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DERIVATION AND APPLICATION OF PERFORMANCE GROUP WEIGHTING FACTORS FOR RAPID SEISMIC LOSS ESTIMATION

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Abstract

Despite most buildings confirming to life-safety requirements in modern seismic design codes, enormous financial losses are still incurring from many recent major seismic events around the globe. One tool to quantify and identify the source of these losses is seismic loss estimation, which considers losses arising from building damage, occupancy disruption (downtime) and death/injury. While significant progress had been made to simplify loss estimation procedures for easier applications, they are still not readily usable in everyday engineering design practice. One reason for this is due to insufficient information being readily available regarding the inevitable variations in the type and density of different structural and non-structural building components present in buildings of different occupancy types.

This study aims to establish groups of building occupancy types based on similar initial cost ratio of the three key performance groups; structural components, non-structural drift-sensitive components, and non-structural acceleration-sensitive components. This involved extracting component construction/installation costs from a New Zealand construction cost handbook for a range of different building occupancy types, summing the costs based on the three performance groups, then grouping the occupancy types based on similar structural and non-structural component costs. Weighting factors for each performance group, which represent the ratio of the performance group cost to the total cost, were then proposed for each building occupancy group. It should be noted that while the methodology adopted in this study can be used in other regions, the specific values and building occupancy groups proposed in this paper is specific to New Zealand application.

A total of 79 different occupancy types were considered and grouped into four different building occupancy categories. Mean values of the performance group weighting factors for each occupancy category was computed and proposed. A case study demonstrating the application of the proposed weighting factors in rapid seismic loss estimation is provided. The results of this case study were compared against ones derived using more resource-intensive component-level seismic loss estimation calculations, where it was found that both approaches provided similar estimates. This showed that the simplified approach was not only easier and quicker to apply, but was also reasonably accurate.

Keywords: component cost; building occupancy group; performance group weighting factor; seismic loss estimation

1. Introduction

The philosophy of modern seismic design codes is to minimize the risk of fatalities by reducing the risk of structural collapse and failure of components within and around buildings. While this objective was largely achieved for modern well-designed buildings during recent earthquakes (e.g. 2010-11 Canterbury earthquake sequence), there were still significant socioeconomic impacts on the society in terms of repair, downtime (i.e. duration of occupation and building functionality disruptions), and injury (*RDI*). Examples of damage, downtime, and injury resulting from the 22nd of February 2011 Christchurch earthquake are shown in Fig. 1.

Fig. 1 – Examples of socioeconomic losses after 22nd Feb 2011 Christchurch earthquake; (a) non-structural damage [1], (b) downtime [2] and (c) injury [3]

The significant losses incurred despite the buildings mostly performing as prescribed in the codes have raised awareness of the need to minimize socioeconomic impacts in future events to increase societal resilience. One way to achieve this is to explicitly minimize seismic losses during the building design phase. Methods to estimate such seismic losses are available, such as the Performance-Based Earthquake Engineering (PBEE) methodology developed by the Pacific Earthquake Engineering Research (PEER) center [4] which estimates earthquake-induced life-cycle cost for structures considering initial construction costs and expected future maintenance/repair costs. This framework provides a versatile and robust approach to estimate seismic losses and has commonly been used in academic researches [5-12]. Nevertheless, it is difficult to apply this framework readily in engineering practice because: (i) information regarding the quantity and type of every single building component are often not known to the engineer at the design stage, and (ii) fragility and loss functions of all components can be difficult to source.

One way to avoid these hurdles is to provide engineers with typical loss distributions. Ramirez and Miranda [7] presented building-specific floor-level loss functions by deterministically combining typical components present on a floor level for different building and floor categories. Dhakal et al. [13] extended this methodology to account for (i) uncertainty in the repair cost values, and (ii) variation in quantity distribution. Dhakal and Saha [14] proposed component losses as a ratio of each story value which inherently accounts for the effects of the type, quantity, and fragility/loss functions of the components. These were termed “contribution functions”. An example of contribution function is shown in Fig. 2.

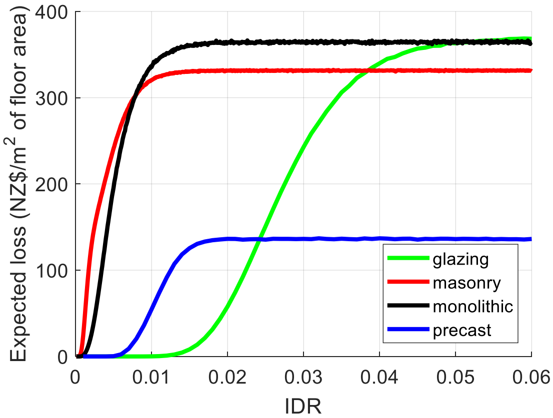


Fig. 2 – Contribution function for cladding [16]

Such functions have been developed for New Zealand-specific practice, such as suspended ceilings and drywall partitions [13], RC structural walls [15] and cladding [16]. Contribution functions for other components are currently being developed. Components can be grouped with other components of similar type (i.e. structural or non-structural) and engineering demand parameter (*EDP*) to form “Performance Groups”. Within each story, the contribution functions for all components within a performance group can be combined and the losses can be normalized by the performance group’s construction cost to obtain “performance group-level losses”. These can be multiplied by weighting factors (W, ratio of performance group to story-level construction costs) and added together to obtain story-level losses; which in turn can be summed up to obtain building-level losses. An illustration of this approach is shown in Fig. 3. Using such an approach, users can rapidly estimate building-level losses if performance group-level losses and weighting factors are provided. Dhakal and Saha [14] proposed applying this simplified framework to engineering design, and termed the approach “Loss Optimization Seismic Design (LOSD)”.

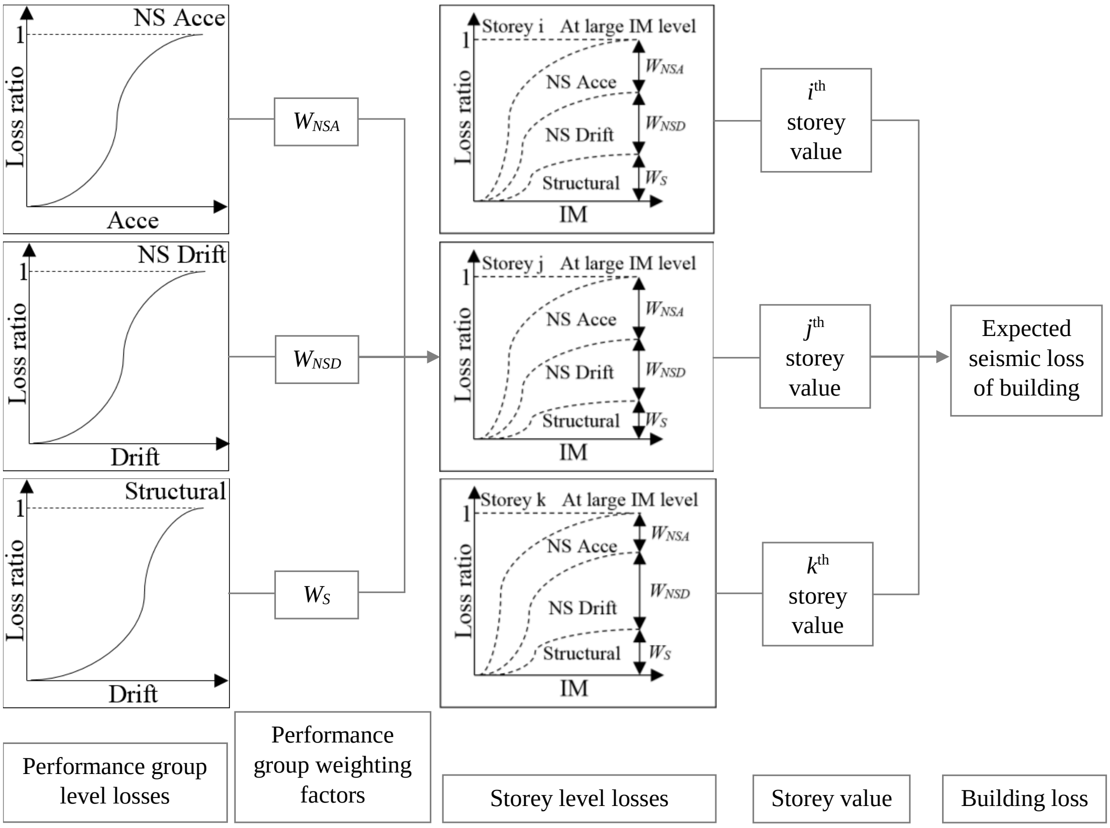


Fig. 3 – Computation of building level loss from performance group level [14]

In most seismic loss estimation frameworks, the three commonly used performance groups are: (i) structural components (e.g. beams, columns, structural walls, etc.); (ii) drift-sensitive non-structural components (e.g. partitions, claddings, glazing, etc.); and (iii) acceleration-sensitive non-structural components (e.g. ceilings, sprinklers, heating, ventilation and cooling systems). The proportion of performance group construction costs can vary greatly with the type of floor-usage. For example, a significant portion of the total construction cost in hospitals and laboratories come from acceleration-sensitive components due to the greater amount of services required. On the other hand, car parking buildings would likely be more dominated by structural-related costs as most contain few non-structural elements. To address such variations, weighting factors for each performance group (W_{NSA}, W_{NSD}, and W_S for non-structural accelerations, non-structural drifts, and structural performance groups, respectively, as shown in Fig. 3) can be provided for a range of different building types.

In this paper, weighting factors for the three performance groups are derived and proposed for a range of story-usage considering typical construction rates in New Zealand. While the values proposed will be specific to New Zealand construction practice, the adopted methodology could be applied elsewhere internationally. A case study demonstrating the application of these weighting factors in seismic loss estimation is provided.

2. Methodology

Derivation of the weighting factors were based on cost-breakdowns provided from the QV cost-builder cost handbook [17], which is one of the most commonly used source for estimating construction costs in New Zealand and lists costs associated with a wide range of building components and usage types. While performance group weighting factors could be derived for each individual building usage type, listing weighting factors for too many usage types could make the framework difficult to use, especially if the building has mixed-usage. Furthermore, some usage types may have a similar cost breakdown. Thus, it is better to define weighting factors which can be used over a wide range of usage-types. However, there will be cases where vastly different weighting factors are required. Therefore, there is a need to categorize the usage-types into as few groups as possible without oversimplifying. This was done by the following steps:

Step 1: Collect component cost breakdown for various building usage;

Step 2: Compute construction/installation costs of the three performance groups for each usage types;

Step 3: Normalize performance group costs by the structural performance group cost for each usage type;

Step 4: Group usage type based on similar non-structural performance group costs; and,

Step 5: Calculate mean values of the performance group weighting factors for each building usage group.

In step 2, drift-sensitive structural, drift-sensitive non-structural, and acceleration-sensitive non-structural performance group costs (C_S, C_{NSD}, and C_{NSA}, respectively) were computed by combining the individual component costs for each performance group. The main components which make up each performance group were:

- **Drift-sensitive structural**: frames, structural walls, upper floors (slabs), and stairs.
- **Drift-sensitive non-structural**: walls, windows, doors, partitions, and wall finishes.
- **Acceleration-sensitive non-structural**: roof, ceiling finishes, floor finishes, fittings and fixtures, plumbing, mechanical services, fire services, electrical services, and lifts.

Grouping of usage type is challenging if similarities in all three performance group costs had to be considered. Therefore, to simplify this approach, the non-structural performance group costs were normalized to the structural performance group's cost as shown in Eqs. (1)-(2), where N_{NSD} and N_{NSA} were the normalized drift-sensitive and acceleration-sensitive non-structural costs, respectively. This implicitly considerd the correlation between the structural and non-structural performance group costs.

$$N_{NSD} = C_{NSD} / C_S \tag{1}$$

$$N_{NSA} = C_{NSA} / C_S \tag{2}$$

After the usage types were grouped based on N_{NSD} and N_{NSA}, the drift-sensitive structural, drift-sensitive non-structural and acceleration-sensitive non-structural weighting factors for each building usage within a given group was calculated following Eqs. (3)-(5).

$$W_S = 1/(1 + N_{NSD} + N_{NSA}) \tag{3}$$

$$W_{NSD} = N_{NSD} / (1 + N_{NSD} + N_{NSA}) \tag{4}$$

$$W_{NSA} = N_{NSA} / (1 + N_{NSD} + N_{NSA}) \tag{5}$$

3. Derivation of building usage groups and performance group weighting factors

3.1 Performance group cost

Based on Steps 1-2 of the methodology, C_S, C_{NSD}, and C_{NSA} were computed for all usage-types listed in the QV costbuilder cost handbook [17]. It should be noted that there are some variations with each usage-type. For example, there are 6 variants of residential buildings considering different heights, type (i.e. townhouse, apartments, etc), and occupancy density. The maximum and minimum value of C_S, C_{NSD}, and C_{NSA} for each building usage type considering all variants are shown in Table 1. The number of variants for each building usage type is denoted in brackets after the usage-type description.

Table 1 – Percentage cost contribution of different performance groups

Building Usage (Number of sub-categories)	**Structural**		**NS Drift-sensitive**		**NS Acceleration-sensitive**	
	C_S (%)		**C_{NSD} (%)**		**C_{NSA} (%)**	
	Min	**Max**	**Min**	**Max**	**Min**	**Max**
Administration (12)	9.4	24.3	23.3	40.1	40.5	60.4
Ancillary Facilities (4)	4.5	9.1	31.2	37.4	58.1	61.5
Banks (3)	10.1	18.0	34.6	38.9	46.8	51.0
Devotional (3)	6.6	18.2	35.2	44.2	45.2	52.7
Educational (15)	8.1	22.9	24.4	42.1	47.9	66.0
Entertainment (3)	21.3	64.4	0.5	15.9	35.1	62.9
Hospitality (5)	8.8	27.6	24.7	31.8	44.8	66.4
Hospitals (4)	7.2	15.8	19.5	31.6	59.1	69.2
Industrial (6)	6.9	41.1	21.9	31.7	34.8	71.2
Apartments (2)	12.5	19.8	32.5	45.3	42.2	47.7
Offices (4)	21.0	28.0	19.1	31.7	41.7	56.4
Parking (4)	35.6	64.3	10.7	30.6	19.1	44.1
Sports Halls (2)	6.8	18.3	28.9	38.2	52.8	55.1
Research Labs (2)	8.4	13.7	19.3	26.9	64.7	67.0
Residential Houses (6)	6.0	11.1	35.3	50.6	41.8	57.6
Retail (4)	11.7	20.4	23.8	43.6	38.1	61.1

3.2 Grouping of building usage

Step 3 of the methodology was performed to normalize the non-structural performance group construction costs by those of the structural performance group. The result of this is shown in Fig. 4a. As discussed previously, each building usage type had multiple variants, and thus each point shown for each usage-type in Fig. 4a represents a different variant.

In order to categorize the building usage type in Step 4 of the methodology, the 16 building usage types were first categorized into 4 groups on the basis of normalized drift-sensitive (tile sign) and acceleration-sensitive (circle sign) non-structural performance costs (N_{NSD} and N_{NSA}) as shown in Fig. 4a. For the majority of the usage types, the normalized costs of the two non-structural performance groups ranged between 1 and 4 and were categorized in Group 1 (green color). Ancillary facilities, residential houses, and devotional buildings had dominant non-structural cost contribution (with their normalized costs ranging between 4 and 11) and were placed in Group 2 (blue color). In contrast, entertainment and parking buildings had dominant structural cost contribution (with the normalized non-structural costs around or less than 1) and were categorized into Group 3 (red color). Group 4 (brown color) was specially created for buildings which typically had building contents of very high values (such as hospitals, research labs, and retail).

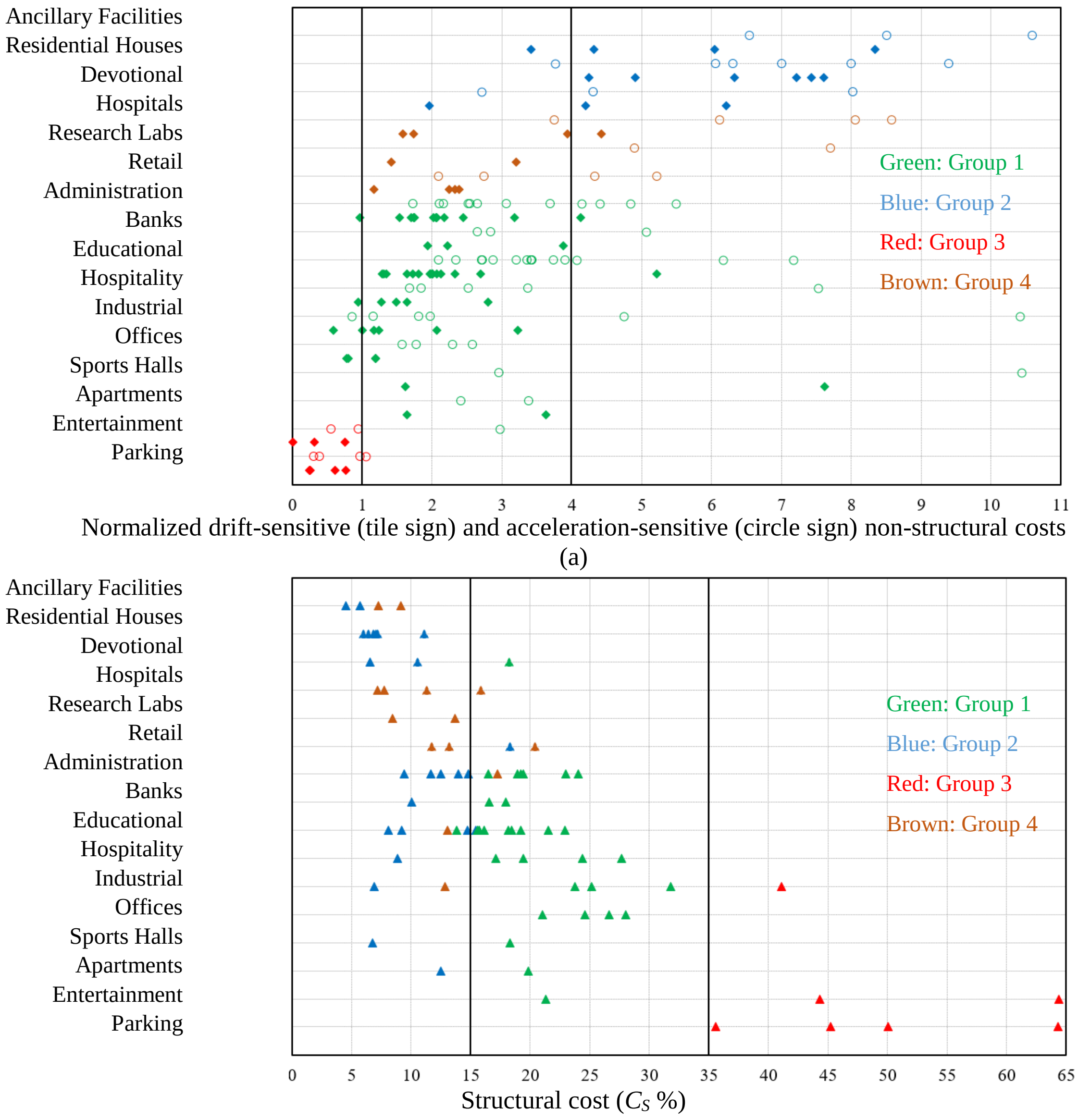


Fig. 4 – Building usage type grouping; (a) phase 1 based on normalized non-structural cost, and (b) phase 2 based on structural cost

After the initial grouping, a secondary criterion was adopted considering C_S (Fig. 4b) to fine-tune the building groupings to identify outlier variants from each usage type and shift them to different groups. Due to this reorganization, different colors were used within each usage type as shown in Fig. 4b. The bounds of

C_S considered here were (i) less than 15%, (ii) 15% to 35%, and (iii) 35% to 65%. Considering both this criterion, and the previous one considering the N_{NSD} and N_{NSA}, four distinct groups of specific building usage types were obtained and are presented in Table 2.

Table 2 – Building usage type grouping

Group	**Building Usage**
1.	Apartments (secondary dormitory, tertiary halls of residence & multiple units 50-100m^2), office buildings (administration & commercial), administration buildings (court, fire station, city library, tertiary educational administration & library), hospitality buildings (liquor outlets, hotels & motels), banks, educational classroom buildings (primary or middle, secondary, secondary art/photo suite, tertiary arts block & music school), industrial buildings (warehouse & fuel depot), recreational buildings (aquarium, sports hall & gymnasium) and high standard devotional buildings.
2.	Residential houses (single/two stories, large & 2/3 stories townhouse), devotional buildings, town hall, civic center, theatres (secondary auditorium & tertiary lecture theatre), clubhouse, workshops (secondary & industrial) and suburban or single story buildings (single story community center/library, suburban library, suburban police station, single story elderly persons home, single story day care center, single story city bar, single story secondary administration, suburban bank & suburban neighborhood shop).
3.	Outdoor entertainment structures (e.g. spectator stand open & roofed), parking buildings (ground level beneath offices, basement, ground plus two levels & multistory) and long span warehouse.
4.	Hospitals (single/multi-story general/private, mental health unit & group surgery), research labs (tertiary science lab, single story research center & 3-5 stories lab), city art gallery/museum, cold store and retail (supermarket, shopping center & department store).

3.3 Derivation of weighting factors

For the four usage type groups, the mean values of the performance group weighting factors were calculated by Eqs. (3-5) and are listed in Table 3.

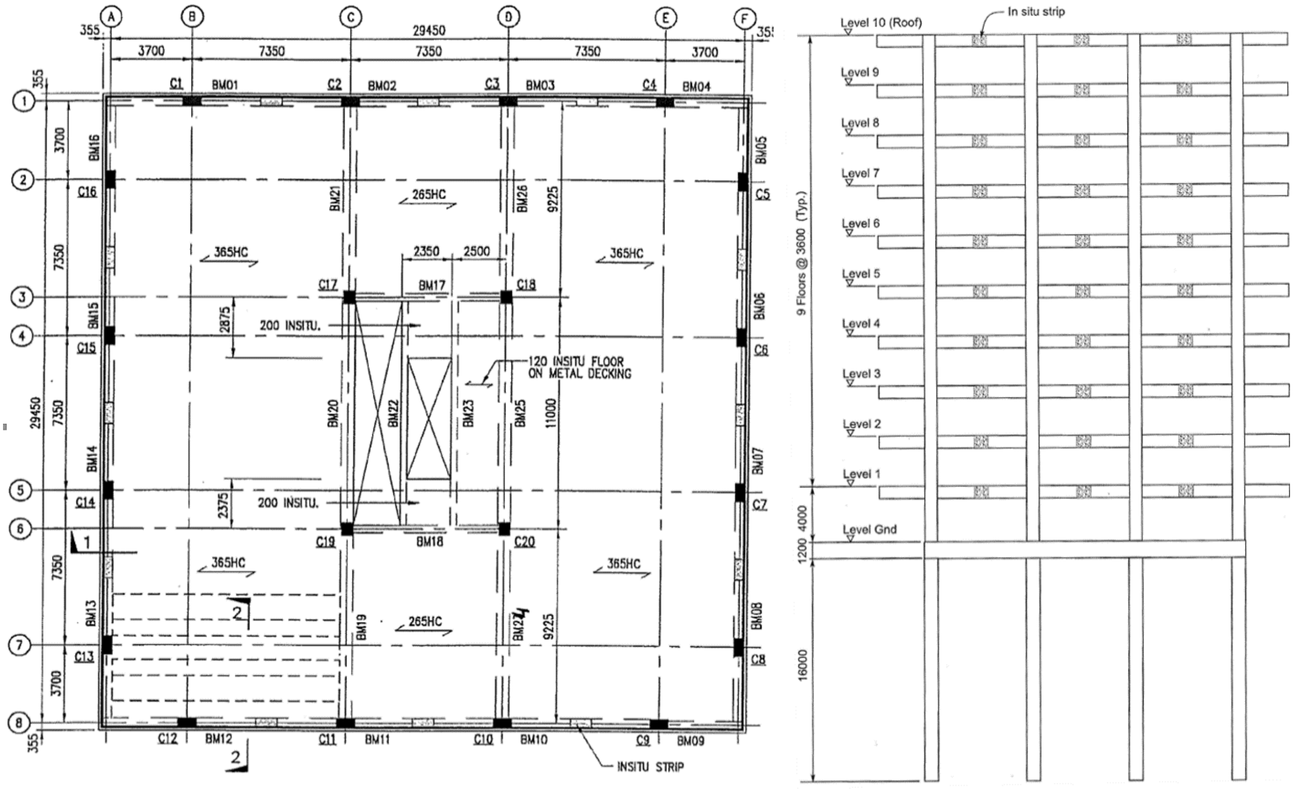
Table 3 – Proposed performance group weighting factors

Group	**Structural, W_S**	**NS Drift-sensitive, W_{NSD}**	**NS Acceleration-sensitive, W_{NSA}**
1.	0.21	0.30	0.49
2.	0.10	0.37	0.53
3.	0.49	0.18	0.33
4.	0.12	0.27	0.61

4. Application of the Proposed Weighting Factors

As illustrated in Fig. 3, the weighting factors obtained from Table 3 can be applied together with the performance group contribution functions to estimate the story-level losses. However, development of contribution functions was still a work in progress, with component-level contribution functions being available for only a few components at the time of writing [13, 15, 16], and thus performance group level losses were not readily available. Instead, an existing case-study was examined.

The case study building considered was the 10-storey Red Book Building [18] for which Bradley et al. [6] performed rigorous seismic loss estimation. This building (shown in Fig. 5) is a fictitious reinforced concrete (RC) frame office building used as a design example following the 1995 version of the New Zealand concrete structures standard [19].



(a) (b)

Fig. 5 – Red Book Building; (a) plan and (b) elevation [18]

Based on the building component quantity, fragility functions and loss functions adopted by Bradley et al. [6], the performance-group-level contribution functions was derived following the approach illustrated in Fig. 6. Firstly, Monte Carlo simulations was performed to calculate the expected loss per unit floor area for each building component category considering the component's fragility and loss functions, and then normalizing it by the performance group construction cost per floor area to obtain the component-level contribution functions. This was then added together with other component-level contribution functions from the same performance group of interest (i.e. glazing, partitions, and general drift-sensitive components are all part of non-structural drift-sensitive components) to obtain the performance-group-level contribution functions. The derived performance-group-level contribution functions are shown in Fig. 7. It should be emphasized here that these performance-group contribution functions are specific to this case study and are only considered for demonstrating the application of weighting factors, and should not be treated as "generic" contribution functions for other usage.

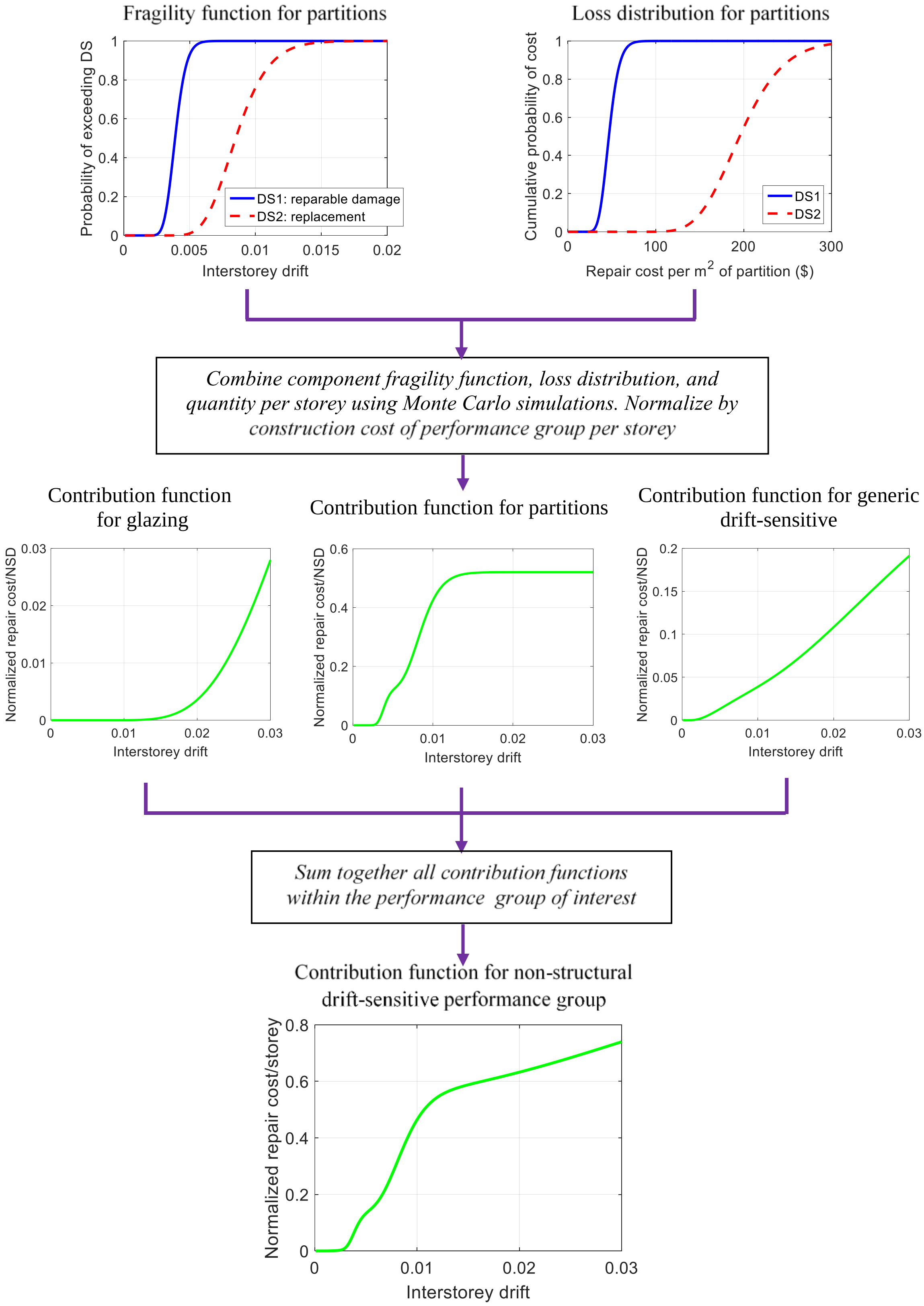
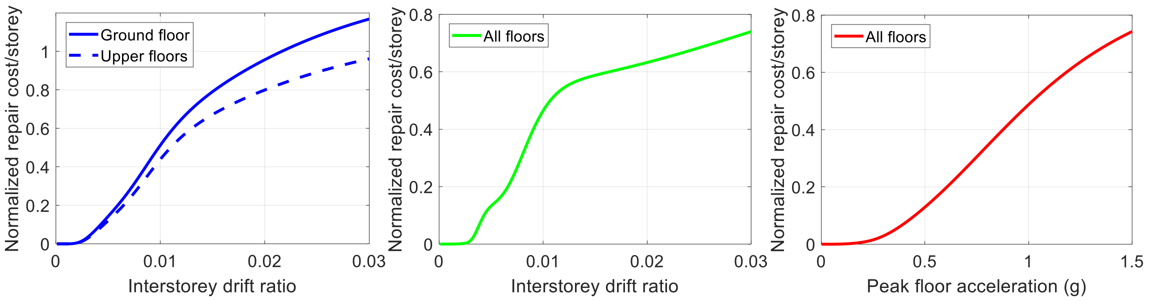


Fig. 6 – Approach to derive performance group contribution functions for the case study building



(a) (b) (c)

Fig. 7 – Adopted performance group contribution functions; (a) structural, (b) non-structural drift-sensitive, and (c) non-structural acceleration-sensitive

As seen in Fig. 7, the maximum non-structural drift-sensitive loss was well below 1 at 3% drift. This was because glazing and generic drift-sensitive components fragility functions adopted had a high drift capacity, resulting in these not being significantly damaged at 3% drift. Bradley et al. [6] conducted response history analyses on the structural model of the building and reported the maximum response profiles at 2500-year return period in terms of maximum inter-story drift and peak floor acceleration as shown in Table 4, which are adopted herein for rapid loss estimation.

Table 4 – Engineering demand parameters for Red Book Building at 2500-year return period [6]

Floor	1	2	3	4	5	6	7	8	9	10
***IDR* (%)**	1.30	2.46	2.50	2.56	2.43	2.26	1.37	0.57	0.43	0.22
***PFA* (g)**	0.76	1.12	0.86	0.76	0.68	0.64	0.61	0.48	0.45	0.47

The normalized repair cost (i.e. ratio of repair cost to the replacement cost) for each performance group within a given story was obtained from the corresponding performance group contribution function (Fig. 7) for the value of the engineering demand parameter (maximum inter-story drift or peak floor acceleration) of that story. Drift-sensitive and acceleration-sensitive losses were estimated for each story of the building as a product of the corresponding performance group weighting factor (from Group 1 for office buildings), the normalized performance group repair cost (Fig. 7), and the total value of the story (NZ$ 0.833M). These performance group losses are compared in Table 5 with the corresponding losses obtained by Bradley et al. [6] using detailed component-based loss estimation.

Table 5 – Comparison between detailed and rapid seismic loss estimation methods for Red Book Building

Seismic loss	**Drift-sensitive (M)**		**Acceleration-sensitive Non-structural (M)**	**Total**
	Structural	**Nonstructural**		
Detailed loss estimation from Bradley et al. [6]	1.05	1.18	0.92	3.15
Rapid loss estimation using the proposed weighting factors	1.05	1.19	1.05	3.30
Difference	0%	2%	14%	5%

Since content costs were not considered in deriving the proposed weighting factors, content losses originally included in the detailed loss estimation conducted by Bradley et al. [6] are excluded for more meaningful comparison. Note that the weighting factors and the rapid loss estimation include contributions of glazing and sprinklers, which are also included in the calculation but not explicitly shown in Bradley et al. [6] because of their trivial (less than 1%) contributions to the total loss. As can be seen in Table 5, the percentage differences between the losses predicted by the rapid method using the weighting factors and the detailed method calculating and assembling component losses were within acceptable limits; both for the total building loss as well as individual performance group losses.

5. Conclusions

This study focused on (i) grouping of building types that have a similar proportion of structural, drift-sensitive non-structural and acceleration-sensitive non-structural component costs, and (ii) development of structural/non-structural performance group weighting factors for various building usage groups. Four different building usage groups were identified based on similar ratios of non-structural performance group costs to the structural performance group cost. Mean values of the performance group weighting factors (W_S, W_{NSD}, and W_{NSA}) were proposed for each building usage group. The building usage types included in each group as well as the relative costs of structural, drift-sensitive non-structural, and acceleration-sensitive non-structural costs (which are also their corresponding weighting factors) are shown in Fig. 8.

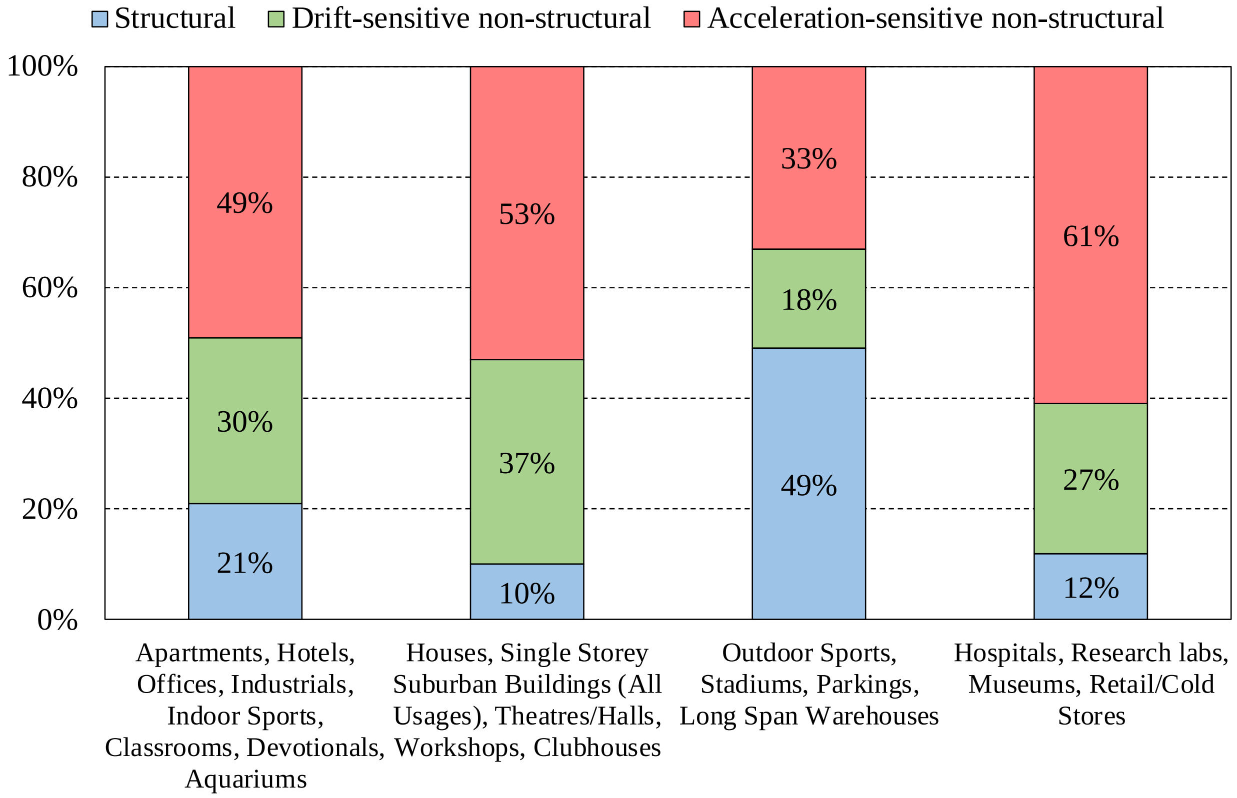


Fig. 8 – Relative costs of performance group for the four building usage groups

The applicability of weighting factors in rapid loss estimation was evaluated by applying the approach to a 10-storey case study building. The losses predicted for a case study building by the rapid method using the proposed weighting factors and the detailed seismic loss estimation approach were almost identical, demonstrating the reasonable accuracy of the proposed approach.

6. Acknowledgements

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