B	3	0.66	0.46	1.00	0.51	1.95	0.61
	2	0.48	0.53	1.15	0.67	2.39	0.87
	1	1.15	0.56	2.36	0.62	4.57	1.04

Figure 12 shows that Option A performs much better than Option B. Option B exacerbated the issue of a concentration of inelastic drift occurring at the ground floor and thus the impact of residual drift on the repair costs was greater. For Option A the FEMA P-58 assessment indicated there is a 15% probability that excessive residual drift will occur at a 475 year return period event. For Option B there is a 35% probability of residual drift occurring at a 475 year return period event.



(a) Probability of occurrence

(b) Median repair time

Figure 12: Laboratory 10% in 50 years – Compare Repair Cost of Option A & Option B BRBF Designs.

It is recommended that designers who are considering using BRBF systems optimize the brace size at each level. Also the authors recommend designers consider using a lower R-Factor than 7 to safeguard against excessive residual drift occurring at a 475 year event. A future study on a more appropriate lower R-Factor appears warranted.

4.5 **Building Rating**

The details of the three dimensions of the SEAONC Rating System (SEAONC Existing Buildings Committee 2008, 2009, 2011, 2012) – Safety, Repair Cost and Functional Recovery Time are provided in Tables 6, 7 and 8, respectively. The New Zealand Quakestar system (Mayes 2012) has not yet developed the detailed definitions of the three dimensions although they are likely to be similar to the SEAONC definitions. The SEAONC definitions will be used for developing a rating of the office building using the median values of the FEMA P-58 results from the 10% in 50 year event.

Safety Rating – the probability of deaths or injuries were assessed to be small in all of the building types for the 10% in 50 year event thus each building, beside the base isolated building and VDMF (980 kN), would receive a four star safety rating. The base isolated building and VDMF (980 kN) would receive a five star safety rating as the limited amount of damage would not cause any entrapment issues.

Repair Cost – the base isolated building and the viscously damped building (VDMF 980 kN) would receive a five star damage rating as the repair cost is less than 5% of the replacement cost. The viscously damped moment frame (VDMF 590 kN), the buckling restrained braced frame (BRBF R= 3.5), the Pres-Lam and the reinforced concrete shear wall would have a four star Repair Cost Rating as the damage is less than 10% for the 10% in 50 year event, based on the residual drift calculations. The buckling restrained based frame (R= 7.0) has a three star repair cost rating as the damage is less than 20% and the moment frame (MF) is very close to a three star rating but would have a two star Repair Cost Rating as the damage is slightly above 20% and below 50%.

Functional Recovery Time – the base isolated building would receive a five star functional recovery time rating as the building's basic functions could be restored within hours and a total repair time of approximately 10 days. The VDMF (980 kN) building would receive a four star functional recovery time as the basic function could be restored within days and a total repair time of approximately 40 days. A majority of the repairs for the VDMF (980 kN) system is for partition damage. For the other building types FEMA P-58 predicts approximately 70 days for the reinforced concrete shear wall, 75 days for the BRBF (R= 3.5) and 75 days minimum for the Pres-Lam, however this does not include structural damage which may increase the recovery time, 100 days for VDMF (590 kN), 130 days for the BRBF (R= 7.0) and 200 days for the moment frame. In order to get a better estimate of the actual downtime and the re-occupancy time it is important to look at what components contribute to the repair time and then assess separately the re-occupancy time and the total repair time. The repair time may need to be increased to account for completing post-earthquake building inspection, secure financing for repairs, mobilize engineering services, re-design damaged structural components, obtain permitting, mobilize a contractor and the necessary equipment. If the damaged components are easily repairable while the building is occupied the re-occupancy time will be less than the repair time. It is noted that the majority of the damage is to the partitions in several of the buildings and much of this repair can be performed while the building is occupied. It is therefore probable the BRBF (R= 3.5) buildings would have a three star functional recovery rating. Assuming the Pres-Lam coupled shear wall system experiences very little damage to the structure it would also receive a three star rating. The moment frame, the BRBF (R= 7.0), and the VDMF (590 kN) is likely to have a two star functional recovery time. The concrete shear wall building was given a two star function recovery time due to the time to repair the concrete walls.

A summary of the SEAONC ratings is given in Table 9.

The Building Rating Systems have not attempted to address the impact of the performance of the contents on the rating. Thus the FEMA P-58 results of the laboratory facility would be of interest to the owner of the facility but cannot be directly used to determine a building rating. It is noted that repair costs expressed as a % of the replacement costs (including contents) increases for the laboratory facility when compared to the office building (Figure 4).

Table 6: SEAONC Rating System – Safety Rating

★★★★★	**No entrapment.** Performance would not lead to conditions commonly associated with earthquake-related entrapment.
★★★★	**No injuries.** Performance would not lead to conditions commonly associated with earthquake-related injuries requiring more than first aid.
★★★	**No death.** Performance would not lead to conditions commonly associated with earthquake-related death.
★★	**Death in isolated locations.** Performance in certain locations within or adjacent to the building would lead to conditions known to be associated with earthquake-related death.
★	**Death in multiple or widespread locations.** Performance as a whole would lead to multiple or widespread conditions known to be associated with earthquake-related death.

Table 7: SEAONC Rating System – Repair Cost Rating

★★★★★	**Within typical operating budget.** Performance would lead to conditions requiring earthquake-related repairs commonly costing less than 5% of building replacement value.
★★★★	**Within typical insurance deductible.** Performance would lead to conditions requiring earthquake-related repairs commonly costing less than 10% of building replacement value.
★★★	**Within industry Scenario Expected Loss (SEL) limit.** Performance would lead to conditions requiring earthquake-related repairs commonly costing less than 20% of building replacement value.
★★	**Repairable damage.** Performance would lead to conditions requiring earthquake-related repairs commonly costing less than 50% of building replacement value.
★	**Substantial damage.** Performance would lead to conditions requiring earthquake-related repairs costing more than 50% of building replacement value (as used by the *International Building Code* as an upgrade trigger).

Table 8: SEAONC Rating System – Functional Recovery Time Rating

★★★★★	**Within hours.** Performance would support the building's basic intended functions within hours following the earthquake.
★★★★	**Within days.** Performance would support the building's basic intended functions within days following the earthquake.
★★★	**Within weeks.** Performance would support the building's basic intended functions within weeks following the earthquake.
★★	**Within months.** Performance would support the building's basic intended functions within months following the earthquake.
★	**Within years.** Performance would support the building's basic intended functions within years following the earthquake.

Table 9: Summary of Buildings SEAONC Rating

Structure	**Safety**	**Repair Cost**	**Functional Recovery Time**
BI	★★★★★	★★★★★	★★★★★
VDMF (980 kN)	★★★★★	★★★★★	★★★★
BRBF (R=3.5)	★★★★	★★★★	★★★
Pres-Lam CWs	★★★★	★★★★	★★★
VDMF (590 kN)	★★★★	★★★★	★★
Conc. SW	★★★★	★★★★	★★
BRBF (R=7.0)	★★★★	★★★	★★
MF	★★★★	★★	★★

5 CONCLUSIONS

The paper has presented the results of using the FEMA P-58 methodology for calculating the performance metrics of *repair costs, repair time* and *casualties* on the earthquake performance of eight three story buildings configured as both an office building and a laboratory facility utilizing six different structural systems: moment frame (MF); buckling restrained braced frame (BRBF); viscously damped moment frame (VDMF); Pres-Lam shear wall (Pres SW), cast-in-place reinforced concrete shear wall (Conc SW) and base isolated braced frame (BI). The authors have not yet developed specific fragility curves for the structural components of the Pres-Lam coupled-walls building. Therefore, for this study structural damage to the Pres-Lam system building components has not been accounted for. The buckling-restrained bracing system was designed as both a conventional building with an R-Factor of 7.0 and as an essential facility using an R-Factor of 3.5. The viscous damped moment frame was initially designed to meet the minimum code drift requirements (590 kN dampers) and then the system was redesigned with an almost doubling in the damping coefficient of the viscous dampers (980 kN dampers). These two additional designs were performed in order to study the relative performance of structural systems that could meet lower drift limits required for essential facilities. Each of the building models were analysed as fully non-linear structures, with each subjected to a total of 15 time histories with 5 each representing the 50% probability of exceedance in 50 years (50 in 50), 10 in 50, and 2 in 50.

The results, presented for the 10 in 50 set of ground motions, demonstrate the superior performance of the base isolated braced frame system for both the office building and the laboratory facility. The steel moment frame was the poorest performer of all the structural systems that were assessed. The VDMF (980 kN) building designed as an essential facility performed better than the other conventional buildings but not as good as the base isolated building. For the office building all of the other structural systems; BRBF's, VDMF (590 kN), reinforced concrete shear wall and the Pres-Lam all performed very well from a safety and repair cost basis but had varying downtimes of significant duration with the VDMF (590 kN) and BRBF R= 7.0 in excess of 100 days and the moment frame at 200 days. It should be noted that the business disruption costs associated with the loss of one or more buildings for significant periods of time are not included in these calculations. They could be assessed by the owner once the downtime estimates have been provided. These include loss of production or operations, loss of sales or services and loss of on-going research and development in some industries (e.g., the biotech industry). These losses translate into major economic issues for a corporation including loss of revenue¸ loss of market share and loss of share value and will generally dominate discussions on the economic issues. The availability of the repair time estimates will initiate this more in depth discussion.

The paper has also provided the translation of the FEMA P-58 results into the current definitions of the proposed SEAONC Rating System. For the office building configuration all of the structural systems performed very well from a safety and repair cost perspective getting either a five or four star rating, except the BRBF (R= 7.0) received a three star repair cost and moment frame (MF) received a two star repair cost. The downtime estimates from FEMA P-58 are not directly translatable into the SEAONC definitions as they are based on re-occupancy rather repair time estimates. As a consequence the structural engineer in conjunction with the owner is required to make an assessment of the components that are damaged and determine their impact on both re-occupancy and the total downtime. The re-occupancy time may be considerably shorter than the repair time computed by FEMA P-58 if a considerable portion of the repairs to some of the non-structural elements, such as partitions, can be performed while the building is occupied. The total downtime may also be much longer than the repair time computed by FEMA P-58 due to the time to complete a post-earthquake building inspection, gain access due to unsafe neighbouring buildings, secure financing for repairs, mobilize engineering services, re-design damaged structural components, obtain permitting, and mobilize a contractor and necessary equipment. Development of models to assess these additional variables is possible, but is not currently included in the FEMA P-58 document.

When assessing low-damage structural design concepts it's imperative that a holistic approach is taken and not focus only on damage to structural items. When an engineer is considering a low-damage design they should consider all aspects of a building including, but not limited to, the expected performance of non-structural components and fragile contents (often the major cost of earthquake damage), soil condition, potential damage from adjacent buildings and repair time of both structural and non-structural elements.

The authors believe the high floor acceleration observed in the Pres-Lam coupled shear wall system is typical in most rocking structural systems. These high floor accelerations have a significant impact on the performance of acceleration sensitive components, as seen in the repair cost comparison of the office and laboratory buildings for the Pres-Lam structure. This makes rocking systems along with the BRBF (R= 3.5) and moment frame systems much less desirable for essential and medical facilities. Rocking systems may limit damage to the structural system but they do not necessarily limit damage to non-structural elements and contents. Also as can be seen in Figure 11, the Pres-Lam coupled shear wall, BRBF (R= 3.5) and moment frame system in this 3 storey configuration produce amplified floor spectral accelerations which are not currently accounted for in the FEMA P-58 floor acceleration fragility curves but should be assessed when considering the relative merits of different structural systems.

This paper focuses on the results from a 10% in 50 year ground shaking (475 year return period). The difference in performance for the structural systems becomes even more apparent when comparing relative performances of the different systems for a 2,500 year return period. The probability of collapse, which translates into the probability of *casualties,* plays a much larger role. Also, residual drift plays a very significant role in *repair cost* for the larger ground shaking.

The conclusion drawn from this comparative study should not be universally applied to buildings of all heights. Depending on a buildings size, shape, detailing and function, different systems may perform relatively better or worse than was assessed for this comparative study.

A number of interesting issues arose as a result of performing one of the early studies using the FEMA P-58 methodology. These include the impact of residual displacements on structural systems that are subjected to large interstory drifts and the use of the peak zero period accelerations rather than some measure of a floor spectral response on the performance of acceleration sensitive components and contents. These will be addressed as more use is made of the extremely useful and beneficial FEMA P-58 methodology and software.

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