Cost-benefit analysis of base isolated and conventional buildings: A case study

2014 NZSEE Conference

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ABSTRACT: Base isolation using lead rubber bearings has been shown to be highly effective in mitigating earthquake damage in buildings. However, the implementation rate has remained low in the New Zealand private sector. Uncertainty about initial cost increases and future benefits remain strong disincentives. This paper presents a case study life cycle analysis of a conventional and base isolated steel braced office building. It is found that the overall performance of the base isolated building is far superior to the conventional building, but the expected financial loss in the isolated building increases markedly in the unlikely event of structural pounding against the surrounding moat wall. The life cycle benefits of base isolation are found to be very significant. However, whether base isolation is cost-effective in a traditional expected cost-benefit analysis is strongly dependent upon the input assumptions, particularly those relating to business downtime.

1 INTRODUCTION

Base isolation using lead rubber bearings (LRB) provides a proven and effective means of protecting buildings from the damaging effects of horizontal ground motions. Superior structural performance of base isolated buildings was again demonstrated in the recent 2011 Christchurch Earthquake, in which the base isolated Christchurch Women's Hospital was able to continue functioning with only minor non-structural damage (Kam et al. 2011). Still, the list of LRB base isolated buildings in New Zealand is predominantly made up of key historic buildings and critical facilities such as hospitals for which post-earthquake function is essential. There are a number of possible reasons for the slow uptake of base isolation in the New Zealand private sector (Mayes et al. 1992). One perhaps is a lack of public awareness of NZ's earthquake hazard due to a lack of significant seismic events over a sustained period. This is illustrated by the events in Japan where there was also a slow uptake of base isolation for the 46 years of relative seismic inactivity prior to the 1995 Kobe Earthquake, and a sharp increase in implementation of base isolation shortly afterwards (Clark et al. 2000). Other possible explanations include a lack of knowledge on base isolation technologies amongst design engineers, a lack of clear design code guidance and a lack of dialogues between design engineers and clients regarding seismic performance objectives. However, perhaps the most important reason is uncertainty regarding the additional financial costs and life cycle benefits of incorporating base isolation.

Several studies have demonstrated the expected financial life cycle benefits of adopting LRB base isolation in buildings. Thiel (1986) used an analytical approach based on Modified Mercalli Intensities; Bruno & Valente (2002) and Suwa & Seki (2005) used nonlinear time history analyses in combination with predictive damage models; and more recently, Terzic et al. (2012) and Mayes et al. (2013) utilized the FEMA P-58 methodology (FEMA 2013a) to evaluate the financial life cycle benefits. In these studies, the expected life cycle benefits were significant and outweighed the first cost increases when they were provided. This provided clear and quantitative evidence for the potential of base isolation to be cost-effective in office and apartment buildings in terms of expected life cycle costs. However, these studies showed that the cost-effectiveness of base isolation was highly sensitive to the seismic hazard levels, the structural design details, the building occupancy, the analysis time period and the discount rate, and whether earthquake insurance and business downtime are considered in the analysis. Hence, the expected costs and benefits of incorporating base isolation in arbitrary building-specific applications remain relatively uncertain.

This paper presents a detailed case study on the expected life cycle benefits of base isolation using the FEMA P-58 methodology, with understanding focus on the costs and benefits of base isolation in typical construction. The study focuses particularly on the influence of moat wall pounding on financial losses in base isolated structures and the impact of differing business interruption assumptions on cost-benefit analyses.

2 CASE STUDY

2.1 Building designs

The case study examines two three-story steel braced office buildings, one base isolated with LRBs and the other with a conventional design. The layout of the buildings are shown in Figure 1. The buildings were designed by Forrell/Elsesser Engineers Inc. of San Francisco for a location outside of Los Angeles (34.50N, 118.2W) based on the 2006 International Building Code (ICC 2006), ASCE 7-05 (ASCE 2005) and AISC 341-05 (AISC 2005). The site was assumed to be class D (V_{s30} = 270 m/s) with short period and one second spectral accelerations (as defined in ASCE 7-05) of S_s=2.2g and S_1=0.74g, respectively. The conventional building was designed as a Special Concentrically Braced Frame (SCBF) with force reduction factor R=6 and the isolated building was designed as an Ordinary Concentrically Braced Frame with force reduction factor R=1. The isolation system was designed for an effective period and effective damping ratio of [T_D, β_D] = [2.85 s, 21%] in the Design Basis Earthquake (DBE) event and [T_M, β_M] = [3.10 s, 15%] in the Maximum Considered Earthquake (MCE) event. More details on the two designs, including section sizes and isolator properties, can be found in a paper by Erduran et al. (2011). The first mode period of the conventional SCBF is 0.43 s, which is slightly greater than the first mode period of the isolated OCBF superstructure (0.39 s). The pre-yield and post-yield periods for the isolation system were 0.79 s and 3.55 s.

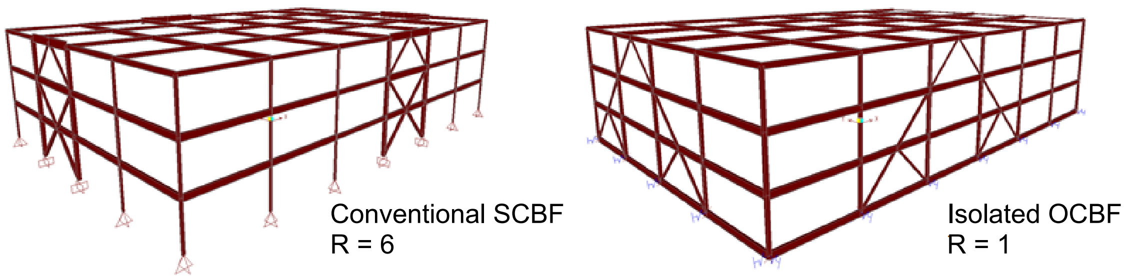

Figure 1. Design layouts for the conventional SCBF and isolated OCBF

2.2 Building modelling

Detailed three-dimensional nonlinear finite element models for each structure were developed using OpenSees (McKenna et al. 2000). The models included variants of the isolated building with and without a moat wall. When included, the moat wall interaction model was based on Masroor & Mosqueda (2013), and assumed a seismic gap of 76.2 cm (30.0 in), which was the MCE design displacement for the isolated building including torsional effects. The steel superstructure was modelled using fibre sections with steel stress-strain properties given by a Giuffré-Menegotto-Pinto model with a strain hardening ratio of 3%. Brace models were calibrated to match the experimental response reported by Black et al. (1980).

During the development of the finite element model, the site class assumption was revised from site class D (V_{s30} = 270 m/s) to site class C (V_{s30} = 540 m/s). This ensured the ground motions applied to the two buildings would not have spectral accelerations that were comparatively skewed compared to their design spectral accelerations. This change did not alter the design base shear for the conventional SCBF but lowered the design base shear for the isolated OCBF by 13%. As a result, the conventional SCBF is minimally code compliant, while the isolated OCBF slightly exceeds code requirements with an effective R = 0.87 on site class C soil.

2.3 Seismic hazard and ground motion selection

Ten discrete hazard levels were selected with corresponding intensities that provided even coverage of the intensity range of interest. Hazard data is summarized in Figure 2. These hazard levels were subsequently categorized into six bins, listed in Table 1, based on similarity in spectral shape.

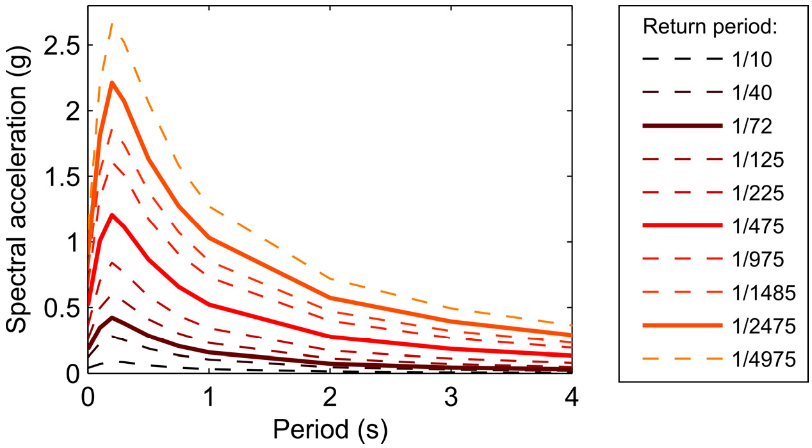

Figure 2. Uniform hazard spectra for the site at ten different hazard levels (USGS 2013).

Table 1. Summary of the significant test properties.

Bin	Hazard levels	Buildings
1	1/10, 1/40, 1/72	Both buildings
2	1/125, 1/225	Both buildings
3	1/475, 1/975	Isolated OCBF only
4	1/475, 1/975	Conventional SCBF only
5	1/1485, 1/2475, 1/4975	Isolated OCBF only
6	1/1485, 1/2475, 1/4975	Conventional SCBF only

In selecting ground motion records, closeness of fit between ground motion response spectra and target spectra was particularly important in this study as the two compared structures had significantly different periods. There were many earthquake records available at the lower hazard levels (bins 1 and 2) that closely fit the target spectrum. However, at the higher hazard levels (bins 3 to 6), very few earthquake records fitted the target spectrum over the whole period range of interest. To overcome this, different ground motions were selected for the isolated OCBF and conventional SCBF buildings. Specifically, the isolated OCBF records were selected according to the closeness of fit to a conditional mean spectrum at 3.0 s period, over a period range of $0.5T_D$ (1.425 s) to $1.25T_D$ (3.875 s) (ASCE 2005), and the conventional SCBF records were selected according to the closeness of fit to a conditional mean spectrum at 0.5 s period, over a period range of $0.2T_1$ (0.086 s) to $2.0T_1$ (0.86 s), where T_1 is the conventional SCBF's first mode period (FEMA 2013a). The selection of dissimilar records for the conventional and isolated buildings led to records with far better spectral matches over the period ranges of interest. This in turn led to more accurate (lower dispersion) demand predictions. Each bin contained motions that were roughly representative of the magnitudes and distances that contributed most to overall seismic hazard, as well as motions with and without near fault effects.

2.4 **Structural response**

For each simulation, 20 bidirectional scaled ground motions corresponding to each building and simulation hazard level were applied aligned to the global x- and y- axis in the structural model, and then again at a 90˚ orientation. As expected, base isolation significantly reduced both peak floor acceleration and peak inter-story drift (see Figure 3). This reduction was most pronounced at the 1/475 and 1/975 hazard levels, where inter-story drifts were lessened by a factor between 5 and 20, and peak floor accelerations were reduced by a factor between 4 and 6, depending on the location in the building.

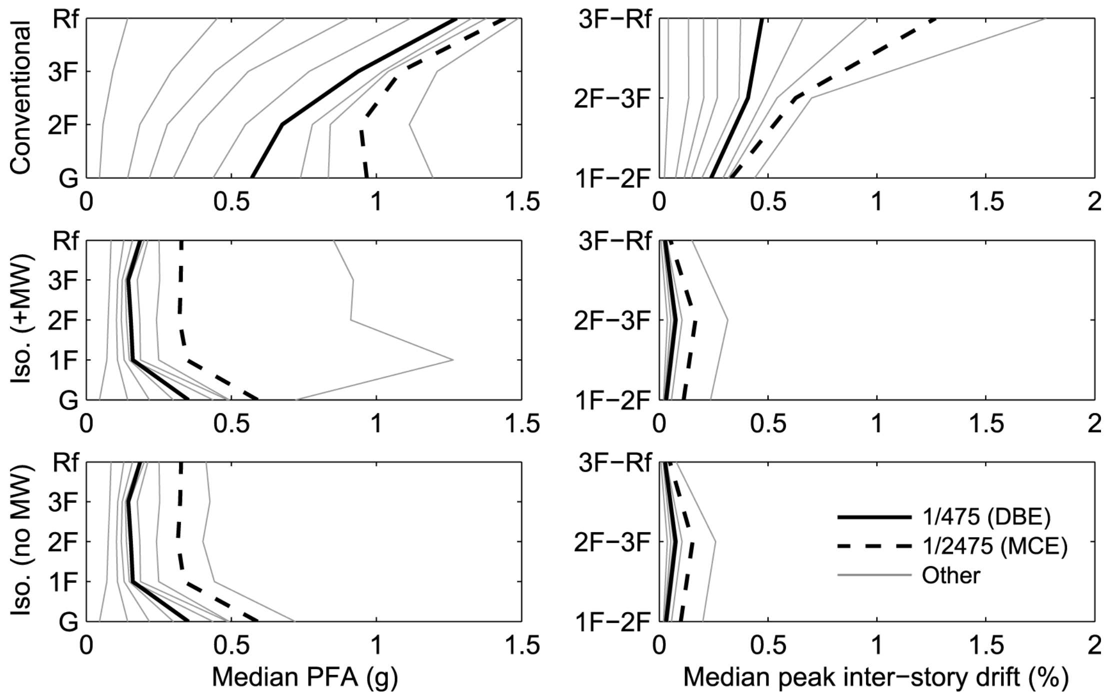

Figure 3. Median values of peak floor acceleration (PFA) and peak x-direction inter-story drift vs. story height, for the conventional SCBF and isolated OCBF with and without a moat wall (MW). All ten hazard levels are plotted from left to right in order of increasing hazard level intensity, with the 1/475 and 1/2475 year responses accented.

The simulation results showed that pounding of the base isolated building against the surrounding moat wall occurred at the 1/1485 hazard level (1 simulation out of 40), the 1/2475 hazard level (13 simulations out of 40) and the 1/4975 hazard level (31 simulations out of 40). Pounding typically caused superstructure peak floor accelerations to increase to between 0.5 g and 1.5 g on the upper stories and 0.5 g and 2.0 g on the first story. At the 1/4975 hazard level, 5 out of 40 simulations produced first floor accelerations in excess of 3.5 g. Pounding-induced amplification of peak floor acceleration at the 1/4975 year hazard level is clearly apparent in Figure 3. Pounding-induced amplification of peak interstorey drift demand was observed, but was found to be highly sensitive to the approach velocity and torsional displacement at the time of impact. The superior 1/4975 year performance of the isolated building with no moat wall is possible at the expense of higher displacements (120-150 cm in some cases). This performance may well be unrealistic due to displacement-induced isolator failure.

Simulations with high transient interstorey drift were observed in both the conventional building (up to 5.7%) and the isolated building with a moat wall (up to 3.6%). None of the simulations predicted a full structural collapse. As such, collapse probabilities were not included in later financial analyses. However, probabilities of the building receiving an unsafe placard or requiring replacement were included in the later analysis. An unsafe placard is a legally enforced notification that the building is unsafe for occupancy until further assessment or repair work is completed. Unsafe placard probabilities were derived using FEMA P-58 procedures (FEMA 2013a), whereby an unsafe placard is issued if a threshold number of structural components reach a prescribed damage state. Replacement probabilities were estimated from residual drifts using a fragility curve for building replacement with a median of 1.0% residual drift and a lognormal dispersion of 0.3.

2.5 Damageable component inventory

The damageable component inventory included structural components (OCBF and SCBF braces, pre-Northridge moment connections and gravity connections), non-structural components (monolithic exterior glazing, fully fixed interior partition walls, a suspended ceiling system, two traction elevators, electrical and plumbing distribution, a fire sprinkler system, roof-mounted HVAC equipment and a transformer) and contents (desktop computers and workstation desks). The quantities of each inventory item were based on the normative quantities suggested in Appendix F of FEMA P-58-1 (FEMA 2013a). Whenever possible, the fragility, repair cost and repair time data for each component was assumed to take on the default values suggested in the FEMA P-58 Performance Assessment Calculation Tool (PACT) fragility specification manager (FEMA 2013b).

2.6 Financial loss from earthquake damage

Demand parameters from nonlinear time history analyses, seismic hazard data and component inventories were assembled and input into PACT software (FEMA 2013b). Performance evaluations were then conducted for each building. These involved the generation of 300 Monte Carlo performance realizations at each hazard level and integration over the intensity range of interest to determine key expected annual values. Table 2 shows the key expected value outputs for each building, where expected annual repair times are the average repair times between parallel and series repair strategies over the building floors. The superior performance of the isolated building types is highlighted here by significant reductions in expected annual repair cost and repair time, and decreased likelihoods of receiving an unsafe placard or requiring replacement.

Table 2. Key expected value output

Value	Conventional SCBF	Isolated OCBF (with moat wall)	Isolated OCBF (no moat wall)
Expected annual repair cost	\$20,500	\$2,000	\$160
Expected annual repair time	1.26 days	0.061 days	0.018 days
Unsafe placard return period	230 years	19000 years	N/A
Replacement return period	7800 years	46000 years	N/A

Earthquakes of all different hazard levels contributed relatively evenly to the overall expected annual loss in the conventional SCBF building – apart from the 1/10 hazard level, all contributions were between 7% and 15%. However, in the isolated building with a moat wall, expected annual loss was dominated by the 1/4975 hazard level, with an 86% overall contribution. This suggests an important role of structural pounding in modeling the financial performance of base isolated structures.

For the 1/475 year hazard level, about one third of the financial losses in the conventional SCBF was derived from damage to the structural system and the remaining two-thirds from damage to non-structural components and contents. At the same hazard level, financial losses in the isolated OCBF was dominated by minor damage to interior partitions. The significant contribution of interior partition damage suggests that the performance of a base isolated building might be expected to worsen as the superstructure flexibility is increased, relative to the isolated building examined herein. This explains the higher financial losses in base isolated buildings observed by Terzic et al. (2013).

Repair cost vs. ground shaking intensity relationships for each building type are shown in Figure 4. In the conventional SCBF, expected repair costs increase almost linearly with spectral acceleration after a threshold spectral acceleration of about 0.2g is reached. Conversely, in the isolated OCBF building, expected losses remain minimal until spectral accelerations well above DBE level. Losses in the isolated building become particularly significant at the 1/4975 hazard level, where response is dominated by moat wall pounding.

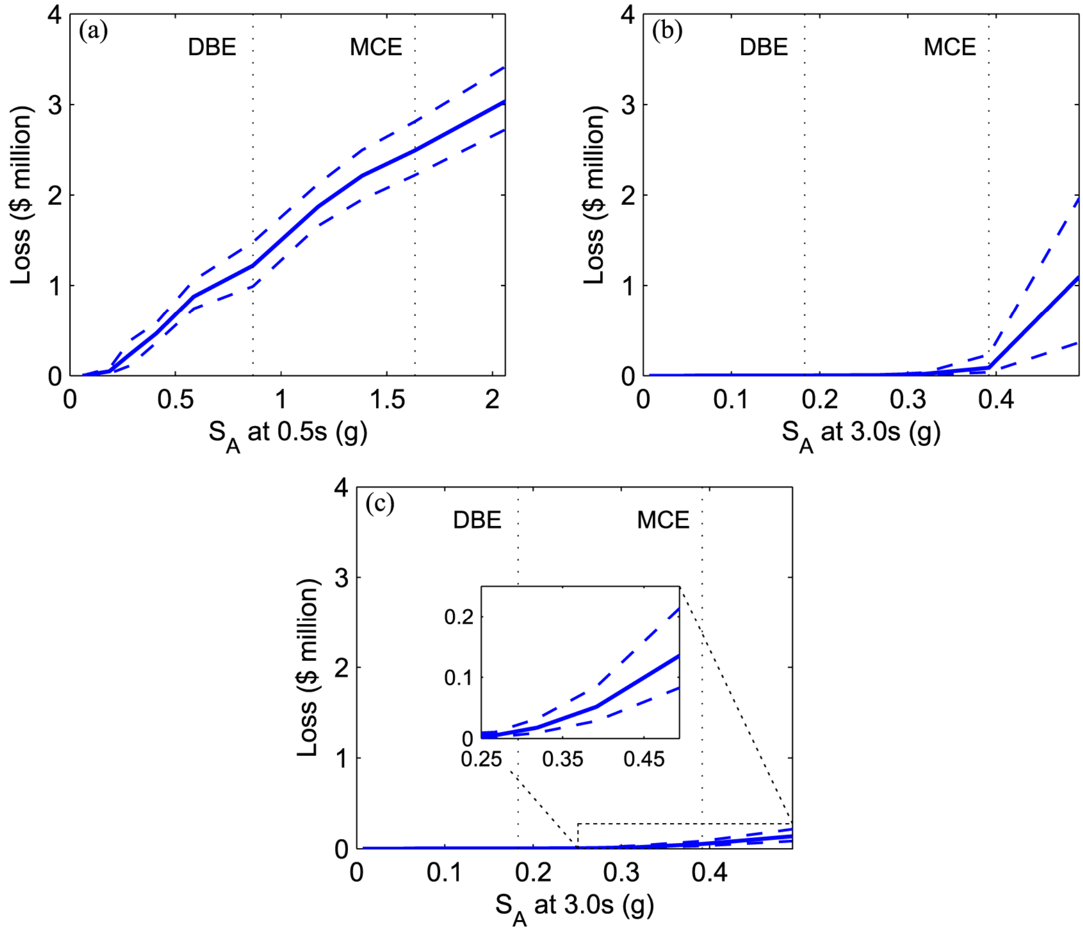

Figure 4. Median and ±1 standard deviation repair costs vs. spectral acceleration for (a) the conventional SCBF, (b) the isolated OCBF with a moat wall and (c) the isolated OCBF without a moat wall, given building replacement is not required.

2.7 Financial loss from business interruption

The business income was assumed to be $60,000 per day based on an estimate for office buildings of the size examined here (NIBS & FEMA, 2003). Subsequently, five different cases of business interruption loss were considered. Case 0 neglected business interruption loss completely. Case 1 assumed that business downtime was equal to total repair time. Case 2 assumed that business downtime was equal to total repair time plus additional planning periods, to account for time needed to inspect damage, obtain financing and develop designs for repair or replacement operations (Comerio, 2006). Case 3 was identical to Case 2 except that it only included time to repair those components deemed critical to building occupancy. Lastly, Case 4 allowed for business to relocate to an offsite location if the business downtime became longer than a two week threshold. The resulting changes to Expected Annual Losses (EALs) are summarized in Table 3.

Table 3. Impact of business interruption losses on EAL

Case	EAL for the conventional SCBF	EAL for the isolated OCBF (with moat wall)	EAL for the isolated OCBF (no moat wall)
0	$20,500	$2,000	$160
1	$100,000	$6,300	$1,200
2	$197,000	$7,800	$1,200
3	$160,000	$5,900	$200
4	$33,200	$2,400	$200

Amplification of EAL due to business interruption is particularly evident in the conventional OCBF. When business relocation is allowed to occur (Case 4), the EAL for the conventional SCBF conventional is only about 1.5 times greater than the default case when business interruption loss is neglected (Case 0). However, when business relocation is not possible (Cases 1 to 3), the EAL for the conventional SCBF is between 5 and 10 times greater than the default case. This suggests that base isolation is much more likely to be cost-efficient if the occupying business is incapable of quickly and efficiently relocating after a large earthquake. The cost-efficiency of base isolation is also likely to be significantly influenced by the business turnover.

2.8 The effects of insurance

This study does not directly consider the apportionment of losses between the building owners and insurers. Nonetheless, it is possible to make some simple predictions about the effects of including earthquake insurance. Based on current market conditions, the percentage reduction in insurance premium between the isolated OCBF and the conventional SCBF is very unlikely to match the true percentage reduction in EAL (Charleson & Allaf 2012). Thus insuring both buildings will reflect negatively on both the isolated OCBF's EAL and its cost-effectiveness in an expected cost-benefit analysis. However, if the conventional SCBF is insured while the base isolated OCBF is left uninsured, the expected cost-effectiveness of implementing base isolation is likely to improve (Whittaker, 2012).

3 CONCLUSIONS

The FEMA P-58 methodology has been applied to a conventional low-rise, braced steel frame building and an equivalent isolated building with and without a moat wall. Overall, the performance of the isolated building models was far superior to the conventional building model; however, this performance degraded somewhat in the unlikely event of structural pounding against the building's moat wall. Hence, considered and conservative selection of the building seismic gap is important for achieving the best performance from a base isolated building. This study also suggests that minor drift-related interior partition damage can become significant in isolated buildings if the superstructure is not designed with a sufficient inter-storey stiffness. The expected financial benefits provided by the isolation system over the building life cycle were found to be highly sensitive to assumptions about business interruption. Base isolation is found to be more cost-effective for businesses that are unable to quickly and effectively relocate after a large earthquake.

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