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EDITORIAL

SEISMIC DESIGN OF BUILDINGS: WHERE TO NEXT?

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ABSTRACT

This paper critically reviews the current building seismic design approach based on the observed performance of modern building stock in recent earthquakes, highlights the inability of the current design approach in controlling seismic damage and losses, and proposes a conceptual framework for next generation seismic design codes that is likely to meet public expectations. In addition to ensuring life-safety in rare earthquakes, the proposed loss-optimization seismic design approach also aims to ensure quick functional recovery and minimum loss (i.e. repair, downtime, and injury/fatality) in moderate-strong earthquakes by limiting damage to building's structural and non-structural components. Based on comparison of performances of building stock in some recent major earthquakes in different countries, the paper presents some simple strategies to render buildings more resilient and suffer significantly less seismic damage (and consequentially incur less loss). Finally, the paper scrutinizes the efficacy of some commonly used low-damage technologies in minimizing building seismic losses.

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INTRODUCTION

When the concept of seismic design started early in the 20th century, it was initially expected that structures can be rendered earthquake-safe if they are designed to be stronger than the maximum seismic force likely to be imposed on them during their lifetime. Due to inadequate understanding of seismic performance of structures, early seismic design practices had inherent flaws. With hindsight, it is now widely accepted that majority of existing old buildings are seismically vulnerable and need urgent intervention to enhance their ability to resist earthquakes. Unsurprisingly, loss of lives in recent earthquakes have originated predominantly from collapse of older buildings. Gradually evolving from the maiden naïve approach, the current version of seismic design targets life-safety in large and rare earthquakes. As a result, collapse of 21st century buildings are far less common, and people have rarely died in such buildings even in severe earthquakes. However, modern seismic design does not intend to avoid damage in minor-to-moderate earthquake-induced shakings. Consequently, modern building stock has invariably suffered damage in all recent earthquakes, and the financial losses to the community arising from damage and downtime of these buildings have been high.

Although most buildings suffered significant damage in the 2010-11 Canterbury earthquake sequence (CES), the building stock in general were claimed to have performed better than expected for that level of shaking. This assertion by the engineering profession has perplexed the New Zealand (NZ) public who are still struggling to recover from the financial impact of these earthquakes. The public is wondering why even such a huge economic dent has not made engineers realize whatever they are doing has not worked. This difference in opinion is mainly because the engineers assess the performance relative to the design objectives which target no more than life-safety (which was mostly achieved by modern buildings), but the general public, in addition to life-safety, also expect better performance in terms of economic consequences. As the purpose of codes and standards is to save and serve people, it is necessary that they are aligned with public expectations.

Observations from recent earthquakes throughout the world have highlighted that a significant fraction of seismic loss in buildings are attributable to damage of secondary components known as *non-structural elements* (NSEs). Hence, seismic performance of non-structural elements (SPONSE) needs to improve in order to minimize financial loss in future earthquakes. Unsurprisingly, awareness of the importance of SPONSE research has significantly increased in NZ in the recent years [1-3], and researchers are striving to identify and amend the inherent weaknesses in the current design and installation practices [4-7] and to develop low-damage solutions for key NSEs [8-11].

CRITICAL REVIEW OF CURRENT DESIGN METHOD

Modern Seismic Design Principles

Modern performance-based seismic design aims to ensure that buildings meet target performances at different levels of seismic excitations. The target performances are building-specific; e.g., for a residential building, severe damage rendering the building uninhabitable is accepted in rare and extreme earthquakes, whereas any damage to high-priority buildings (e.g., hospitals) is required to be minor so that such important facilities continue to function even after a major earthquake. Currently, many seismic design codes require buildings to satisfy more than one seismic performance targets, typically requiring buildings to remain (i) serviceable in frequent and minor earthquakes; (ii) life-safe in major earthquakes; and/or (iii) prevent collapse in rare and extreme earthquakes.

In modern building seismic design codes, target performances are specified against up to three different levels of seismic hazard. The lowest level (with 25 years return period, as per NZ design practice) represents frequently occurring earthquakes, and the other two are commonly known as design basis earthquake (DBE) with 475 years return period (i.e., 10% probability of exceedance in 50 years) and maximum considered earthquake (MCE) with 2475 years return period (i.e., 2% probability of exceedance in 50 years). The ground

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motion intensities corresponding to these hazard levels depend on the seismicity of the location of interest.

As shown in Figure 1, the required building performance at these three hazard levels depends on the building's importance. In general, the required performances can be categorized into four categories; namely *operational-continuity* (functioning fully after an earthquake), *immediate-occupancy* (limited minor damage that can be repaired without evacuating the building), *life-safety* (significant damage needing extensive repair requiring the building to be evacuated, with no threat to lives), and *collapse-prevention* (severe damage but no collapse, often requiring demolition). Among the four performance categories, the first and the last are easy to ascertain; i.e., *operational-continuity* requires the building to avoid any noticeable damage and *collapse-prevention* requires the building remain integral and standing regardless of the extent of damage. The interpretation of the other two categories can be subjective. Typically, *immediate-occupancy* corresponds to minor damage that can be repaired without having to vacate the occupants, and *life-safety* (also loosely interpreted as *reusability*) corresponds to a stage where damage incurred to the building's structural and non-structural components is not life threatening and can be repaired.

Buildings that house emergency facilities (shown as Group III in Figure 1) are more important than normal residential buildings (i.e. Group I) and need to be inhabitable/usable even after rare and severe earthquakes (i.e., MCE). Similarly, important buildings (Group II in Figure 1) are required to satisfy the *life-safety/reusability* criteria in extreme earthquakes (i.e., MCE), whereas normal buildings (Group I in Figure 1) are required to satisfy only the *collapse-prevention* criteria.

The framework shown in Figure 1 may appear to suggest in first sight that *life-safety* in MCE is compromised for normal (Group I) buildings. However, threat to lives originates mainly from collapse (rather than from severe damage). Therefore, *life-safety* will be largely achieved if collapse is prevented. In DBE, normal structures are required to avoid severe (irreparable) damage, whereas more important structures are required to be immediately inhabitable. Similarly, after frequent earthquakes, normal structures are allowed to undergo minor damage, the repair of which does not require the building to be closed (i.e., *immediate-occupancy*), whereas more important structures are required to remain undamaged (i.e., *operational*).

Usually, the lateral load resisting components/systems of a building are sized and detailed to meet the target performance at one of the three design intensity levels and then checked whether the performances at the remaining levels are satisfied or not (and the design is revised if any of these targets is not met). Currently, most existing seismic codes explicitly require design checks only for two performance objectives in the form of serviceability limit state (SLS), which arguably corresponds to smaller more frequent earthquakes and ultimate limit state (ULS), which corresponds to DBE. Commonly, once the *life-safety* criteria in a seismic action representing DBE is checked in the form of ULS, *collapse-prevention* requirement at MCE is assumed to be satisfied (e.g., NZ Standard NZS1170.5 [12]). The sequence of ULS and SLS design checks also differ between codes. For example, in Japan [13], a building is designed first to meet the SLS demand corresponding to immediate-occupancy at frequent/moderate earthquakes and then its performance is checked (and adjusted, if needed) against the ULS demand corresponding to the life-safety at DBE. In contrast, buildings in NZ are designed first to satisfy the ULS demand and then checked (and revised, if needed) against the SLS criteria.

Performance of Buildings Designed to These Principles

If we recall the performance of buildings in recent earthquakes, we can find widely varying performance across different building types. For example, performance of building stock observed in the 2010-11 CES can be summarized as:

- Old buildings that were not retrofitted/strengthened suffered severe damage (and many partially/fully collapsed) [14].
- Casualties were mainly due to collapse of older buildings; modern buildings largely satisfied the life-safety requirement [15].
- Modern buildings did not collapse but almost all suffered damage of varying extent [15,16].
- Significant land damage (in the form of liquefaction, lateral spreading and differential settlement) rendered many buildings with little structural damage uninhabitable [17].
- Secondary non-structural components and contents suffered severe damage rendering many buildings unsuitable for continued occupancy [18].
- With demand of skilled labour and other resources exceeding the supply (and capacity), the repair of damaged buildings and infrastructure took significantly longer than normal. In addition, repairing damage to structural and non-structural components of buildings was found to be more difficult and significantly more expensive than expected. The inflated repair time and cost led to demolition of multiple buildings with seemingly modest damage [19].
- For many damaged buildings, the delay in repair was further compounded by the long-time taken to resolve insurance claims [19].
- Extensive damage and downtime had a huge economic impact totalling $40B to the regional/national economy [20].

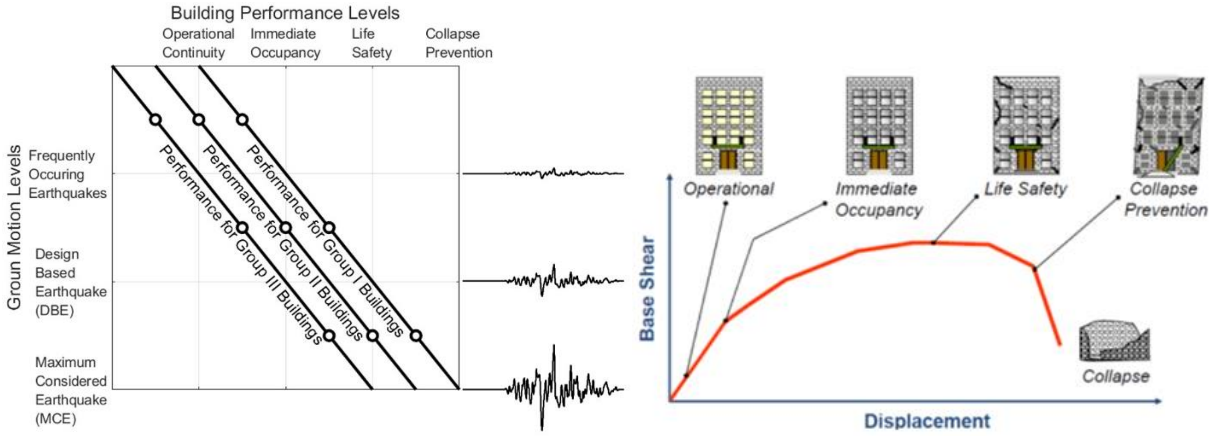


Figure 1: Framework for performance-based seismic design of buildings.

Comparing these observations against the criteria used in designing buildings will help answer whether these observed building performances satisfied the design goals or not. Moreover, answering this question also requires evaluation of the severity of the recorded ground motions against the seismic intensity used in building design. Figure 2 plots the response spectra of ground motions recorded within the Christchurch CBD during the 4th September 2010 Darfield Earthquake (magnitude M_w 7.1 at 32 km away from the city) and the 22nd February 2011 Lyttleton Earthquake (magnitude M_w 6.3 less than 10 km from the city). Also shown in the figure for comparison are the 500 year DBE (solid lines) and 2500 year MCE (dashed lines) design spectra for Christchurch city as per the seismic design standard [13] prevailing at the time of the earthquake (black lines) and the increased design demand after the 2016 amendment (grey lines).

As can be seen in the plots, the shakings recorded during the 2010 September earthquake were close to DBE, for which buildings are expected to undergo repairable damage. Hence, modern buildings can be argued to have fared slightly better than expected in the 2010 earthquake as they suffered largely minor damage. On the other hand, the shakings recorded in the 22 February 2011 earthquake were significantly more severe than DBE and closer to MCE, for which modern buildings are expected to undergo severe damage (even irreparable damage would be within expectation). Any building that did not collapse at this level of shaking can be interpreted to have satisfied the design objective. Thus, according to the expected outcomes for which these buildings were designed, the observed performance of the modern building stock in these earthquakes was not unexpected (arguably slightly better than expected) [21].

Modern buildings designed as per capacity design principles and using ductile detailing practice are inherently better in avoiding collapse than those built before the 1980s when the capacity design principles had not been adopted in the standards. It is therefore not surprising to see that the two multi-storey concrete buildings (CTV and PGC), whose collapse caused majority of the casualty in the 2011 Christchurch earthquake, were both designed as per the design standards prevalent in the 1970s-80s. As older buildings were designed to inferior/premature design standards, they were unable to sustain the seismic demands imposed by these ground motions. Moreover, as ductile detailing provisions were not included in the NZ standards until the 1980s, old buildings were not detailed to sustain large inelastic deformation demands. Hence, the severe damage incurred to old buildings was not surprising; it was perhaps fortunate that only a small proportion of such buildings collapsed.

This may raise the question "If buildings have been historically designed to prevent collapse and save lives, why did so many buildings collapse, with some also leading to casualty, in the 2011 February earthquake?" This can be attributed to our understanding of earthquake engineering, which has been evolving continuously throughout the last century, and even as recently as the last few decades. Consequently, codes and standards used for earthquake resistant design of buildings have also been regularly amended/improved by incorporating the new knowledge. For example, following poor performance of unreinforced masonry (URM) building stock in the 1931 Napier earthquake, URM became less common in new construction, and was finally abandoned in the 1960s. Nevertheless, URM buildings already built before then and not strengthened/retrofitted since are inherently deficient in resisting earthquakes, and majority of such buildings would not be able to prevent collapse in an intense shaking like that of February 2011.

Based on the preceding discussions, it can be argued that the modern building stock in general met (if not exceeded) their design targets, which aim to avoid only the loss of lives without any intent to limit damage to building components and minimise any other forms of loss. Unsurprisingly, most buildings suffered severe secondary damage and consequently incurred significant financial losses during these earthquakes [22]. While none of the 181 fatalities in these earthquakes originated from modern buildings, damage incurred by modern buildings contributed predominantly to the financial losses in the form of direct (repair) and indirect (downtime, business interruption) costs. The Canterbury earthquakes are not an exception in this regard. As shown in Table 1, financial implications of building damage incurred in several other recent earthquakes are also reported to be in tens of billions of dollars.

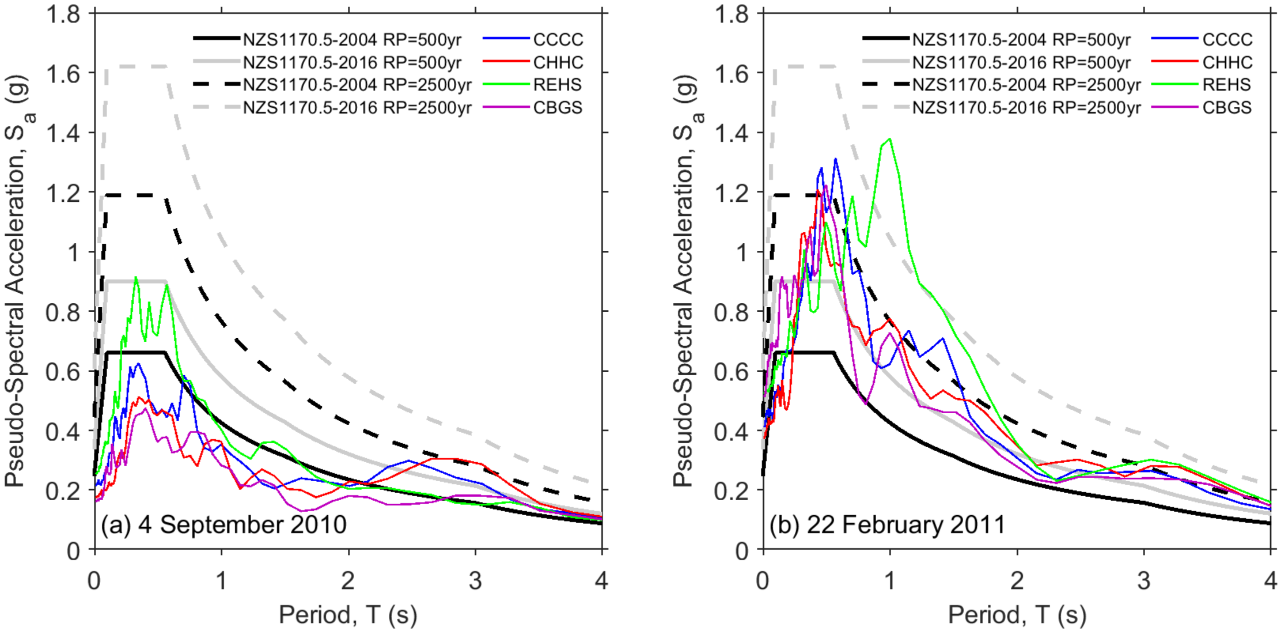


Figure 2: Ground motions recorded in 2010-11 Canterbury Earthquake Sequence (CES).

Table 1: Total losses incurred in recent major earthquakes [22].

Turkey (2023)	Canterbury (2010-11)	Tōhoku (2011)	Chile (2010)	Kobe (1995)	Northridge (1994)
Total loss estimated at US$104 billion (i.e. 11% of 2022 GDP). Housing loss ~ $82 billion [23].	Rebuild costs of around NZ$20 billion (US$15 billion) excluding disruption costs, or 10% of GDP. Insured losses of around NZ$40 billion (~US$25 billion).	Overall losses of over US$200 billion (over 3 to 4% of GDP). US$35 to US$40 billion represented insured losses.	Losses of around US$30 billion (20% of GDP). Insured losses of around US$8 billion.	Losses estimated at over US$100 billion (around 2% of GDP), insured losses of approximately US$3 billion.	Over US$40 billion (less than 1% of GDP). Insured losses of US$15 billion.

LIMITING LOSS BY DESIGN: ARE WE READY?

Need for Loss Based Design Approach

The performance of building stock in the abovementioned recent earthquakes have exposed a glaring mismatch between the performance targets used in current design and the public's expectations from their buildings. On one hand, given the ground motions were more intense than that used in designing buildings, the extent of incurred damage was less than that expected by engineers. On the other hand, given the buildings were designed by chartered professional earthquake engineers, the loss incurred in these earthquakes was much greater than what the public expected. While the structural engineers claimed the seismic design methods worked well because there was no fatality due to collapse of seismically designed or strengthened buildings despite the intense shakings, the public are understandably countering that a 40 billion dollar loss (more than 20% of NZ GDP) is unacceptable.

Following the public outcry after the 2010-11 CES, the engineering community in NZ admitted that although the observed performance of the buildings in these earthquakes was not out of sync with that aimed in design, it did not meet public expectations. This is in line with the findings of the *Resilient Buildings* project [24], which has concluded that while current building code provisions are reasonably effective in meeting the *life safety* expectations in an extreme event, there is an 'order of magnitude' gap between the societal expectations and building performance when it comes to damage and loss of functionality.

It is clear that the cause of the sub-par performance of the building stock lay profoundly in the adopted design principles. Lately, there has been a gradual realisation that the performance objectives currently used for designing buildings are not enough, and engineering design principles need to start looking beyond *life-safety*. It is intuitively obvious that the new target (in addition to, not in lieu of, *life-safety*) should explicitly or implicitly aim to limit damage, as this is where the modern ductile design fails because it invites damage even in moderate shakings. Nevertheless, damage is not easy to quantify objectively, particularly in a manner that is easily understood and digested by asset owners and key stakeholders. In this regard, a better design target may be to limit (i.e., minimize) financial loss, as it is the next most important factor for the public after *life-safety*. Moreover, losses measured in monetary terms are easily and unambiguously understood by all stakeholders. Hence, the next generation of seismic design provisions must aim to minimize losses.

Framework for Loss Optimization Seismic Design (LOSD)

Until now, one of the main objectives of earthquake engineering has been to design, construct, and maintain structures whose performance during earthquake exposure is satisfactory and in compliance with the targets specified in building codes. In the future, this is likely to change to design and construct economically efficient structures, which, during earthquakes, save lives and incur limited financial loss that is acceptable to the key stakeholders of the building. Such economically efficient seismic design methods are hereafter referred as "loss optimization seismic design (LOSD)" [25]. Like in current seismic design practice, a building designed based on LOSD approach also has to satisfy target performances at multiple earthquake intensity levels, with performance measures including financial losses in addition to *life-safety*. A framework for LOSD is illustrated in Figure 3.

Losses incurred in earthquakes can be classified into three distinct categories; traditionally termed as *dollar*, *downtime* and *death* (commonly known as 3D's). The first category of seismic loss (*dollars*, also referred as *damage*) includes the cost required to repair the physical damage incurred to all components of a building. The second category (*downtime*) includes indirect financial losses (such as occupant relocation cost, business interruption cost, loss of income) due to the building being unavailable for occupation during repair. The loss related to downtime is proportional to the total time a building becomes unavailable for occupation/business following an earthquake. This includes time taken to: (i) assess damage to the building components, (ii) decide whether to repair/demolish, and (iii) plan, design and execute the repair/retrofit of the building. The third category (*death*) includes the loss related to fatality and injury to occupants, which is governed by the collapse probability of the building and its components and sliding/toppling of the contents.

The abovementioned three categories of losses are linked to the extent of damage sustained by different building components in an earthquake. For seismic loss assessment, building parts are divided into two broad groups; namely *structural components* and *non-structural elements* (NSEs). Depending on the functionality of buildings, these components contribute differently to the total building value [26]. Structural components are those that contribute to a building's load path (i.e., participate in resisting the vertical and lateral loads) and provide strength and stiffness to a building, such as floors, beams, columns, walls, and foundations. On the other hand, NSEs represent building parts that do not contribute to the building's strength and stiffness but are necessary for the building to deliver its intended function. NSEs include architectural and functional elements (e.g., ceilings, claddings, glazing, facades, canopies, plaster and paints, partitions, chimneys, windows, doors, etc.) and mechanical-electrical-plumbing (MEP) components like cables, pipes, ducts and fit-outs providing different essential services to the building (e.g., heating, ventilation, air-conditioning, electricity, communication, water and gas supply, fire sprinklers, waste water, etc.).

In addition to the building components, *damage*, *downtime*, and *injury* can also be caused by uncontrolled movement (sliding, toppling, falling, overturning, etc.) of heavy household commodities (such as computers/servers, whiteware, furniture, decorations, etc.) that are present in a building but are not part of the building itself. To include these kinds of losses, a separate building part category, identified as *contents*, is also commonly included in seismic loss estimation procedures.

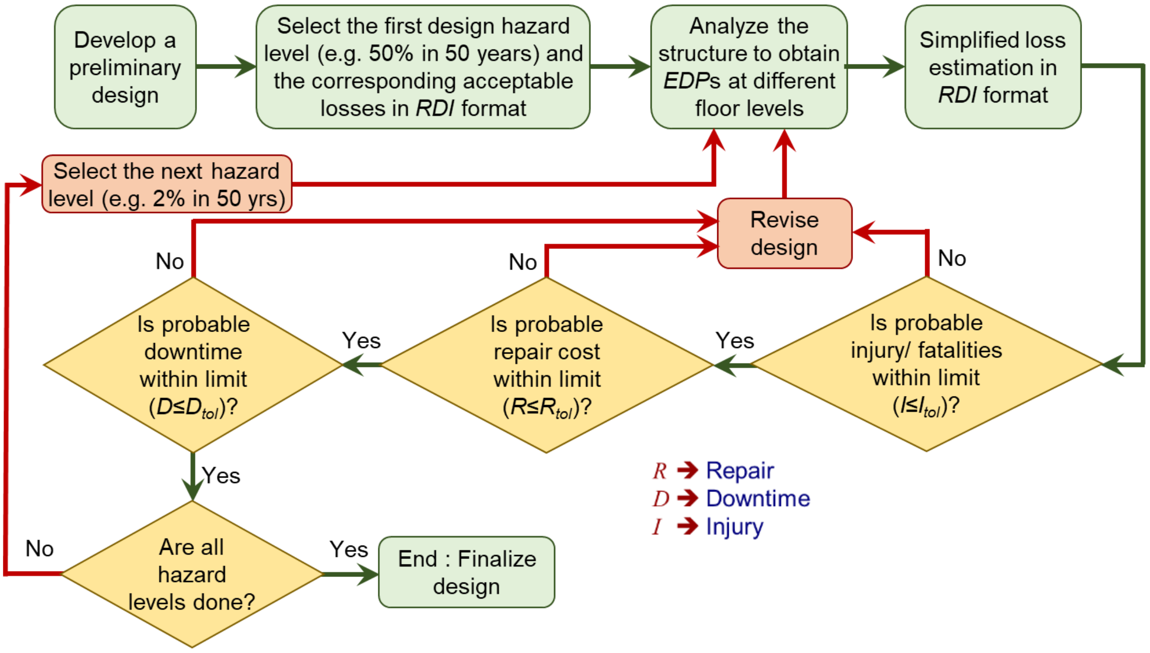


Figure 3: Framework of Loss Optimization Seismic Design (LOSD).

The performance criteria for LOSD can be expressed in an RDI format, where *R* is the cost to repair the damaged components and to replace the damaged content (expressed as a percentage of the building value including contents), *D* is the number days required to repair/replace the building (i.e., downtime), and *I* is an injury vector specifying the probability of minor injury, major injury and death. An example of the required performances for different building categories for different ground motion intensities is shown in Table 2. Note that the values shown in Table 2 are only placeholders, and an extensive consultation with stakeholders is needed to confirm widely acceptable levels of tolerable losses.

Performance measures such as response drift that are commonly used in current seismic design methods need not be explicitly specified in LOSD because the design criteria based on loss measures implicitly ensure that the response is within reasonable limits. For example, for the expected repair cost and downtime to be within their allowable limits, a building cannot be severely damaged, which automatically ensures the *reusability* criteria. Similarly, once the criteria related to repair, downtime, and injuries are imposed, *life-safety* and *collapse-prevention* criteria are met as a corollary. Threat to *life-safety* comes mainly from severe damage or collapse, both of which will require the building to be replaced. This will not satisfy the repair and downtime criteria, except in the case of residential buildings in an MCE where severe damage requiring the building to be demolished is permitted as long as the probability of casualty is small. Damage will be naturally minimized by LOSD, but unlike in current prescriptive design, response parameters such as drift and acceleration will not need to be explicitly restricted.

LOSD encapsulates ULS and SLS checks within its framework, but allows structures to respond beyond the current limits if the three loss criteria are met which automatically restricts damage to structural components and NSEs. This enables innovative structural systems and non-structural components that can sustain larger drifts and accelerations with minimal damage (thereby incurring less loss) to meet the LOSD design criteria, whereas they would not necessarily satisfy the maximum drift limits used in the current seismic design. The LOSD framework also enables different stakeholders to prioritize their preference in making decisions related to their building. For example, decisions regarding performance measures an owner and an occupant makes will differ, with the owner being principally interested in minimizing structural damage and business downtime, while the occupant is mainly interested in minimizing contents damage and avoiding injury/casualty.

Table 2: Example of performance requirements in RDI format for buildings in different levels of ground motion in LOSD [27].

Ground Motion Intensity Corresponding to:	**Performance Measures**	**Allowable/Tolerable Loss**		
		Residential Buildings	**Commercial and Office Buildings**	**Emergency Facilities**
Frequently occurring earthquake (FOE); 50% in 50 yrs.	Repair: μ_R (%)	10^{-2}	10^{-3}	10^{-4}
	Downtime: μ_D	10^{-2} days	10^{-3} days	10^{-4} days
	Injury: μ_I (%)	10^{-2}, 10^{-3}, 10^{-4}	10^{-2}, 10^{-3}, 10^{-4}	10^{-4}, 10^{-4}, 10^{-4}
Design basis earthquakes (DBE); 10% in 50 yrs.	Repair: μ_R (%)	10	1	10^{-2}
	Downtime: μ_D	10 days	1 day	10^{-3} days
	Injury: μ_I (%)	1, 10^{-1}, 10^{-4}	1, 10^{-1}, 10^{-4}	10^{-2}, 10^{-3}, 10^{-4}
Maximum considered earthquake (MCE); 2% in 50 yrs.	Repair: μ_R (%)	No limit	10	10^{-1}
	Downtime: μ_D	No limit	10 days	10^{-2} days
	Injury: μ_I (%)	10, 1, 10^{-4}	10, 1, 10^{-4}	10^{-1}, 10^{-2}, 10^{-4}

Like in traditional design, the design motto of "capacity greater than demand" remains central and vital in LOSD as well. However, the capacity is interpreted as the allowable/tolerable loss from repair, downtime, and injury, and the demand is the expected value of the corresponding form of loss a building may incur in an earthquake. As is normal in performance-based design, the capacity (i.e., allowable losses) is structure specific (with respect to its importance and use). In LOSD, it is also client specific (e.g., a risk adverse client may set lower allowable limits) and specific to stakeholders. Insurers and owners will benefit from a stricter allowance for damage repair, whereas occupants will be more interested in limiting the injury/casualty probability and commercial tenants will prefer their building to suffer little downtime following earthquakes. On the other hand, the estimation of demand (μ_R, μ_D, μ_I) requires a comprehensive probabilistic risk assessment methodology that considers all forms of uncertainties and randomness.

Challenges in Implementing Loss Based Design Methods

The major impediment to adoption of LOSD (or any other loss based design method) is the lack of simple (yet reliable) loss estimation methods that can quantify damage, downtime, and injury/fatality during earthquakes. Efforts are currently underway in the earthquake engineering community to develop such methodologies, though it will take some time before simplified methods to estimate these demands (μ_R, μ_D, μ_I) can be robust and validated against enough case studies to be prescribed in building design codes.

The first generation of seismic loss estimation methods are based on the probabilistic *performance-based earthquake engineering* (PBEE) framework which can be mathematically expressed in the form of a triple integral equation as shown in Equation (1) [28]. This framework incorporates the interrelationships between (and uncertainties associated with) the local seismic hazard, shaking intensity, critical structural response, and damage measures to estimate the annual rate of satisfying/exceeding a desired decision variable.

In Equation (1), $f_a(x)$ = the annual rate of exceedance of (x); *im* = ground motion intensity measure (quantifying severity of ground motions); *edp* = engineering demand parameter (quantifying critical structural response); *dm* = damage measure (quantifying extent of damage); *dv* = decision variable (a damage related milestone whose occurrence, or non-occurrence, provides a basis for an important decision); and $G(x|y)=P(x>X|y=Y)$ is the conditional complementary cumulative distribution function (CCDF). Absolute value signs are required for the terms in Equation (1) because some of the derivatives of the CCDFs may be negative. In PBEE, it is common to use capital letters (IM, EDP, DM, DV) to represent the variables/parameters, whereas small letters (*im, edp, dm, dv*) are used to indicate specific values of these parameters. For different sources of seismic risk, the definitions of these parameters are provided in Table 3.

As can be seen in Table 3, differences between the three sources of loss exist in the interpretation of decision variables. The decision variable in Equation (1); i.e., *dv*, can be replaced by a desired quantity, such as direct repair cost or number of closure days, depending on which source of loss is being considered. Alternately, all of them can be converted to an equivalent dollar amount if the average loss of income per day of downtime, average cost of treating a minor/major injury, and the average monetary value of a life are known.

Equation (1) gives the mean annual rate of exceedance of a decision variable *dv*. In assembly-based vulnerability, where the loss of a building is derived by combining the losses of its components, expected value of a decision variable (i.e., loss measure) is more useful than its rate of exceedance. For example, expected repair cost of a building can be reasonably approximated by combining the expected repair costs of its components, whereas no meaningful insight can be attained by combining the mean annual rates of exceeding a certain level of demand/damage of different building components. Hence, this equation has been extended by adding one more integral to form a quadruple integral equation [29,30] that probabilistically combines the consequences of all possible seismic events to estimate a single representative measure of seismic loss that is easily and unambiguously understood by different stakeholders of a building. This measure, named the *Expected Annual Loss* (EAL), is shown in Equation (2).

EAL estimated using only the direct loss (i.e., cost to repair/replace damaged components and contents) provides a good measure of the annual insurance premium (excluding profit) of policies covering earthquake damage. In the above formulation, EAL can easily be used as a general term to represent expected downtime or expected probability of injury/casualty if an appropriate decision variable representing downtime or injury/casualty is used instead of the loss ratio l_r.

$$f_a(dv) = \int\int\int G(dv \mid dm) \mid dG(dm \mid edp) \parallel dG(edp \mid im) \parallel df_a(im) \mid \qquad (1)$$

$$EAL = \int\int\int\int l_r \, dG(l_r \mid dm) \mid dG(dm \mid edp) \parallel dG(edp \mid im) \parallel e^{-f_a} df_a(im) \mid \qquad (2)$$

Table 3: Variables for assessment of loss from damage, downtime and death.

	Damage			**Downtime**	**Death**	
	Structural components	**NSEs**	**Contents**		**Injury**	**Casualty**
IM	Ground motion parameter (PGA, S_a etc.)					
EDP	maximum drift	maximum acceleration		maximum drift maximum acceleration		maximum drift
DM	extent of damage (cracking, yielding, collapse, etc.)		damage due to movement (sliding, toppling, flying)	extent of damage, reparability	extent of damage, probability of collapse	
DV	repair/replacement cost		cost to repair/replace and relocate/refix	length of closure for repair/replace	probability and severity of injury	probability of casualty

To conduct a comprehensive seismic loss estimation using Equation (2), it is necessary to form probabilistic relationships between the multiple facets of the assessment process (i.e., hazard, response, damage, loss). In particular, four interrelationships are required: (i) $f_a(im)$: annual probability of occurrence of earthquakes of a given intensity (also known as ground motion hazard relationship); (ii) *im-edp*: probabilistic structural response curves (obtained through special structural analysis methods); (iii) *edp-dm*: probabilistic response versus damage relationship (commonly known as fragility curves); and (iv) dm-l_r: probabilistic damage versus loss relationships (also called loss functions). These aspects are discussed extensively in literature [31].

Combining the aforementioned relationships can provide useful measures of seismic performance for making efficient decision-making. For example, by using collapse as the damage measure, the probability of collapse at different levels of ground motion can be communicated in the form of collapse fragility curve, which is essential in estimation of all three forms of seismic loss. Similarly, using loss ratio (i.e., repair cost to the replacement cost ratio) as the decision variable can result in expected direct loss in an earthquake of a given intensity, and can also lead to the loss hazard curve, which plots the annual rate of exceedance of different values of loss ratios. The area under the loss hazard curve gives an estimate of the EAL, which takes into account the consequence of all possible earthquakes. Using the aforementioned four relationships in appropriate forms, similar loss hazard curves can be generated for damage, downtime, injury and casualty, and the corresponding measures of EAL can be estimated by using this loss assessment framework.

As of now, quantification of seismic risk based on this PBEE probabilistic methodology requires significantly more rigor than is currently employed in seismic design and assessment of conventional structures. However, to spare users from conducting the rigorous mathematical operations involved in the probabilistic loss assessment process, an automated computer-based tool (named PACT; i.e., *Performance Assessment Computation Tool*) has been developed [32].

While this seismic loss estimation method is two decades old now, it has only found limited use in engineering decision-making. This is mainly because the method is complex and beyond the comfort level of average engineers without expert knowledge. Moreover, it requires different components of a building to be treated separately using their component-specific fragility and loss functions, and the type and quantity of structural components and NSEs in a building inevitably vary between buildings of different usage. This renders the building loss estimation process lengthy and tedious. Of late, researchers have tried to simplify the seismic loss estimation process to make it more enticing for practicing engineers. Such simplifications include condensing/combining multiple steps of the seismic loss estimation process and/or simultaneously considering a group of building components in a single loss estimation cycle. An example of ongoing efforts is this direction is summarized in the Appendix.

DISSECTION OF BUILDING SEISMIC LOSSES

Seismic Losses from Earthquakes of Different Intensities

In general, earthquakes with low probability of occurrence trigger more intense shaking and cause severe damage to buildings. On the other hand, frequent earthquakes are less intense and cause only minor-moderate levels of damage. As described earlier, EAL is calculated by integrating the likely loss from all probable earthquakes, which is given by the area under the loss hazard (i.e., loss ratio versus the annual probability) curve. The disaggregation of one such loss hazard curve is shown in Figure 4. The total area under the curve is 0.35%, which means the EAL is $3,500/year for a million-dollar building. The breakdown of the EAL between four different ranges of annual probability (including earthquakes of return periods less than 100 years, between 100 and 1000 years, between 1000 and 10000 years, and more than 10000 years, respectively) are also shown in the figure. As can be seen, out of the total EAL, half is contributed by the range including the most frequent and smallest earthquakes (i.e., annual probability greater than 0.01). Although loss per event is the greatest for the rarest range (i.e., annual probability less than 0.0001), they collectively contribute less than 3% of the total EAL.

Although the above discussion focuses on the direct seismic loss arising mainly from repair or replacement of the damaged components, similar loss hazard curves can be generated in terms of downtime and injury. To facilitate explanation, typical loss hazard curves including all three forms of loss are schematically shown in Figure 5a. Note the vertical axis in this illustration is normalized with respect to the total loss from each source, and it should not be misinterpreted as being comparable in absolute values. If converted to equivalent dollar values, it is anticipated that costs of injury/fatality of the building inhabitants will be a lot higher than maximum downtime loss, which itself will be significantly higher than the building replacement value (i.e., 100% damage repair cost).

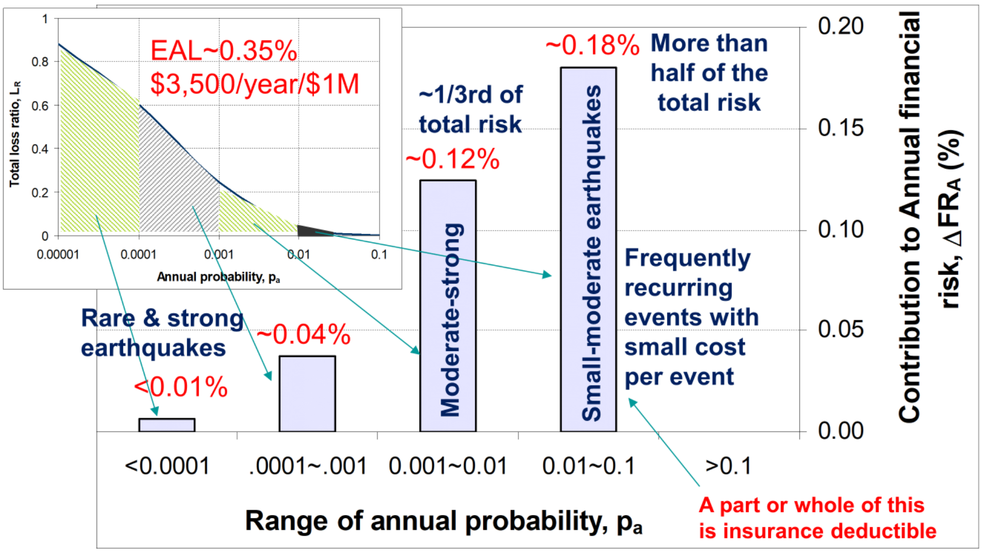


Figure 4: An example of disaggregation of the expected annual loss (EAL).

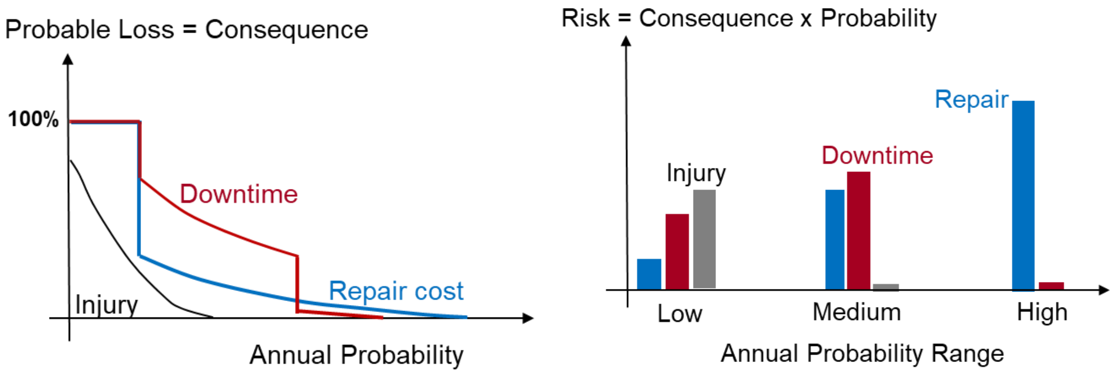


Figure 5: Variation of losses due to repair, downtime, and injury with hazard probability.

As illustrated in Figure 5, minor damage requiring repair can be caused by much smaller (and more frequent) earthquakes, but not all trivial repairs require the building to be vacated. Hence, downtime will eventuate only when the building is significantly damaged at moderate-major earthquakes. Nevertheless, the need to assess building damage when the local ground motion is beyond a threshold level of shaking intensity will mean the building will not be available for use for a short while and will lead to a small downtime [33]. When a building must be closed during repair, it will incur a significant business interruption and relocation cost, creating the vertical offset at the lower end of the downtime hazard curve. Once the damage exceeds a critical threshold, often the preference of the building owner is to demolish the building rather than spending a large sum on repairing. This is the reason behind the sudden jump to 100% of the repair and downtime hazard curves in the low annual probability range in Figure 5. The likelihood of injury starts appearing only when some of the building components fail (or heavy contents move) during severe earthquakes. Hence, injury loss tends to be negligible until the repair and downtime losses are significant. Unlike repair and downtime losses, injury loss is unlikely to reach 100%.

In Figure 5, comparison between EAL due to the three sources of loss (area under the loss hazard curves shown in Figure 5a) is illustrated for three different ranges of seismic hazards: frequent minor-moderate earthquakes (denoted "High"), moderate-severe earthquakes in the range of DBE (denoted "Medium"), and very rare severe-extreme earthquakes (denoted "Low"). Damage repair cost evidently dominates the risk posed by minor earthquakes that occur frequently (with trivial contribution from downtime), downtime and repair costs contribute comparably to the risk from moderate-severe earthquakes (with trivial contribution from injury), and injury/fatality becomes the dominating contributor to the risk posed by severe-extreme earthquakes.

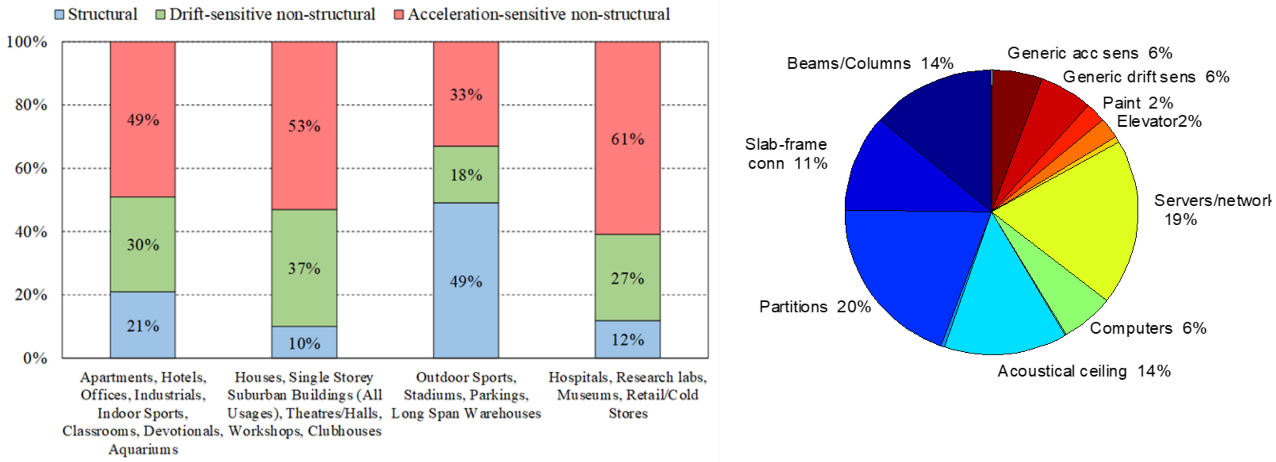
Figure 5 helps explain the additional benefits of LOSD while still meeting traditional *life-safety* requirement. Rare and extreme earthquakes are low-risk but high-consequence events and are hugely important for safety of the inhabitants. Building collapse leading to fatality at such extreme events must be avoided to ensure the indispensable *life-safety* criteria. On the other hand, smaller earthquakes with medium to high annual probabilities of occurrence contribute the most to EAL from repair and downtime despite not posing any noticeable life-safety risk. The consequence of an isolated event of this scale will be minor to individual buildings, but because of their high probability of occurrence, they collectively lead to high financial risk. This risk can be mitigated via earthquake insurance, but currently insurance penetration in different countries vary widely. Hence, to ensure the building industry is not exposed to huge seismic risk/loss in minor-moderate earthquakes, we will have to adopt a seismic design approach that helps to avoid damage and downtime in minor-moderate shakings.

Damage to NSEs Dominating Building Losses in Minor-Moderate Earthquakes

As already established, seismic loss assessment procedures divide building inventory into *structural components* and NSEs. While damage to structural components largely governs the collapse of buildings and consequently the injury/death related loss in severe earthquakes, the repair and downtime related losses in minor-moderate earthquakes are dominated by damage to NSEs. Note that unlike the structural damage which depends solely on the inter-storey drift (forcing structural members to deform and consequently damage), damage to NSEs are caused by both inter-storey drift (causing some NSEs, internal partition walls for example, to deform and damage) and floor acceleration (inducing inertial forces exceeding the capacity of some NSEs, ceilings for example, and/or their seismic restraints). Hence, to relate to their respective primary cause of damage (corresponding to the EDP), NSEs are further divided into two categories, namely *drift-sensitive* and *acceleration-sensitive* NSEs.

Figure 6a shows the breakdown of building construction costs between structural, and drift- and acceleration- sensitive NSEs for buildings with different usage [26]. It is evident in the figure that for all types of buildings, the NSEs cost significantly more than the structural skeleton of the building; the most extreme being nine times greater NSEs cost compared to structural cost for the second group of buildings. Therefore, when a damaged building is to be demolished and rebuilt, much greater proportion of the total loss incurred is attributable to NSEs. This also means that when some NSEs damage severely or fail in moderate shakings and need to be replaced, the cost incurred will be significant. Figure 6b shows breakdown of the estimated total repair cost (i.e., direct loss) of a typical RC multi-storey office building in Wellington following a maximum considered earthquake [31]. The figure illustrates that structural damage contributes only approximately 25% to the total loss, and the remaining 75% comes from damage to different NSEs.

The cost/loss disaggregation shown in Figure 6 highlighting the dominance of NSEs resonate closely with the experience of 2010-11 Canterbury earthquakes, whereby many buildings with minor and repairable structural damage suffered disproportionately severe damage to NSEs [18] and were ultimately demolished because the projected repair cost for the damaged components, majority of which were NSEs, was too high. Note that the above discussion is based solely on the direct damage repair cost, and consideration of other forms of indirect losses further magnifies the importance of NSEs. While damage to NSEs and contents can also lead to loss of lives (ceiling/façade/cladding failures have caused fatalities in recent earthquakes), the most crucial impact of NSEs damage is the disruption of the building's functionality leading to overwhelming business interruption and relocation costs, which can outweigh the direct repair cost by an order of magnitude.



a) Building construction cost disaggregation [26]

b) Building seismic loss disaggregation [31]

Figure 6: Contribution of different building components to the building repair and replacement costs.

Improving Seismic Performance of NSEs

Structural system of a building solely control the inter-storey drifts and floor accelerations, which cause damage to the NSEs. Hence, damage to NSEs can be avoided/minimized if the structural system is selected such that the maximum storey-drifts and floor accelerations in design level earthquakes are within the drift/acceleration capacities of the NSEs designed and installed as per current practice. Even if the structural system resulted in higher drifts and/or accelerations than what can be resisted by traditionally designed/installed NSEs, building losses in earthquakes can still be minimized (if not avoided) by designing the NSEs to remain undamaged despite the large drifts/accelerations by adopting resilient (low-damage) NSE designs. Some innovative low-damage versions of NSEs that can resist large drifts and accelerations have been recently developed and experimentally verified. For example, fully floating ceilings with shock absorbers along the perimeter was found to resist much larger floor accelerations without any damage in comparison to traditional perimeter fixed grid ceilings [8]. Similarly, novel designs to accommodate higher drift demands (in excess of what structures are designed for) by rocking have been developed and validated for internal partitions and external claddings [9-11]. Note that the enhancement in drift/acceleration capacity of NSEs in these innovative solutions have been achieved by reconfiguring the connections without the use of significant additional/costly materials. Hence, any increase in cost between traditional NSEs and the novel low-damage NSEs will be modest, if any.

Awareness of the importance of NSEs has been steadily increasing of late because of the repeated experience of NSEs dominating the building damage in recent earthquakes. Consequently, resources being invested to improve the state-of-knowledge and practice related to NSEs are growing steadily, and many researchers worldwide have been drawn into NSE-related research aiming to better understand the reasons behind their poor performance and develop resilient solutions. In addition, practicing building engineers are also proactively trying to identify and address the critical weaknesses in the existing design and construction practices around NSEs. To facilitate communication and collaboration between researchers and practitioners worldwide and to help address the abovementioned issues, the engineering community focusing on such issues have established a professional organization named the *International Association of SPONSE (Seismic Performance of Non-Structural Elements)* (see www.sponse.eu for details).

Nevertheless, despite all the ongoing efforts in research and profession, construction industries worldwide are still facing significant issues related to NSEs [1], due mainly to: (i) inadequate procurement/tendering practice; (ii) standards not up-to-date with rapidly evolving state-of-the-knowledge; (iii) inconsistency between design standards/practices; (iv) non-compliance to existing standards; (v) lack of coordination among different NSE-related trades; and (vi) faulty installations not identified due to inadequate quality control measures. Needless to mention, these problems cannot be solved by improving only a single aspect of the spectrum and will need all stakeholders to work together for many years to come.

SIMPLE DESIGN PRINCIPLES EFFECTIVE IN MINIMIZING BUILDING SEISMIC LOSSES

It is well-established that loss is a by-product of damage, hence seismic losses can be minimized only by reducing damage to building structure and NSEs in earthquakes. Based on scrutiny of building damage patterns observed in recent earthquakes in NZ [14-16], Nepal [34], Japan [35], and Mexico [36], the Author has deduced the following fundamental principles to help reduce building damage in earthquakes (regardless of the seismicity and structure type):

1. ***Avoid buildings to have fundamental period close to the underlying soil period:*** This came out very strongly in 2015 Gorkha (Nepal) earthquake, 2016 Kaikōura earthquake and 2017 Mexico earthquake. In Kathmandu valley, mid-rise street-front frame buildings with slender columns and modern high-rise buildings were found to damage severely (many collapsed) whereas majority of the low-rise building stock (mostly made of masonry without any engineering design) remained largely undamaged and functional. Note that the peak ground acceleration recorded inside Kathmandu valley was modest (less than 0.2g). Nevertheless, as the soft soil on the lakebed of Kathmandu valley had filtered the high frequency (short period) content and magnified the energy in the low frequency range, flexible buildings with longer natural periods were subjected to amplified demand due to resonance. In 2016 Kaikōura earthquake too, low-rise unreinforced masonry buildings in Te Aro Basin in Wellington suffered little damage despite the shaking amplified by the soft soil when several modern mid to high-rise buildings suffered significant damage; leading to demolition of 9 buildings [20]. Similar observations were made in Mexico City where multiple local engineers confided to the Author that after

the 1985 Mexico earthquake, they have been paying special attention to avoid constructing buildings with periods close to the range of the subsurface soil period and this simple principle (i.e., avoiding the *double resonance effects*) was noticed to have paid dividends in the 2017 earthquake.

2. ***Design buildings to have higher yielding strength:*** The main reason buildings get significantly damaged even in moderate earthquakes is because their elastic/yielding strength is very small because of the current practice of significantly reducing (by multifold) the elastic base shear demand in lieu of ductility. While the high ductility and associated rigorous detailing ensure that the *life-safety* and *collapse-prevention* criteria are largely assured in severe earthquakes, the reduction of design force makes buildings vulnerable to damage in much smaller earthquakes (than the DBE). Arguably, a better approach would be to limit the strength reduction so that buildings inherently have a higher threshold of damage and can remain functional even after moderate earthquakes. Nevertheless, even if the design force at threshold of yielding (or damage) is increased and the ductility demand at ULS is consequently reduced, ductile detailing practice should not be compromised to ensure collapse is avoided and *life-safety* is guaranteed at severe-extreme earthquakes. This approach is also strongly advocated by a group of senior Chilean engineers [37] after analyzing the building performances in the 2010 Maule earthquake. Adopting the lessons learnt from the 2010 Maule earthquake, the Chilean building design code has been revised in 2011 [38,39] to require buildings to achieve *immediate occupancy* at DBE and *collapse prevention* at MCE [37], which is a paradigm shift compared to the design approach currently adopted by other codes (i.e. to design buildings to remain *life safe* at DBE). In NZ too, the Seismic Risk Working Group [19] seems to be stepping in this direction by recommending a new limit state between SLS and ULS called *damage control limit state* (DCLS).

   The importance of building strength in limiting seismic damage/loss came at the forefront when comparing building performances in the 2016 Kumamoto and 2011 Christchurch earthquakes [35]. Modern building stock in Kumamoto that were designed to resist higher base shear corresponding to ductility of 1.8-3.3 visibly suffered significantly less damage/loss compared to Christchurch modern buildings, which were designed to have a greatly reduced strength because of high ductility (up to 6.0). Hence, it will not be an overstatement that the current seismic design approach of reducing design strength in lieu of good detailing through the force reduction (or ductility) factor is the main reason behind the current damage-prone building stock.

   A common counterargument thrown against designing stronger buildings relates to the increase in cost. However, research has shown that changing the force reduction factor from four to one (i.e., a four-fold increase to the design strength) for typical low and mid-rise RC frame buildings increases the structural material cost by approximately 20%, and the total project cost by no more than 7% on average [40]. Also, a study by Porter [41] claimed the increase in construction costs in the United States will increase only by approximately 1% if the material costs for a lateral load resisting components in a building is doubled to increase the building's strength and stiffness. As the total project cost increase is modest and the associated gain in seismic performance is significant, it seems desirable and financially feasible to design buildings to respond elastically (or with minimal inelastic response causing no downtime for repair) in a design level earthquake.

3. ***Limit the inter-storey drifts in designing multi-storey buildings:*** This principle has been strongly advocated in the past by many prominent engineers throughout the world [37,42-44]. Howe [42], as early as 1936, highlighted the key role played by a building's stiffness (termed by Howe [42] as "rigidity") and strength in its seismic performance. Similarly, Sozen [44], in 1980 identified the desirability to rehabilitate roof and inter-storey drifts as the single most important response parameter for structural and non-structural response of a building, and concluded "*drift control should be centerpiece of design methods for multistory buildings rather than presented as simply another check on the completed design*". Recently, Lagos et al. [37] offered the following analogy to highlight the role of a building's stiffness in its seismic performance: "*While ductility plays the role of life insurance, that is, something a building must possess to prevent collapse with the hope of never having to use it, lateral stiffness plays the role of health care insurance, something the building will make use of frequently to remain operative throughout its life*".

   The importance of drift control via designing stiffer buildings came through very strongly in the 2016 Kumamoto earthquakes, which were similar to the 2010-11 CES in terms of the nature, intensity, and series of earthquakes in close proximity to a major urban center. While the total casualty in the two earthquakes were comparable, the visibly different extent of building damage in the two cities highlighted the relatively poorer resilience of NZ buildings and the subsequent prolonged impact on Christchurch as a whole. Two months after the earthquake, Kumamoto was a normally functioning city where majority of the population were able to continue their daily function with minimal disruption and no sight of any cordoned *Red Zone*. In contrast, public access to several parts of Christchurch CBD was prohibited for over 2 years following the earthquakes.

   A scrutiny of Japanese seismic design guidelines pointed to a design philosophy emphasizing stiffer and stronger buildings than those commonly seen in NZ and revealed that they do not focus on ensuring a ductile response and capacity design to the same extent as NZ Standards [35]. It was found that the ULS-level inter-story drifts of buildings designed to the Japanese code are invariably less than half of the 2.5% inter-story drifts allowed by the NZ standard. Hence, it was not a surprise that modern buildings in Kumamoto suffered limited damage and by-and-large exhibited distinctly better performance than the buildings in Christchurch, whereby there were hardly any modern buildings that could be occupied after the earthquakes. In addition to Japan, stricter design drift limits are also a key feature of Mexican design code, where damage to modern buildings was visibly less extensive than in Christchurch. The current Chilean code [38,39], amended after the 2010 Maule earthquake, allows a drift limit of only 0.002 at the design force level, which after multiplying by the maximum permissible ductility factor, is still less than half of the maximum interstorey drift of 0.025 permitted in the NZ standard. The Author believes it is time NZ standards are also revised to substantially reduce the interstorey drift limit permitted in designing multistorey buildings.

   Intuitively, one can recognize that reducing drifts by designing stiffer buildings will lead to less structural and non-structural damage and subsequently less loss from repair costs and downtime. There are published literature that highlight the benefits of designing stiffer buildings and quantify the gains in terms of reduction of seismic damage and losses. Williamson et al. [45] showed that tightening the maximum inter-storey drift allowed in seismic design of buildings will significantly reduce seismic losses. Similarly, Koopaee [46] showed that designing for a reduced design drift enhances the collapse capacity and significantly reduces the collapse probability of RC frame buildings at severe-extreme earthquakes. In this context, using stiffer structural walls to provide the required design lateral force demand appears to be a smarter choice than using frames, which are inherently more flexible. This is consistent with the findings of Pujol [47] based on comparing the performance of RC buildings in the 2023 Turkey earthquake with those from several previous earthquakes. Pujol [47] strongly advocated for building codes to be revised to require a minimum threshold for wall index (i.e., proportion of the total floor area occupied by RC walls) to ensure they can resist design level earthquakes with limited drift and damage. This is also consistent with the findings of Shiga et al. [43], based on the performance of concrete building observed in Hachinohe city in the 1968 Takachioki earthquake, that seismic damage to concrete buildings can be minimized if they have sufficient amount of walls (in excess of 30 cm^2/m^2 floor area).

4. ***Make buildings as regular as possible:*** While engineers have known this adage for decades, the importance of building regularity was highlighted strongly again in 2010-11 CES. There were several instances where despite similar ground conditions, structural form, and age, irregular and torsionally sensitive buildings were found to damage much more severely than nearby buildings of similar vintage.

   Henry Degenkolb, a well-known earthquake engineer in California rightly said:

   "*If we have a poor configuration to start with, all the engineer can do is to provide band-aid – improve a basically poor solution as best as he/she can. Conversely, if we start off with a good configuration and a reasonable framing system, even a poor engineer can't harm its ultimate performance too much*."

HOW EFFECTIVE ARE THE EMERGING LOW-DAMAGE BUILDING TECHNOLOGIES IN MINIMISING SEISMIC LOSSES?

Low-Damage and Less-Loss: Not Synonyms

Following the extensive damage to buildings in recent earthquakes resulting in high financial losses, large proportion of buildings constructed in the last decade (including those built to replace earthquake-damaged buildings) have intentionally avoided the traditional ductile structural systems. Lately, the number of buildings adopting "low-damage" structural systems is increasing steadily. Such "low-damage" systems include a spectrum of damage avoidance or reduction measures ranging from historically known methods like base isolation to new and emerging technologies like buckling restrained braces (BRBs) [48,49] and novel connections (and mechanisms) designed to efficiently absorb seismic energy [50-52]. In many cases, the adopted structural systems are not covered by existing design standards and are approved as alternate solutions through expert peer-review. The "low-damage" attribute of most structural systems has been validated by component (or sub-assembly) level experimental tests [53], but their interactions with other building components and implications of their use in buildings have yet to be rigorously investigated.

The Author believes that a low-damage "structural" system does not necessarily result in a low-loss building. For a given building, different low-damage technologies fetch different gains in terms of seismic loss reduction. In this context, four categories of low damage structural technologies are scrutinized below. Note that there exist other technologies not covered by these categories, but they are left out of discussion here because the Author is not aware of studies investigating seismic performance of buildings with these technologies in sufficient detail.

1. ***Hybrid post-tensioned rocking (HPR) frames:*** Also identified in the literature as DAD (Damage Avoidance Design) [54] or PRESSS (Precast Seismic Structural System) [55], this "low-damage" precast frame building technology consists of prefabricated members joint together using unbonded post-tensioned tendons supplemented by energy dissipating connections that can absorb seismic energy and accommodate large drifts via rocking. There is plenty of evidence in the published literature demonstrating their superior "structural" performance in comparison to monolithic frames.

   Experimental investigations [56-58] have proved that this system avoids damage to the frames even when exposed to large drifts. This removes the need to repair any structural damage, which will save on structural repair costs, though it is only a small part of the total building loss. As drift demand on rocking wall buildings is found to be higher than traditional monolithic buildings [59], intuitively it can be argued that the same applies to rocking frame buildings as well. Hence, despite avoiding structural damage via controlled rocking, as HPR buildings deform more, there will be greater damage to the drift-sensitive NSEs (e.g., partitions, facades, windows etc.). Limited investigation so far has also indicated that acceleration responses can also be higher in rocking buildings [60], which suggests that damage to acceleration sensitive NSEs (e.g., ceilings, piping) and contents in HPR buildings will not be less than that in traditional buildings. Hence, despite avoiding structural damage, HPR frames cannot reduce damage to other building components. Therefore, in terms of total loss, they do not offer significant benefit unless the building comprises of low-damage NSEs built using novel and innovative technologies that reduce/avoid damage despite higher drift and acceleration demands [61].

   However, such a system becomes an excellent choice for buildings that comprise mainly of a structural skeleton, with limited NSEs (such as multi-storey garages and stadia). The damage-free HPR frames are likely to enable these buildings to survive major earthquakes with little damage, and to remain functional with little or no downtime.

2. ***External bracing/damping devices:*** Using additional bracing elements to improve seismic performance of buildings is a common practice; both in new construction as well as in seismic strengthening of existing buildings. External bracing of all shapes and configurations act on the principle of stiffening the structure to reduce their drift/displacement response, which leads to less damage to the structural system and drift-sensitive NSEs. One trade-off is that the increased stiffness of the braced buildings reduces the building period; thereby attracting greater seismic forces and higher floor accelerations [62]. Hence, adding braces in a building normally leads to an increase in the damage to acceleration-sensitive NSEs and contents, thereby providing little concession on total seismic losses for some buildings. In buildings where services and contents are very valuable/hazardous (e.g., hospitals, museums, research labs), this option should not be preferred unless the contents are isolated or braced/secured properly to the floor/walls to withstand larger floor accelerations.

   When braces are used with dampers and/or dissipaters, reduction of seismic losses is likely to be more significant. Dampers can be broadly classified as hysteretic dampers (i.e., damping force proportional to displacement, such as buckling restrained braces (BRBs), friction dampers, yielding dampers etc.) and viscous dampers (i.e., damping force proportional to velocity). A hysteretic damper functions in parallel with the main structural system and is designed to yield at a fraction of the design seismic forces.

They are ductile in nature and absorb seismic energy by plastic deformations, but they also add strength and stiffness to the system. On the other hand, as velocity is out of phase with displacement, damping force in a viscous damper becomes maximum at zero displacement and reduces to zero at the maximum displacement; thereby adding little to the total force in the system. Both types of dampers add to the initial stiffness of the structure, but the viscous dampers can compensate for its adverse consequence to a great extent by adding greater damping to the system. While all types of dampers reduce building drifts across the height of buildings, they offer different return in terms of acceleration response. In low and mid-rise buildings, using hysteretic dampers like BRBs result in higher peak floor accelerations, which is in contrast to viscous dampers that slightly reduce the peak floor accelerations [60]. Hence, among different practices of bracing/damping buildings, viscous dampers appear to be more effective in reducing seismic losses from all sources and are a better option for all types of buildings.

3. ***Seismic isolation:*** Seismic isolation decouples a structure from potentially damaging earthquake-induced ground motions. The concept of seismic isolation can also be applied to safeguard valuable contents from damaging during floor vibrations. In most applications, the seismic isolation system is mounted at the base of a building and is referred to as 'base isolation'. A building (or its content) can be decoupled from the ground/floor by introducing isolator(s) that can deform/displace and absorb the energy induced by the motion underneath the isolators. Base isolation increases the flexibility of the system and provides additional damping, and it reduces both drift and acceleration demands on multi-storey buildings [63].

   As base isolation makes the overall system softer, it reduces the building’s acceleration response; thereby reducing the peak floor accelerations and damage to acceleration-sensitive NSEs and contents. Although the total displacement of the system increases, a major share is taken by the isolator and the building deforms relatively less, causing less damage to the superstructure and drift-sensitive NSEs. Overall, base isolation results in a substantial reduction of overall building loss in an earthquake.

4. ***Demountable buildings:*** Precast concrete frame buildings with detachable dry steel connections between the structural components render the whole building rapidly erectable and partially/fully demountable when needed [64]. Such buildings allow quick replacement of components damaged in earthquakes; thereby drastically reducing the building downtime. If such buildings are equipped with innovative low-damage connections to join the precast components, damage (and hence any need for repair) can be avoided in moderate earthquakes. As indirect losses caused by building downtime (i.e., business interruption, occupant relocation, loss of income, etc.) at severe ground shakings is usually an order magnitude greater than direct loss due to damage repair cost, such easily/quickly repairable buildings induce significantly less seismic losses despite not necessarily reducing the extent of damage compared to traditional buildings.

   This becomes more important in seismic regions where insurance penetration is high. As was evident after 2010-11 CES, damaged RC buildings resulted in a lengthy dispute between insurers and owners because of the term in the insurance policy requiring damaged buildings to be repaired to “as new” condition. Because of inherent uncertainty around residual performance/capacity of damaged RC buildings and around the “newness” of repaired RC buildings, reaching a mutually agreeable “repair or demolish” decision took several years, during which the building could not be used. Such unnecessary delay (i.e., long downtime) can be avoided if damage is forced by design to restrict in easily and quickly replaceable elements, which unambiguously ensures that the building would be repaired to “as new” condition.

   Such a building system, named *Rapid, resilient, recyclable, reduced-carbon modular building system* (R4MBS in short) has been conceived recently [65]. Conventional precast concrete buildings offer several advantages over traditional cast-in-situ construction in the form of quick construction, better quality control, less site labor and site formwork. Nevertheless, their current construction practice emulating monolithic behavior by assembling the precast members via wet joints creates multiple issues. For example, it slows construction speed due to the requirement of formwork/curing, and the irreversible integration of the components via wet joints makes it impossible for the precast components to be detached, which makes such buildings difficult to strengthen/repair and leaves the environmentally unfriendly demolition as the only option for termination of such buildings. R4MBS claims to address all these issues.

   R4MBS is characterized by standard precast concrete components, detachable/demountable steel connections, dry connections requiring no onsite pouring, low-damage connections that are easy to fabricate, designed to remain undamaged in moderate earthquakes, capacity designed to ensure damage is restricted to beams in perimeter seismic frames for easier access, and internal gravity frames are pin-connected to avoid any damage. These characteristics of R4MBS lead to the following advantages over traditional precast buildings; (i) enhanced seismic resilience (no damage in moderate earthquake and quickly repairable to “as if new” after major damaging earthquakes), (ii) rapid construction (resulting in reduction of project duration/cost), (iii) partially/wholly demountable and replaceable as/when needed (making it easy to modify/upgrade/repair), and (iv) environmentally friendly and sustainable (eliminating the need of demolition, recycling of demounted components, reduction of building’s life cycle carbon footprint).

Hurdles to Adoption of Low-Damage Technologies

In recent years, number of new buildings equipped with low-damage technologies that will significantly reduce seismic losses due to damage/repair cost, business interruption, and injury/fatality in earthquakes is increasing. Nevertheless, their overall use in buildings to date is still limited, mainly because of the additional cost incurred when adopting these technologies in buildings (or the lack of convincing evidence to assure the owners that the cost increase, if any, is trivial). For example, the cost of base isolating a building is claimed to be around 3% of the total project cost [66]. Although the additional cost can be easily justified based on saving in seismic repair and downtime costs over the life of a building, building owners need immediate tangible benefits to compensate for the higher initial costs. Experience in NZ indicates that public buildings are quick in adopting such technologies because the additional costs come from public coffers, but private building owners are unlikely to voluntarily embrace the cost-increase associated with these technologies without being mandated by legislation or without being offered upfront incentives for doing so (or conversely, a penalty for not doing so).

The owners (or builders) pay the extra cost for retrofitting existing buildings or adopting new low-damage building systems, but they do not get higher rent for retrofitted or low-damage buildings as the rent is normally decided based on floor area. Neither do they get higher price when selling retrofitted/low-damage buildings, except perhaps when the buyer can appreciate the additional value in the form of reduced seismic risk (which is seldom the case). Ideally, the insurance premium should be set in line with the risk posed, but the current insurance practice does not distinguish buildings based on their seismic resilience. Hence, there is little incentive for adopting these modern technologies as building owners do not get any discount in insurance premium for retrofitted or low-damage buildings.

Seismic assessment and strengthening policies focus mainly on life-safety risk, and currently there is no mandate requiring building owners to go beyond the bare minimum (provided by the design codes) needed to ensure the life-safety risk is within the tolerable limit. By not retrofitting an earthquake-prone building or not using low-damage building technology, the owners or builders will not face any greater risk (financially or otherwise), as insurance covers all losses incurred due to earthquake damage. Even the increased life-safety risk associated with these buildings in comparison to low-damage buildings does not worry building owners because it is the tenants, not the owners, who are exposed to (and will have to bear) this increased risk of injury/casualty in earthquakes.

Despite the absence of any incentives, if the owners voluntarily decide to invest additional money in adopting these low-damage technologies, the benefits of the owners' investment will go to the insurers (less frequent and smaller insurance claims) and tenants (reduced risk of injury and/or business interruption). Therefore, it is not surprising that commercially motivated private owners/builders do not find a sensible reason to spend the extra money in going beyond the minimum legislative requirement of ensuring life-safety.

CONCLUSIONS

Current seismic design methods rely on capacity design and ductile detailing to ensure life-safety in DBE and prevent collapse in MCE. This approach relies on dissipating seismic energy through inelastic deformation of well-detailed plastic hinge regions and allow for buildings to be designed with significantly reduced strength in lieu of ductility. Such design approach attracts damage at shakings that are much smaller than DBE. Unsurprisingly, modern building stock has suffered extensive damage in recent moderate-major earthquakes, including the 2010-11 Canterbury earthquake sequence; resulting in a long delay before the buildings are brought back to full function. The long downtime caused by lengthy insurance repair/demolish dispute resolution, and time taken to design/plan/execute repair, has inflicted a huge financial loss to the industry in the form of direct repair cost and indirect costs associated with business interruption, relocation, and loss of income. This has perplexed the public, who expect a better performance from modern buildings that are designed for earthquake-resistance by professional engineers following state-of-the-art seismic design codes. There is clearly a mismatch between what buildings are currently designed for (*life-safety*) and what the public expects (limited financial loss in addition to *life-safety*). Hence, seismic design philosophy should evolve to meet public expectations in future earthquakes.

This can be achieved by adopting building design philosophy that requires building damage and loss in different earthquakes to be restricted within acceptable limits. Loss Optimization Seismic Design (LOSD), which explicitly aims to minimize seismic losses in addition to ensuring *life-safety*, offers such an option. The framework of LOSD enables explicit consideration of direct loss (in the form of damage repair cost) as well as indirect losses (in the form of downtime and injury/casualty) in design decision-making. However, any loss/risk based seismic design requires a simple and easy-to-use seismic loss estimation method so that practicing engineers can adopt it in everyday design. Hence, researchers should strive to develop simplified, yet reliable, methods to estimate building seismic losses.

Although threat to *life-safety* and collapse originates mainly from failure of structural skeleton of a building, direct and indirect seismic losses (i.e., damage repair cost and downtime related losses) are largely governed by damage to *non-structural elements* (NSEs) and *contents*. In any building, replacement cost of NSEs significantly outweighs that of *structural components*, and damage to NSEs is responsible for a predominant share of the total building loss in an earthquake. In many recent earthquakes, NSEs suffered more severe damage compared to the *structural components*, causing significant financial losses. Hence, existing methods of designing, configuring and assembling NSEs in buildings need to be improved. Efforts should be made to identify and mitigate inherent weaknesses in the incumbent NSE design and installation practices, and to develop resilient low-damage technologies for NSEs.

RC building performance observed in past earthquakes has shown that damage can be minimized if buildings with periods close to the natural period of the underlying soil are avoided. Moreover, regular buildings with strong and stiff lateral load resisting systems (e.g. with adequate amount of walls) were found to suffer significantly less damage than those without these features. In particular, controlling the deformation/drift of buildings by using stiffer structural systems appears to a crucial condition for minimizing building damage. This approach has already been adopted by building design codes in Japan, Mexico and Chile to enhance seismic resilience of new buildings in future earthquakes. The 2.5% inter-storey drift permitted by NZ standard renders buildings damage-prone in earthquakes, and it is time for NZ standards to be revised to reduce the drift limit permitted in building design.

Different forms of low-damage technologies are being used lately in new buildings and strengthening of existing buildings, albeit with little scrutiny of their ability to reduce different streams of seismic losses and their effectiveness in different types of buildings. Nevertheless, there is increasing research on low-damage technologies that enable quick repair after a damaging earthquake, resulting in a minimum seismic downtime and consequent financial loss. Among the common low-damage technologies readily available in the market, base-isolation is convincingly the most efficient in reducing seismic losses of all kinds. Wide adoption of low-damage technologies in buildings, however, still seems far due to many practical challenges in current real-state and insurance market setups, as commercially motivated building owners currently do not find immediate and tangible benefits to entice them to invest the extra initial cost to adopt low-damage technologies in their buildings. Current insurance and real estate models as well as regulatory framework will have to be modified to provide incentives to adopt (or impose penalty for not adopting) proven low-damage technologies to reduce seismic risk arising from their buildings.

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APPENDIX

EXAMPLE OF SIMPLIFIED SEISMIC LOSS ESTIMATION METHODOLOGY

Khakurel et al. [26] proposed a simplified loss estimation methodology, which enables quick calculation of the total loss in a building using normalized loss functions for groups of drift and acceleration sensitive components that are specific to the building usage category. The input information required for this simplified loss estimation method are: (i) building usage type (the method can cater for mixed usage across the height of a building); (ii) total cost of the building divided into different floors; and (iii) maximum drifts and peak accelerations in different storeys/floors for the shaking under consideration. A flow of key steps used in this methodology is shown in Figure A1.

In this method, all structural components and NSEs sensitive to the same EDP (i.e., maximum drift of a storey or peak acceleration of a floor) are grouped into a performance group, and generic weighting factors and loss functions (i.e., normalized loss ratio vs. EDP relationships) are developed a-priori for different performance groups in buildings of different usage. The fragilities and repair/replacement costs of different components are combined using appropriate weighting factors to derive the normalized loss functions of the performance groups, and the relative quantity and costs of different components in buildings of different usage are considered in establishing the performance group weighting factors for buildings of different usage. Seismic loss for each floor is calculated by taking a weighted sum of normalized losses of the different performance groups in the floor, and the total loss of a building is estimated as an arithmetic sum of the floor losses. As it is envisaged that the weighting factors and loss functions for different performance groups will have been derived in advance, this method enables estimation of seismic loss without requiring the users to separately consider individual building components.

Figure A2 identifies the key tasks involved in making the method (with all necessary functions) readily available to designers for quick seismic loss estimation in everyday design practice. As of now, significant progress has been made on all six tasks, but significant gaps still exist in Tasks 1, 2 and 6. For example, pre-establishing the normalized loss functions for all components will require the fragility and cost data of the components, most of which are available in FEMA P-58 [32] but may not be readily usable in all cases as they are typical of the design/construction practice in the US. Similarly, simple methods to estimate peak drift and acceleration profiles across the height of buildings are available only for some lateral load resisting systems [67-70].

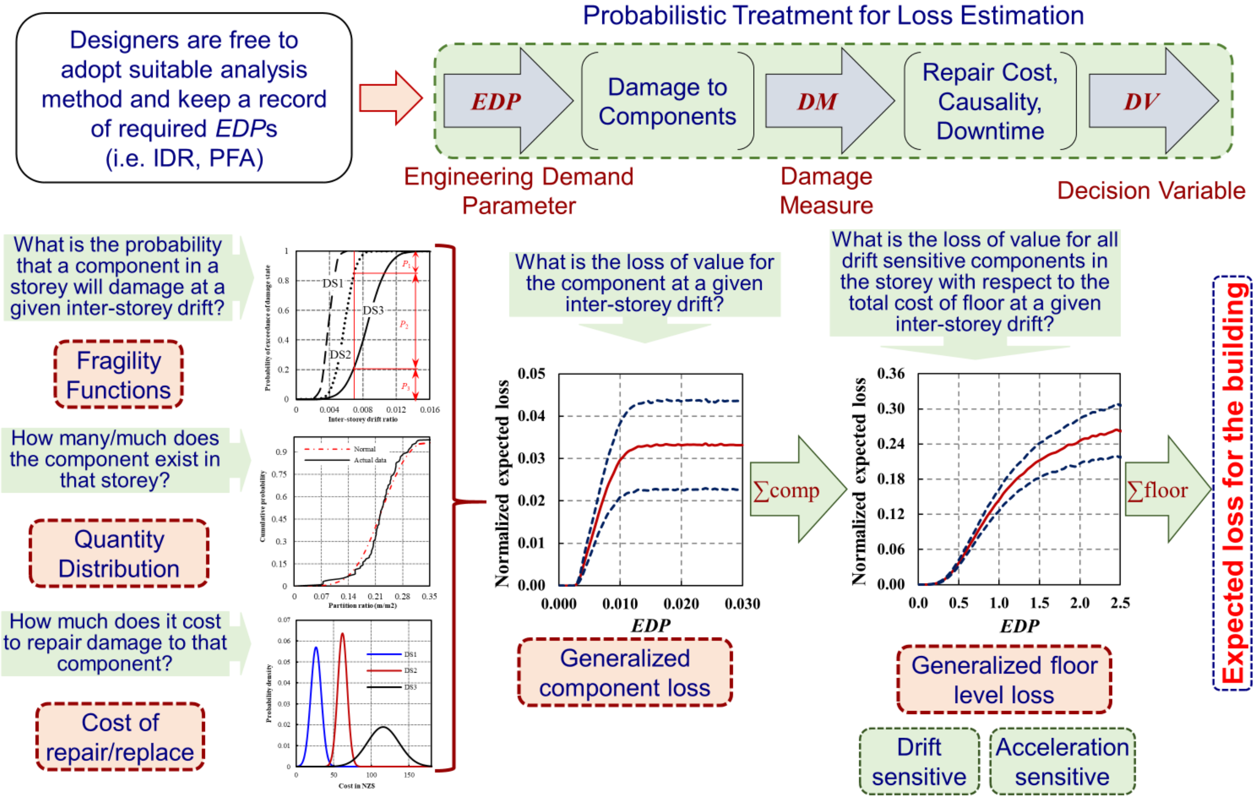

Figure A1: Simplified loss estimation methodology based on performance group weighting factors (Khakurel et al. [26]).

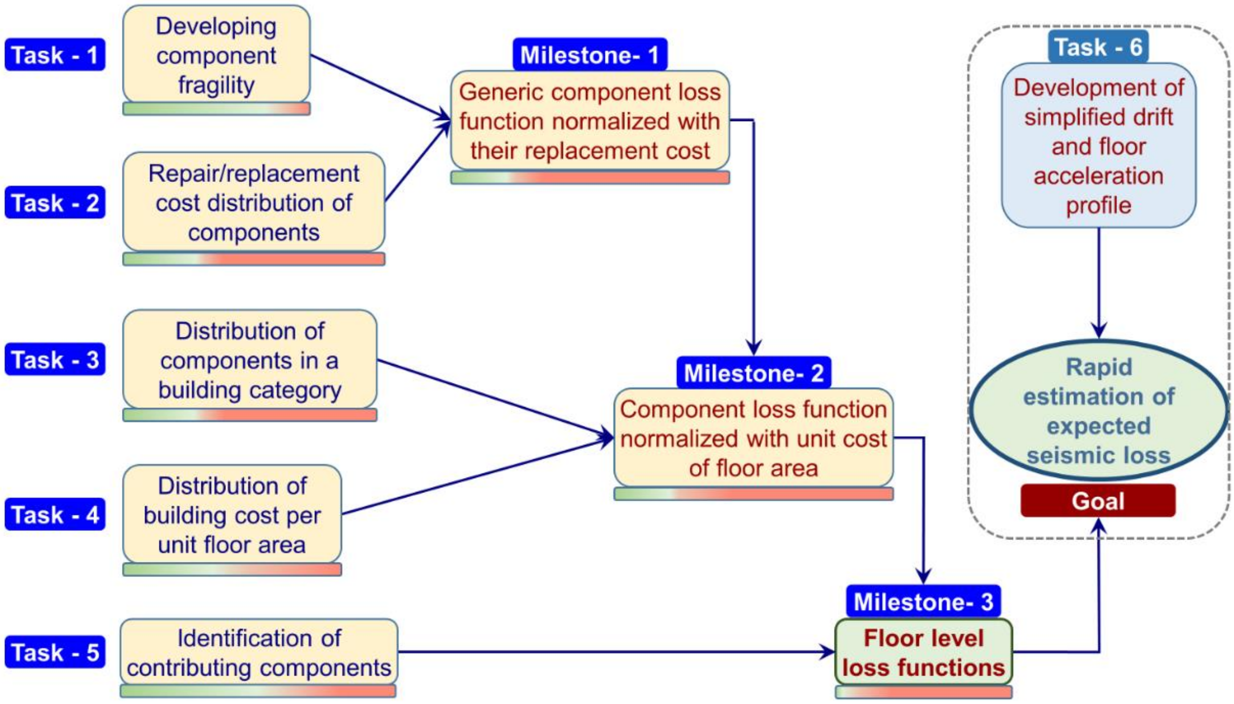

Figure A2: Tasks to be completed to develop the simplified loss estimation methodology.