
Low-damage design to enhance seismic performance of reinforced concrete buildings

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ABSTRACT

Low-damage or recovery-based design and practice to enhance building seismic performance has gained momentum over the past decade. However, wider adoption of Low-Damage Seismic Design (LDSD) in the engineering and building sectors requires heightened awareness of stakeholders about the benefits that such practices can offer and associated cost implications. This study conducts detailed seismic risk assessment of five building archetypes with reinforced concrete moment-resisting frame and shear wall-frame systems and quantifies the mitigating impacts of several LDSD solutions and Recovery Planning (RP) measures under four shaking intensities with 43, 475, 950, and 2475 years return periods. The findings suggest that collectively, the considered LDSD and RP solutions can shorten the average downtime of basic building functions from eight and 16 months to two and four months, given the 475- and 950-year earthquakes, respectively. Furthermore, average repair to replacement cost ratios of 30% and 48% can be mitigated to 11% and 22% and the average likelihood of building demolition reduces from 22% and 42% to 6% and 21% following the 475- and 950-year earthquakes, respectively. Although basic functions would likely be undisturbed following the 43-year earthquake, LDSD and RP solutions can reduce average recovery time to pre-hazard functionality by 89%. Moreover, life-safety is better preserved, where the average probability of collapse given the 2475-year earthquake reduces from 18% to 9% with the adoption of LDSD. Conversely, the average direct upfront cost implication is estimated at 4%. The findings of this research will provide quantitative evidence for development and adoption of LDSD.

1 INTRODUCTION

Recovery-based or Low-Damage Seismic Design (LDSD) has become a solution to enhance building seismic performance. Evidence suggests that adopting LDSD solutions can mitigate building repair costs, lower the risk of demolition, and shorten recovery time following earthquakes with moderate to high intensities (Habibi et al. 2025a, 2026). Accordingly, development of LDSD guidelines and construction practices to enhance building seismic performance has been the primary focus of the engineering society in New Zealand (NZ) (Li

et al. 2024). This is largely a result of awakening experiences from both the Canterbury earthquake sequence and the Kaikōura earthquake over the past two decades with consequences that far exceeded societies' expectations (Kim 2015; Marquis et al. 2017). Internationally, recent technical and scientific advancements in seismic risk assessment (Almufti and Willford 2013; FEMA 2018a; ATC 2021; Cook et al. 2022) has also driven the adoption of recovery-based design in earthquake-prone countries such as the United States (US).

The recent LDSD guidance series published by the Ministry of Business, Innovation and Employment (MBIE 2024, 2025a, b) and the upcoming 2026 NEHRP Recommended Seismic Provision are exemplary efforts of developing LDSD guidelines. The literature also identifies several LDSD solutions/initiatives including the use of lower design drift limits to increase building lateral strength/stiffness (Molina Hutt et al. 2022; Pledger et al. 2024b, a; Opabola and Elwood 2024; Cook et al. 2024; Habibi et al. 2025a, b, 2026), more robust structural systems/elements (Henry et al. 2021; Liu et al. 2023; Li et al. 2024), damage-controlled connections (Yeow et al. 2018a; Büker et al. 2022), base isolation technologies and energy dissipation mechanisms (Tatarsky and Filiatrault 2019; Li et al. 2024), and less vulnerable non-structural components including partition walls (Bhatta et al. 2023), suspended ceilings (Pourali et al. 2017), exterior claddings (Baird et al. 2014), and water/sanitary plumbing (Tian et al. 2014; Soroushian et al. 2015). Findings of previous studies suggest a great potential for such LDSD solutions to mitigate overly long downtime following moderate to high shaking intensities to tolerable few months (Molina Hutt et al. 2022; Liel et al. 2023; Mohammadgholibeyki et al. 2023; Opabola and Elwood 2024; Cook et al. 2024; Habibi et al. 2025a, b, 2026). However, widespread and more uniform adoption of LDSD still requires evidence-based incentives about the level of performance enhancement that is expected from them compared to any upfront cost implications (Habibi et al. 2024; Li et al. 2024). This study aims to provide research-based quantitative evidence to support the development and adoption of LDSD practices.

This paper reports the findings from intensity-based detailed seismic risk assessment of five low-, mid-, and high-rise office building archetypes with Reinforced Concrete (RC) Special Moment-resisting space Frame (SMF) and Shear Wall-frame (SW) systems in Wellington, NZ. The assessments are conducted according to the FEMA P-58 (FEMA 2018a) and ATC-138 (ATC 2021; Cook et al. 2022) frameworks using the Performance Assessment Calculation Tool (FEMA 2018b) and the SP3 software tool (Haselton Baker Risk Group 2025), given four shaking intensities. The paper then quantifies the effects of several structural and non-structural LDSD solutions to enhance building seismic performance following each shaking intensity. The investigated LDSD solutions include: 1) the adoption of a 1% design drift limit, 2) the use of alternative damage-controlled practices for several non-structural components, 3) the use of seismically pre-qualified non-structural components plus the adoption of a 50% higher earthquake force for non-structural component design. Furthermore, the effects of organisational preparedness measures to facilitate post-hazard inspection and repair mobilization are investigated. The findings reveal substantial benefits for the adoption of LDSD including lower repair costs, faster restoration of basic functions, and reduced risk of building demolitions following moderate to high shaking intensities. For more frequent serviceability-level earthquakes, buildings with LDSD would likely encounter little disruption with no loss of function and a fast recovery to pre-hazard functionality just in few days. Buildings that adopt LDSD are also shown to better preserve life-safety following the Maximum Considered Earthquake (MCE) with lower probabilities of collapse.

2 CASE-STUDY

The case-study building archetypes consist of three RC SMF buildings with three, six, and ten stories as well as two RC SW buildings with five and ten stories, respectively. The buildings are all located at a site in Wellington, NZ with shallow soil. The SMF and the SW buildings have a three-by-three and a four-by-four plan grid with a floor area of 324 and 576 square meters, respectively, where span length is six meters for all buildings. Story height is 4-4.5m for the first story and 3.6m for the stories above. The structural design

detailing of the building archetypes, such as material properties, cross-section size of beams, columns, and walls, and reinforcement detailing, is adopted from Pledger et al. (2024b, a). Pledger et al. (2024b, a) kept all detailing constant throughout the building height, which helps to maintain a uniform vertical distribution of stiffness/strength and avoid unfavourable single-storey collapse mechanisms as discussed in Habibi et al. (2023). Table 1 summarises main design parameters and naming convention of the case-study building archetypes. Further detailing and information are available in Habibi et al. (2025a, b, 2026).

Table 1: Introduction of the building archetypes and their naming convention (Pledger et al. 2024b, a; Habibi et al. 2025a, b, 2026).

Building Name	Number of stories	Structural system	Maximum allowable story drift ratio	Design base shear coefficient	Dynamic 1 st mode period (T_n in s)	Construction cost (NZD ^{***} /m ²)
3RC-SMF-C*	3	RC SMF	2.00%	0.07	0.868	2741
3RC-SMF-LD**	3	RC SMF	1.00%	0.10	0.483	2802
6RC-SMF-C*	6	RC SMF	2.50%	0.04	1.537	3968
6RC-SMF-LD**	6	RC SMF	1.00%	0.08	0.698	4163
10RC-SMF-C*	10	RC SMF	2.50%	0.03	2.206	3968
10RC-SMF-LD**	10	RC SMF	1.00%	0.06	0.996	4135
5RC-SW-C*	5	RC shear wall-frame	2.50%	0.10	0.474	3968
5RC-SW-LD**	5	RC shear wall-frame	1.00%	0.24	0.254	4217
10RC-SW-C*	10	RC shear wall-frame	2.50%	0.07	0.619	3968
10RC-SW-LD**	10	RC shear wall-frame	1.00%	0.15	0.413	4051

* Current code-minimum design according to the life-safety-centred standards.

** Basic Low-Damage design.

*** NZD: New Zealand Dollar.

Four design types are considered for each building archetype in this study to compare their seismic performance. Table 2 presents detailing of all the considered design types, which include: 1) the Current code-minimum design according to NZ Standards (NZS) 1170.5 (NZS 2004), 2) the basic Low-Damage design, where the structure is designed to a 1.0% maximum story drift limit, instead of the 2.5% code-minimum limit (NZS 2004) and several alternative damage-controlled components are used for partition walls (Bhatta et al. 2023), suspended ceilings (Pourali et al. 2017), and exterior claddings (Baird et al. 2014) as shown in Table 2. Reducing the design story drift limit leads to higher building lateral strength/stiffness, which will reduce story drifts but increase floor accelerations. It will also increase the upfront construction cost of buildings. This is shown in Table 1, where the construction cost is on average 3.9% higher for the basic Low-Damage design compared to the Current code-minimum design. It is noted that only the direct cost implications of a higher structural frame cost are considered in the estimations. Detailed information on construction cost estimations is available in Habibi et al. (2025a, b, 2026). The other two design types are: 3) the Low-Damage ($SQ+I_p=1.5$) design, where prequalified components with seismic bracing, anchorage, and isolation and a 50% higher component importance factor (I_p) are employed for critical acceleration-sensitive non-structural components per suggestions from Cook et al. (2024) as shown in Table 2, and 4) the Low-Damage ($SQ+I_p=1.5 + RP$) design, where additional Recovery Planning (RP) measures are also implemented to facilitate and accelerate post-hazard safety inspections and engineering/contractor mobilization through pre-arranged contracts.

Table 2: Details of different design types considered for each building archetype (Habibi et al. 2025a).

Component/Design Type	Current (code-minimum)	Low-Damage	Low-Damage ($SQ+I_p=1.5$)	Low-Damage ($SQ+I_p=1.5 + RP$)
Structural	Maximum design story drift ratio = 2.5%	Maximum design story drift ratio = 1.0%	Maximum design story drift ratio = 1.0%	Maximum design story drift ratio = 1.0%
Partition walls	common practice steel stud	with slotted & bracketed head-tracks	with slotted & bracketed head-tracks	with slotted & bracketed head-tracks
Ceiling system	two-way exposed suspended	pendulum-type fully floating	pendulum-type fully floating	pendulum-type fully floating
Exterior cladding	with long-threaded rod connections	with UFP connections	with UFP connections	with UFP connections
Stairs	single flight precast	similar with seismic joints	similar with seismic joints	similar with seismic joints
Elevator, piping, & HVAC*	without bracing or isolation & $I_p=1$	without bracing or isolation & $I_p=1$	Prequalified with bracing/isolation & $I_p=1.5$	Prequalified with bracing/isolation & $I_p=1.5$
Recovery planning	None	None	None	Inspector, engineer, & contractor on-retainer plans

* HVAC: Heating, Ventilation, Air-conditioning, and Cooling systems.

Next, seismic loss measures and recovery time of all the building archetypes at all the design types are assessed, given four earthquake intensities that are representative of 1) a serviceability-level earthquake, 2) a design-level earthquake, 3) the Wellington Fault Line scenario event (Aurecon 2019), and 4) the MCE with return periods of 43, 475, 950, and 2475 years, respectively. Figure 1(a) and (b) respectively show the 5%-damped spectra and target spectral acceleration, represented by Sa_{target} , for all the buildings. Sa_{target} is the target intensity measure that is derived from the earthquake spectrum at the building natural period of vibration, T_n , and is used for the seismic risk assessments. As expected, SW buildings have larger target intensity measures due to their higher stiffness and lower natural period compared to SMF buildings. Under each shaking intensity, nonlinear response history analyses of 3D finite element models of the structure in the Open System for earthquake engineering simulation (OpenSees) analysis platform (McKenna 1997) quantify structural responses, such as story drifts and floor accelerations, using the FEMA P695 (FEMA 2009) far-field ground motion record set and parallel processing. Modelling details of RC moment frames and RC shear walls as well as more information about dynamic response history analyses are discussed in Habibi et al. (2025a, b, 2026). Next, building damage and loss analyses are performed according to the FEMA P-58 framework (FEMA 2018a), given the structural responses, which requires damage fragility curves and loss consequence functions. This study employs fragility curves and consequence functions that have been developed specifically with NZ construction practices in mind (Yeow et al. 2018b; Fox et al. 2024) where such data are available. Otherwise, FEMA P-58 curves and functions (FEMA 2018b) are used with adjustments of the repair cost as suggested by Fox et al. (2024). More information about building components, component quantities, fragility curves, and consequence functions can be found in Habibi et al. (2025a, b). Probability distribution of the impending time prior to the start of recovery to conduct safety inspection, financing, and repair mobilization is quantified next using the impending curves in the ATC-138 framework (ATC 2021; Cook et al. 2022). Subsequently, probability distribution of the time to achieve reoccupancy and recovery of basic intended functions, hereafter called the functional recovery time, is quantified using the ATC-138 (ATC 2021; Cook et al. 2022) fault trees. The fault trees determine building functionality based on the ability of each building system, e.g. exterior, interior, egress, fire suppression, plumbing, elevator, HVAC, and exhaust, to perform its intended functions, given damage and loss measures of the corresponding components within that system.

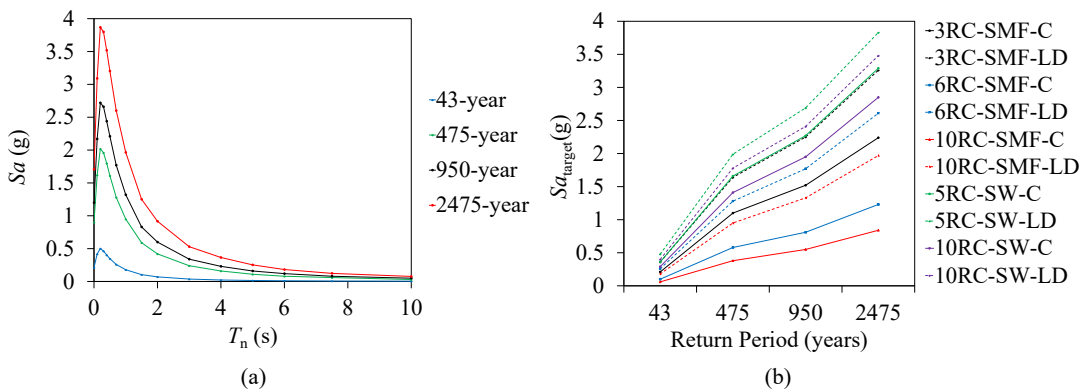


Figure 1: (a) Median 5%-damped spectra and (b) target intensity measures of the building archetypes, given all the earthquake intensities (GNS Science 2022).

The following presents the outputs of risk and recovery analyses of this study and discusses reduction of expected consequences by adoption of the investigated LDS and RP solutions. Several loss measures and recovery timeframes will be presented according to intended objectives at each earthquake intensity. Figure 2(a) and (b) show the likelihood that buildings would require demolition and replacement following the 475- and 950-year earthquakes, respectively, according to the FEMA P-58 replacement criteria (FEMA 2018a): 1) partial/complete collapse, 2) excessive residual (permanent) deformations, or 3) the need for extensive repairs that cost more than 40% of what it would cost if the building were to be replaced in-kind. Detailed information about the estimation of replacement cost of the building archetypes is available in Habibi et al. (2025a, b). As

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shown in Figure 2, the Current code-minimum design has an average 22% and 42% risk of demolition following the 475- and 950-year earthquakes, respectively. These probabilities of demolition are lower than what was observed in Christchurch following the Canterbury earthquake sequence (Kim 2015; Marquis et al. 2017) due to the larger structural capacity of the case-study buildings compared to the buildings in Christchurch at the time of the earthquake. This is in turn due to the use of the new NZ National Seismic Hazard Model (NSHM) (GNS Science 2022) for the Current code-minimum designs in this study and that these designs are intended to meet 100% New Building Standard (NBS) rating. Nevertheless, the probability of demolition of the case-study buildings is still considerably high, which substantiates the need for a better-than-code design. Figure 2(a) and (b) suggest that the basic Low-Damage design is expected to lead to an average 84% and 46% reduction in the likelihood of building demolition following the 475- and 950-year earthquakes, respectively. The higher risk of demolition of the three-storey SMF building, even at the Low-Damage design, is due to its lower natural period and higher Sa_{target} compared to the six- and ten-storey SMF buildings as shown in Figure 1(b). For instance, Sa_{target} of the 475-year earthquake is 90% and 189% higher for the Current code-minimum design of 3RC-SMF compared to that of 6RC-SMF and 10RC-SMF, respectively. The findings here suggest that a 1.0% drift limit might still not be enough to sufficiently lower seismic risk of low-rise moment frame buildings under major earthquakes, considering their lower stiffness compared to wall-frame structures.

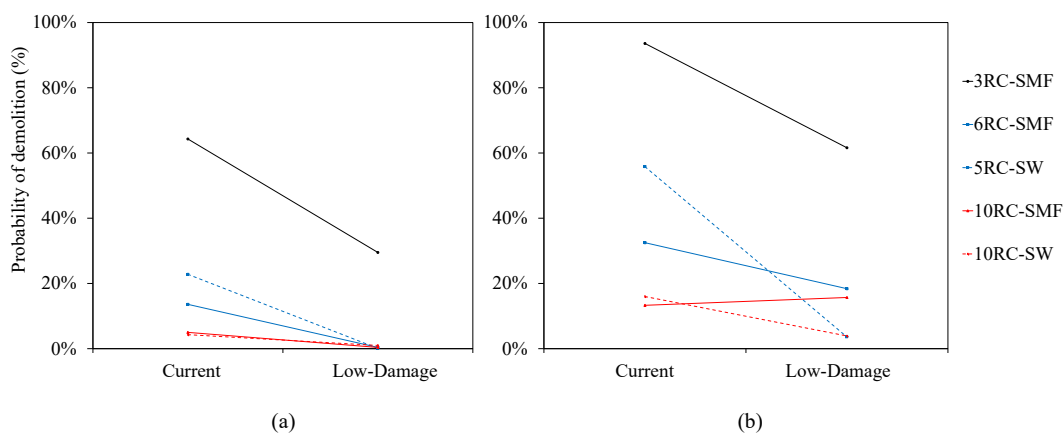


Figure 2: Likelihood of building demolition, given the (a) 475- and (b) 950-year earthquakes; the slightly higher risk of demolition of 10RC-SMF-LD is due to a higher dispersion in estimation of its residual drift.

Figure 3 shows the median repair cost and functional recovery time per total floor area for all the building archetypes at different design types, given the 475- and 950-year earthquakes. Figure 3(a) and (b) suggest high median repair costs for the Current code-minimum designs with average repair to replacement cost ratios of 30% and 48%, given the 475- and 950-year earthquakes, respectively. As Figure 3(a) and (b) show, the basic Low-Damage design is expected to lead to an average 44% and 41% reduction in median repair cost, given the 475- and 950-year earthquakes, respectively. Furthermore, adding $SQ+I_p=1.5$ design option is expected to further reduce the median repair cost by an additional average of 17% and 12%, given the 475- and 950-year earthquakes, respectively. This is shown in Figure 4, which shows the average reduction of seismic losses and recovery time between all the building archetypes by adopting the recommended LDS and RP solutions. Also, Figure 3(c) and (d) show long median functional recovery time of average eight and 16 months, given the 475- and 950-year earthquakes, respectively. The findings suggest that the basic Low-Damage design can reduce median functional recovery time by average 40% and 53%, given the 475- and 950-year earthquakes, respectively. According to Figure 4, adopting $SQ+I_p=1.5$ is expected to lead to 16% and 6% average further reductions in median functional recovery time, respectively. Figure 4 also shows that implementing RP measures would lead to an additional average of 20% and 8% reduction, given the 475- and 950-year earthquakes, respectively. These findings suggest a relatively higher benefit for the adoption of structural LDS solutions but also simultaneously highlights the importance of both non-structural design enhancement options and RP measures to mitigate post-earthquake downtime. Figure 2 and Figure 3 also suggest generally

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higher earthquake consequences for the Current code-minimum design of the SW building archetypes than that of the SMF building archetypes of the same height level due to substantially lower period and higher Sa_{target} of the SW buildings as shown in Figure 1(b). However, benefits of the considered LDS design solutions seem to be more significant for the SW buildings due to their already higher structural stiffness/strength.

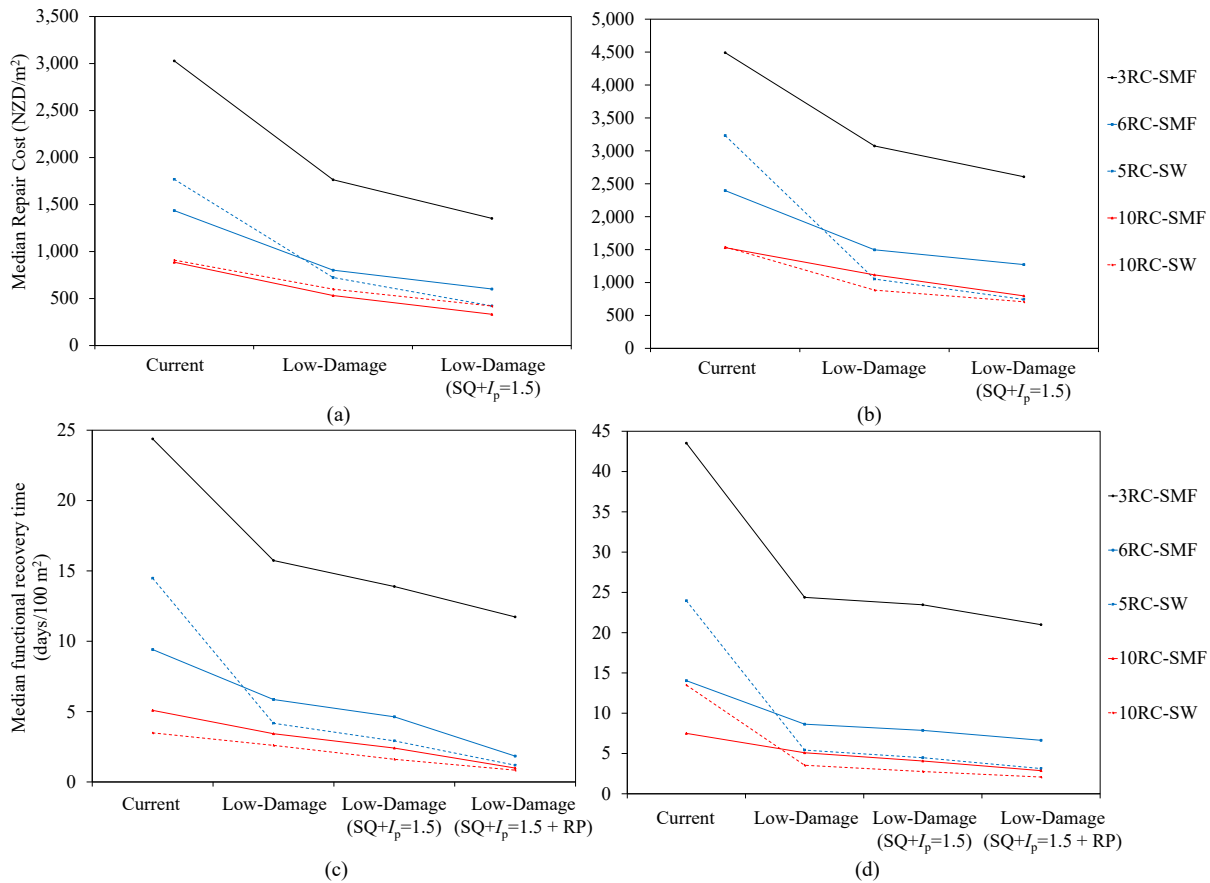


Figure 3: Median repair cost per floor area, given the (a) 475- and (b) 950-year earthquakes; median functional recovery time per floor area, given the (c) 475- and (d) 950-year earthquakes.

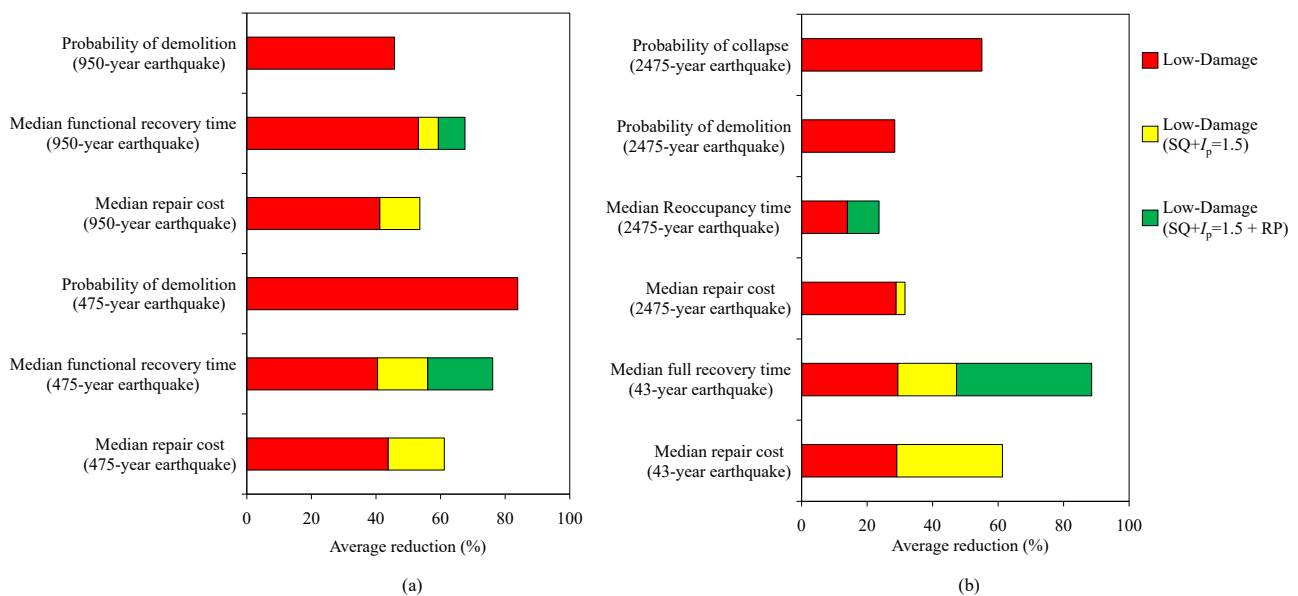


Figure 4: Average reduction of seismic loss and recovery time between all the building archetypes, given the (a) 475- and 950-year earthquakes and (b) 43- and 2475-year earthquakes.

Figure 5 shows expected benefits of the considered LDSD solutions at other shaking intensities with return periods of 43 and 2475 years. Although Current code-minimum designs are likely to meet immediate functionality following the 43-year serviceability-level earthquake, Figure 5(a) suggests that a long delay with an approximate average of 3 months exists before full pre-hazard functionality could be restored. Figure 4 shows that collectively, the considered LDSD and RP solutions can reduce median full recovery time following the 43-year earthquake by an average 89%, where the RP measures have the highest contribution followed by the basic Low-Damage design. This shows that the delay in full recovery following the 43-year earthquake is governed by the impact of the impeding factors. Under the 2475-year MCE, there is an average 71% chance of demolition and replacement and a long recovery with an average median reoccupancy time of approximately 2.3 years for the Current code-minimum designs due to severe structural damage. Figure 4 shows that the probability of demolition and median reoccupancy time following the 2475-year MCE would be respectively reduced by average 28% and 14% when adopting the Low-Damage design. However, preserving life-safety would be the main objective under the MCE. Figure 5(b) suggests an average probability of collapse of 18% following the 2475-year MCE for the code-minimum design, which is expected to reduce by 55% with the adoption of the basic Low-Damage design. More information about collapse assessment criteria is available in Habibi et al. (2025a, b). Habibi et al. (2025a, b) also showed that Current code-minimum designs meet life-safety objectives with low mean casualties (less than one person) even at the MCE. Finally, Figure 5(c) and (d) show median repair costs of the building archetypes, given the 43- and 2475-year earthquakes, respectively. The findings, as depicted in Figure 4, suggest that the basic Low-Damage design can reduce median repair costs by average 29%, given both the 43- and 2475-year earthquakes, which is lower than the observed reductions under the 475- and 950-year earthquakes. This suggests higher benefits for LDSD under moderate to intense earthquakes compared to earthquakes with very low or very high intensities. Figure 4 also shows that the $SQ+I_p=1.5$ option can further reduce median repair cost by average 32% under the 43-year earthquake, whereas it has a minimal impact with less than 3% average further reduction under the 2475-year earthquake due to the governing impact of structural damage on repair costs following the 2475-year MCE.

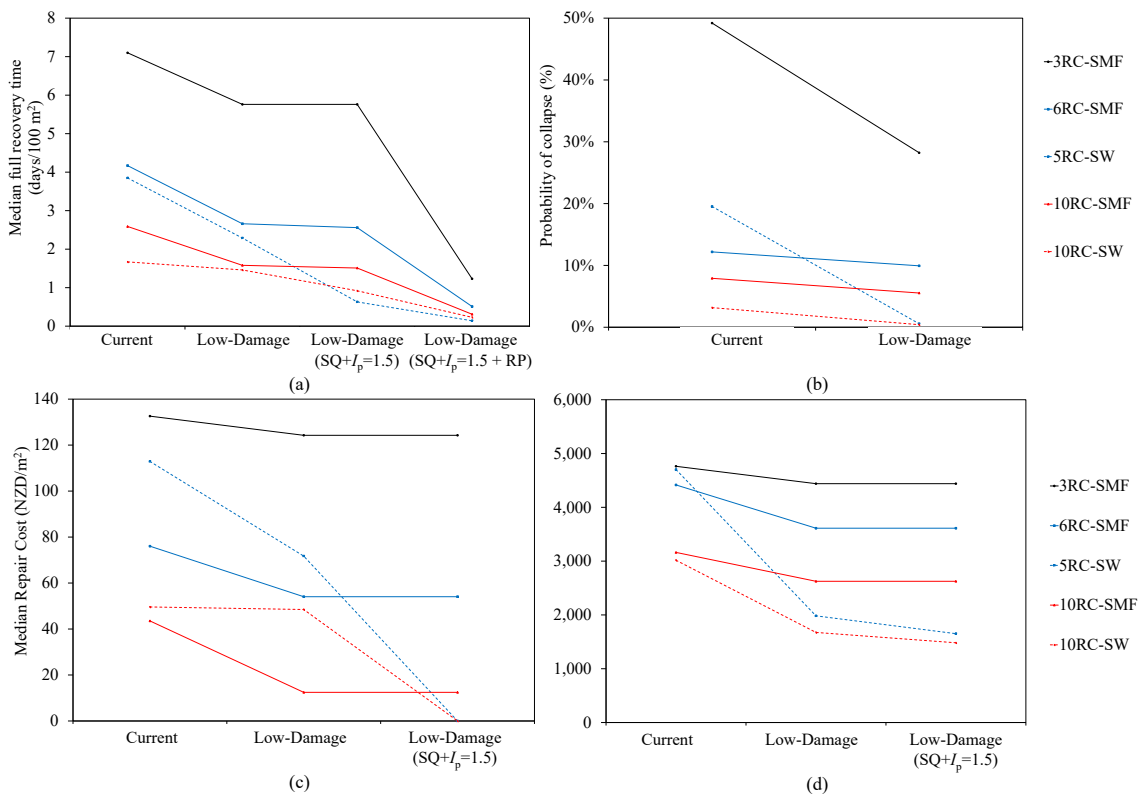


Figure 5: (a) Median full recovery time per floor area at the 43-year earthquake; (b) collapse probability at the 2475-year earthquake; median repair cost per floor area at the (c) 43- and (d) 2475-year earthquakes.

An important consideration here is that building functionality depends not only on the incurred building damage but also on the serviceability of utility infrastructure. In other words, functional recovery of buildings would not be possible without a matching performance from infrastructure systems, especially electrical power and potable water (Hare et al. 2012; Almufti and Willford 2013; Cook et al. 2022). Figure 6 compares median functional recovery time of the building archetypes at the considered design types with the expected disruption time of power and water services following the 950-year Wellington Fault Line earthquake event; the latter is taken from GNS Science (2017). According to Figure 6, in most cases, recovery of basic building functions at the Current code-minimum design would take longer than infrastructure downtime, whereas the disruption time of utility services far exceeds median functional recovery time of buildings that adopt the LDS and RP solutions. This highlights the importance of accompanying infrastructure resilience intervention initiatives to ensure meeting building post-hazard functional recovery objectives (Aurecon 2019). As an example, Figure 6 shows that power and water service disruption time is expected to reduce by almost 80% given the same shaking intensity when a set of preferred intervention programmes is applied according to GNS Science (2017).

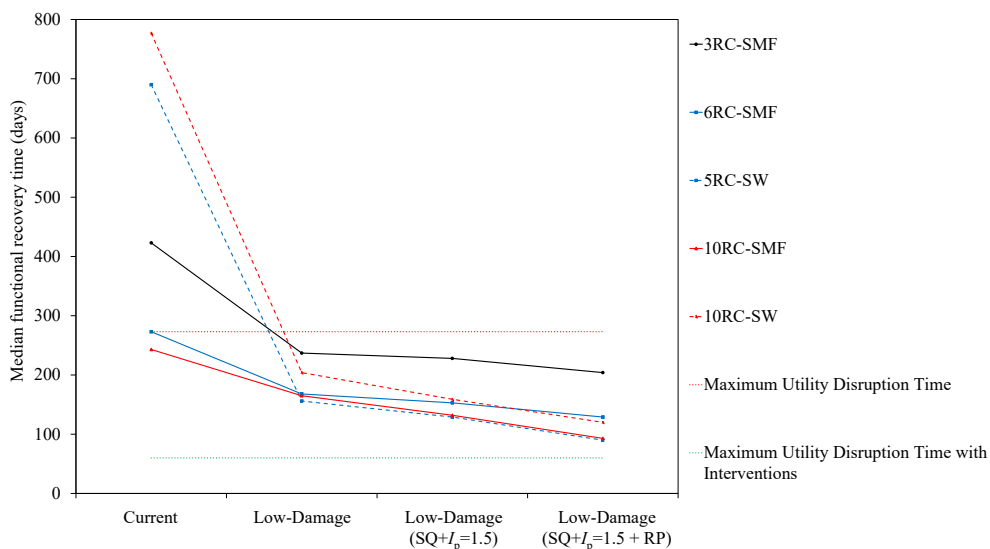


Figure 6: Expected recovery time of the buildings and utility services, given the 950-year earthquake.

3 CONCLUSIONS

LDS practices provide a promising solution to mitigate earthquake-induced consequences, such as high repair costs and prolonged recovery periods. Development of LDS guidelines and practices have accelerated following the lessons from recent seismic experiences and technical/scientific advancements that have enabled feasible and quantifiable seismic performance enhancement. This research aims to provide quantitative evidence for adopting LDS to enhance building seismic performance. For that, this paper conducts seismic performance assessment of five building archetypes with RC moment frame and wall-frame systems of various heights and quantifies the effectiveness of several LDS solutions under four earthquake intensities with return periods of 43, 475, 950, and 2475 years. The LDS solutions include: 1) the adoption of a design drift limit of 1% to increase building lateral stiffness and strength, 2) the use of several alternative damage-controlled components for partition walls, suspended ceilings, and exterior claddings, 3) the use of seismically prequalified components that are designed to a higher seismic force for several highly vulnerable acceleration-sensitive non-structural components. Furthermore, the effect of Recovery Planning (RP) measures to accelerate post-hazard safety inspections and repair mobilizations is also evaluated. The findings suggest high repair costs, high risk of building demolition, and long recovery time for code-minimum designs following moderate to high shaking intensities. For instance, average repair to replacement cost ratio of 48%, average 42% likelihood of building demolition, and average 16 months downtime of basic building functions are expected following the 950-year earthquake. The considered LDS and RP solutions are collectively shown to mitigate

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these seismic risk measures to 22%, 21%, and four months, respectively. On the other hand, the disruption time of utility services is expected to be six to twelve months under the 950-year earthquake, which significantly hinders functional recovery of the buildings that adopt LDSD. This highlights the importance of simultaneous infrastructure resilience initiatives to accompany the adoption of LDSD for individual buildings. Furthermore, the considered LDSD solutions in this study are expected to shorten average recovery time to full pre-hazard functionality following serviceability-level earthquakes from above 12 weeks to about one week. The LDSD solutions can also reduce the average probability of collapse following the 2475-year MCE from 18% to 9%. On the other hand, the average direct upfront structural construction cost is estimated to increase by an approximate 4% with the adoption of a lower design drift limit.

The seismic risk measures that have been quantified here may highly depend on the underlying risk models that are used, including damage fragility curve, loss consequence functions, and impeding curves. This study has used the FEMA P-58 (FEMA 2018a, b) and ATC-138 (ATC 2021; Cook et al. 2022) models and assumptions, where equivalent NZ-specific data were unavailable. Future research should look at calibrating all underlying data to the local conditions of NZ. Although Habibi et al. (2025a, b) has validated the outputs to some degree using the damage/loss reconnaissance data from the Canterbury earthquake sequence, it is suggested to also use insurance records or real case study buildings that have adopted LDSD to further validate the findings. Also, future research should evaluate the benefits of LDSD adoption for other building types with different structural systems and configurations. In conclusion, this paper provides quantitative evidence for the seismic performance enhancements that LDSD can offer to incentivise stakeholders, including owners, developers, tenants, and policymakers to implement LDSD. It is hoped that the findings of this research help to provide the necessary drivers for change towards enhancing seismic resilience of NZ communities.

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REFERENCES

- Almufti I and Willford M (2013). “*REDi Rating System: Resilience-based Earthquake Design Initiative for the Next Generation of Buildings*”. Arup publication, 133pp.
- ATC (2021). “*Seismic Performance Assessment of Buildings: Volume 8-Methodology for Assessment of Functional Recovery Time*”, ATC-138-3 Preliminary Report, Applied Technology Council, Redwood City, California, US, 49pp.
- Aurecon (2019). “*Wellington Lifelines Project: Protecting Wellington’s Economy Through Accelerated Infrastructure Investment Programme Business Case*”. Technical Report, Prepared by Aurecon, Prepared for Wellington Lifelines Group, Wellington, New Zealand, 299pp.
- Baird AC, Smith T, Palermo A, and Pampanin S (2014). “Experimental and numerical study of U-shape flexural plate (UFP) dissipators”. *2014 NZSEE Conference*, 21–23 March, Auckland, New Zealand. Paper Number P2.
- Bhatta J, Dhakal RP, Sullivan TJ, Bartlett J, and Pring G (2023). “Seismic performance of internal partition walls with slotted and bracketed head-tracks”. *Journal of Earthquake Engineering*, 27(12): 3435–3470. <https://doi.org/10.1080/13632469.2022.2137709>.
- Büker F, Hogan L, Brooke N, Elwood KJ, and Bull DK (2022). “Design recommendations for seating angle retrofits”. *SESOC Journal* 35(1): 55–68. <https://doi.org/10.3316/informit.498370414679393>.
- Cook DT, Liel AB, Haselton CB, and Koliou M (2022). “A framework for operationalizing the assessment of post-earthquake functional recovery of buildings”. *Earthquake Spectra*, 38(3): 1972–2007. <https://doi.org/10.1177/87552930221081538>.

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- Cook DT, Liel AB, and Safiey A (2024). “Earthquake functional recovery in modern reinforced concrete buildings”. *Journal of Structural Engineering* 150(9): 04024117. <https://doi.org/10.1061/jsendh.steng-12904>.
- FEMA (2018a). “*Seismic Performance Assessment of Buildings: Volume 1-Methodology*”. FEMA P-58, Prepared by the Applied Technology Council, Prepared for the Federal Emergency Management Agency, Washington, D.C., US, 340pp.
- FEMA (2018b). “*Seismic Performance Assessment of Buildings: Volume 3- Supporting Electronic Materials and Background Documentation*”. FEMA P-58, Prepared by the Applied Technology Council, Prepared for the Federal Emergency Management Agency, Washington, D.C., US.
- FEMA (2009). “*Quantification of Building Seismic Performance Factors*”. FEMA P695, Prepared by Applied Technology Council, Prepared for Federal Emergency Management Agency, Washington, D.C., US, 421pp.
- Fox MJ, Yeow TZ, Keen JM, Sullivan TJ, and Pavese A (2024). “New Zealand specific consequence functions for seismic loss assessment”. *Bulletin of the New Zealand Society for Earthquake Engineering* 57(1): 18–26. <https://doi.org/10.5459/bnzsee.1642>.
- GNS Science (2022). “*New Zealand National Seismic Hazard Model 2022 Revision: Model, Hazard, and Process Overview*”. GNS Science Report 2022/57, Prepared by GNS Science, Lower Hutt, New Zealand, 117pp.
- GNS Science (2017). “*Wellington Resilience Programme Business Case: Lifelines Outage Modelling*”. Consultancy Report 2017/236, Prepared by GNS Science, Prepared for Wellington Lifelines Group, Lower Hutt, New Zealand, 84pp.
- Habibi K, Campos Cardwell RJ, Chang-Richards A, and Filippova O (2025a). “Quantification of direct benefits of functional recovery-based design for seismic resilience” (under review). *Earthquake Spectra*.
- Habibi K, Campos Cardwell RJ, Chang-Richards A, and Filippova O (2025b). “Analytical dataset for quantification of direct benefits of functional recovery-based design for seismic resilience” in “Economic Drivers for Functional Recovery of Multi-Storey Buildings”. DesignSafe-CI. <https://doi.org/10.17603/ds2-x4y9-2m13>.
- Habibi K, Cardwell RJ, Chang-Richards A, and Filippova O (2024). “Quantification of economic benefits of functional recovery-based design: a stepwise review of the methodology”. *2024 NZSEE Conference*, 9-11 April, Wellington, New Zealand, Paper Number 174.
- Habibi K, Chang-Richards A, Campos Cardwell R, and Filippova O (2026). “Recovery-based design for reinforced concrete wall-frame buildings: quantification of benefits and costs”. *13th National Conference in Earthquake Engineering*, 13-17 July, Portland, Oregon, Paper 4347.
- Habibi K, Hosseini Varzandeh SS, and Mahsuli M (2023). “Quantification of optimal target reliability for seismic design: methodology and application to steel buildings”. *Soil Dynamics and Earthquake Engineering* 170: 107870. <https://doi.org/10.1016/j.soildyn.2023.107870>.
- Hare J, Oliver S, and Galloway B (2012). “Performance objectives for low damage seismic design of buildings”. *2012 NZSEE Conference*, 13-15 April, Christchurch, New Zealand, Paper Number 035.
- Haselton Baker Risk Group (2025). *Seismic performance prediction program (SP3)*. <https://sp3risk.com> (Accessed 16 April 2025).
- Henry RS, Zhou Y, Lu Y, Rodgers GW, Gu A, Elwood KJ, Yang TY (2021). “Shake-table test of a two-storey low-damage concrete wall building”. *Earthquake Engineering & Structural Dynamics* 50: 3160–3183. <https://doi.org/10.1002/eqe.3504>.
- Kim JH (2015). “*Quantitative Analysis of Factors Influencing Post-earthquake Decisions on Concrete Buildings in Christchurch, New Zealand*”. Master Thesis. University of British Columbia, Vancouver, Canada, 139pp.
- Li L, Chang-Richards A, Boston M, Elwood KJ, Molina Hutt C (2024). “Building seismic resilience for New Zealand-past, now, and future”. *18th World Conference on Earthquake Engineering (WCEE)*, 30 June- 5 July, Milan, Italy.
- Liel AB, Echeverria MJ, Koliou M, Mohammadgholibeyki N (2023). “Potential for achieving post-disaster functional recovery for existing buildings: lessons from earthquakes for other hazards”. *ASCE Inspire 2023*, 16-18 November, Arlington, Virginia, US, pp 396–403.

- Liu Z, Wang M, Samuel Hogan L (2023). “Evaluation of seismic performance of precast concrete walls with X-shaped steel plate bracings”. *Structures* 48: 1548–1566. <https://doi.org/10.1016/j.istruc.2023.01.055>.
- Marquis F, Kim JJ, Elwood KJ, Chang SE (2017). “Understanding post-earthquake decisions on multi-storey concrete buildings in Christchurch, New Zealand”. *Bulletin of Earthquake Engineering* 15: 731–758. <https://doi.org/10.1007/s10518-015-9772-8>.
- MBIE (2024). “*Low Damage Seismic Design, Volume 1-Benefits, Options and Getting Started*”. Produced by the Ministry of Business, Innovation and Employment, Building System Performance branch, Lower Hutt, New Zealand. ISBN (online): 978-1-991316-23-3. 34pp.
- MBIE (2025a). “*Low Damage Seismic Design, Volume 2-Performance Framework*”. Produced by the Ministry of Business, Innovation and Employment, Building System Performance branch, Lower Hutt, New Zealand. 42pp.
- MBIE (2025b). “*Low Damage Seismic Design, Volume 3-Technical Guidance*”. Produced by the Ministry of Business, Innovation and Employment, Building System Performance branch, Lower Hutt, New Zealand. 209 pp.
- McKenna FT (1997). “*Object-oriented Finite Element Programming: Frameworks for Analysis, Algorithms and Parallel Computing*”. Ph.D. Dissertation. University of California, Berkeley, California, US.
- Mohammadgholibeyki N, Echeverria MJ, Safiey A, Cook DT, Koliou M, and Liel AB (2023). “Assessing the feasibility of achieving functional recovery goals through seismic retrofit of existing reinforced concrete buildings”. *Earthquake Spectra* 39(4): 2123–2151. <https://doi.org/10.1177/87552930231197669>.
- Molina Hutt C, Hulseley AM, Kakoty P, Deierlein GG, Eksir Monfared A, and Hooper JD (2022). “Toward functional recovery performance in the seismic design of modern tall buildings”. *Earthquake Spectra* 38(1): 283–309. <https://doi.org/10.1177/87552930211033620>.
- NZS (2004). “*Structural Design Actions-Part5: Earthquake Actions-New Zealand*”. NZS 1170.5, Standards New Zealand, Wellington, New Zealand. 82pp.
- Opabola EA and Elwood KJ (2024). “Seismic design of concrete structures for damage control”. *Earthquake Spectra* 40(3): 2038–2058. <https://doi.org/10.1177/87552930241235487>.
- Pledger L, Pujol S, and Calcagño R (2024a). “Designing to lower drift limits: the impacts on construction costs and non-structural components”. *18th U.S.-Japan-New Zealand Workshop on the Improvement of Structural Engineering and Resilience*, 2–4 December, San Diego, California, US.
- Pledger L, Pujol S, and Chandramohan R (2024b). “Reducing Design Drift Limits”. *18th World Conference on Earthquake Engineering (WCEE)*, 30 June– 5 July, Milan, Italy.
- Pourali A, Dhakal RP, Macrae G, and Tasligedik AS (2017). “Fully floating suspended ceiling system: experimental evaluation of structural feasibility and challenges”. *Earthquake Spectra* 33(4): 1627–1654. <https://doi.org/10.1193/092916EQS163M>.
- Soroushian S, Zaghi AE, Maragakis M, Echevarria A, Tian Y, and Filiatrault A (2015). “Analytical seismic fragility analyses of fire sprinkler piping systems with threaded joints”. *Earthquake Spectra* 31(2): 1125–1155. <https://doi.org/10.1193/083112EQS277M>.
- Tatarsky M and Filiatrault A (2019). “Seismic response of viscously damped braced thin-wall piping system: a proof-of-concept case study”. *Bulletin of Earthquake Engineering* 17: 537–559. <https://doi.org/10.1007/s10518-018-0447-0>.
- Tian Y, Filiatrault A, and Mosqueda G (2014). “Experimental seismic fragility of pressurized fire suppression sprinkler piping joints”. *Earthquake Spectra* 30(4): 1733–1748. <https://doi.org/10.1193/111011EQS278M>.
- Yeow TZ, Orumiyehi A, Sullivan TJ, MacRae GA, Clifton GC, and Elwood KJ (2018a). “Seismic performance of steel friction connections considering direct-repair costs”. *Bulletin of Earthquake Engineering* 16: 5963–5993. <https://doi.org/10.1007/s10518-018-0421-x>.
- Yeow TZ, Sullivan TJ, and Elwood KJ (2018b). “Evaluation of fragility functions with potential relevance for use in New Zealand”. *Bulletin of the New Zealand Society for Earthquake Engineering* 51(3): 127–144. <https://doi.org/10.5459/bnzsee.51.3.127-144>.