DISPLACEMENT-BASED FRAGILITY FUNCTIONS FOR NEW-ZEALAND BUILDINGS SUBJECT TO GROUND MOTION HAZARD

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Abstract

Building fragility functions provide a probabilistic representation of a building damage potential due to a hazard of a varying intensity. A simplified probabilistic displacement-based framework is adopted to develop fragility functions for NZ building inventory subject to ground motion hazard. To account for the diversity of building characteristics within a given building class, a Monte-Carlo procedure is adopted to simulate geometrical and material property variables of buildings. The adopted displacement-based approach uses mechanically derived formulae to describe displacement capacities of classes of buildings for four different damage states. A practical and simplified approach is suggested to consider the uncertainty associated with spectral displacement demands. The probability of damage state failure is then determined by comparing the spectral displacement demand with spectral displacement capacity computed from building characteristics.

Keywords: Building fragility functions; displacement-based method; damage states; uncertainty; probabilistic approach; earthquake risk assessment.

1. Introduction

New Zealand is exposed to different levels of risk from multiple natural hazards such as earthquakes, volcanoes, landslides, floods, storms and tsunamis. A multi-hazard loss modelling tool for New Zealand, "Riskscape" is being developed and is intended to be used across a region by emergency, asset, and environmental managers to support planning and investment decision-making prior to a natural disaster and to provide timely estimates of the consequences and disruption to the community following a natural disaster.

An integral component of any regional loss modelling tool is to develop a suitable building classification scheme so that buildings with similar behavioural characteristics can be grouped into classes and the differential performance and associated losses to each particular class can be ascertained. The objective of the paper is two fold: (i) to discuss the building classification scheme developed for NZ building inventory; and (ii) to describe the methodology adopted for deriving fragility functions that is capable of considering the inherent variability of building characteristics and the uncertainty in ground motions within the region of interest.

2. Building Inventory

One of the biggest challenges in deriving the physical vulnerability model is to acquire an appropriate database of building inventory. As a part of the Riskscape project, pilot studies were conducted on three regions (Christchurch, Hawke's Bay and Westport) to capture an estimation of the common building types within New Zealand. The three regions were chosen as representatives of distinctly different categories, viz. large city (about 300,000 buildings), small city/rural (30,000 buildings) and town (2000 buildings).

The rule by which each inventory item is assigned to a fragility class is based on measured or assessed attributes for those items. It is important to appreciate the implications of code recommendations on existing building stock to underline the inherent building characteristics with respect to the building system and the vintage of the code. Buildings constructed in the decades between 1935 and the early 1970s exhibit a complex distribution of structural characteristics. Reinforced concrete buildings were generally low-rise with regular and substantial wall elements between 1940 and 1950. Many of these structures would be capable of near elastic response, with local detailing exceptions. However, reinforced concrete buildings built between 1960s and early 1970s were generally taller, less generously proportioned, with less redundancy and greater irregularity often evident in frame structures.

Ductility is the essential ability of the structure to deform inelastically without brittle failure. Buildings constructed prior to the 1976 code lack ductile detailing. The 1976 and 1984 codes included a ‘structural form factor’ to reflect ductile performance, but relevant material codes were not ready with guidelines for detailing to achieve ductility in the structure. However, ductile detailing for the structure was provided based on judgement. Material codes from 1992 provide guidelines for ductile detailing. So, it can be considered that the structures built before 1976 are with limited ductility of maximum 3 and the post 1976 buildings are expected to show higher ductility levels up to 6 [1]. However, it is worth noting that the recommended seismic design level for short period structures have increased appreciably after the 1976 code.

2.1 Building classification

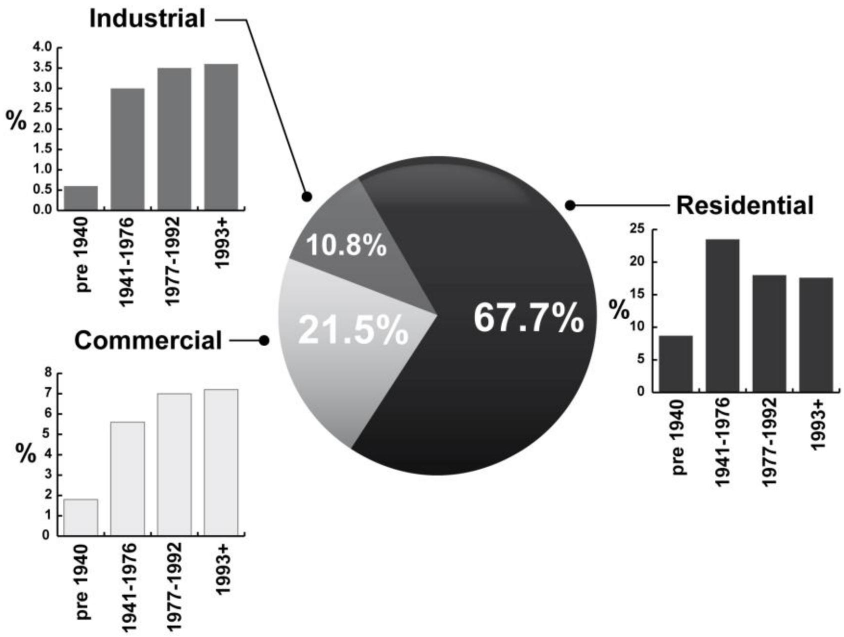

Figure 1 New Zealand building inventory, percentages by value

Based on use and occupancy the building inventory can be divided into three main categories, namely residential, commercial and industrial in relative proportion of 67.7%, 21.5% and 10.8% respectively as shown in Figure 1. The percentage of buildings in each year band for each category is also shown. Residential buildings are mostly low-rise timber buildings, accommodating single-families, and apartment buildings with multiple-families. Commercial buildings used as offices, public services, and hospitals range from low to high-rise buildings constructed from timber, reinforced concrete and steel. The structural forms can be moment resisting frame in one direction and shear wall in the other direction or with core shear walls taking lateral loads and gravity frames on the exterior. Most of the buildings are constructed with shear walls. Industrial buildings featuring factories and warehouses are typically low-rise with steel moment resisting or portal-frame structural forms in one direction and cross bracing in the other direction. There are a number of buildings with precast walls using Tilt-up construction. Further details can be obtained from elsewhere [2].

Table 1: Building classification

Material	Structural form
Wood	Light Timber buildings (LR)
Masonry	Un-reinforced masonry (LR)
Reinforced concrete	Block masonry (LR)
	Moment resisting frame (LR, MR, HR)
	Shear wall (LR,MR,HR)
Steel	Moment resisting frame (LR, MR, HR)
	Portal frame – braced (LR)
	Braced frame (LR, MR, HR)
Precast	Tilt-up (LR)
Advanced-design	Base-isolation, energy dissipating devices (LR,MR, HR)

For the purpose of developing fragility functions, various building classes have been formulated according to their structural form, height and material of construction as listed in Table 1. Buildings of various heights are grouped into 3 major groups: (a) low-rise (LR) having up to 3 storeys; (b) medium-rise (MR) having between 4 to 7 storeys; and (c) high-rise (HR) having between 8 or more storeys.

3. Fragility Functions

Fragility functions are used to express probabilities of exceeding different damage levels for various levels of hazard. Methods of creating fragility functions from various kinds of data are discussed by Porter [3]. The probability of damage to components can be related to force, deformation and acceleration responses which collectively are called engineering demand parameters (EDP). When buildings experience inelastic response, larger damage occurs due to increasing displacements with strength reduction for degrading systems. In general, the displacement experienced by the building is the best indicator of damage except for structures with brittle-type failure and for acceleration sensitive elements. Therefore, it is important to estimate displacement with reasonable accuracy to correlate with the expected damage level. Depending on the extent of damage, the damage states are qualitatively described as slight, moderate, severe and extensive. Large amount of damage data (either from post-earthquake damage surveys or from experimental research studies) and sound engineering judgements are essential elements in describing the relationships between such qualitative damage measures and the quantifiable structural EDPs. A few methods for deriving fragility functions that are adopted in loss assessment tools are discussed below:

(i) Empirical statistical methods provide best estimation of fragility curves, when sufficient and reliable post-earthquake damage data are available. In this context, the modified Mercalli intensity (MMI) approach has been extensively used. In the MMI method, intensity is directly related to damage. The determination of intensity of shaking and relating to the observed damage in a building is based on expert opinion and engineering judgement only. The observed damage in old buildings during past events is also unlikely to be directly applicable to the damage potential of new buildings with new construction practices.

(ii) HAZUS99 [4] adopts engineering judgement to estimate the seismic displacement capacity of structures through a set of parametric values. Fragility functions are developed based on the capacity spectrum method using the estimated seismic capacity curve which could only best suit USA buildings. This approach involves an iterative procedure to obtain a 'performance point' as the intersecting point of capacity and demand curves, which provides reasonable estimates of the spectral displacement of a building corresponding to a damage state.

(iii) The displacement-based method approach uses mechanically derived formulae (or equations) to describe displacement capacities of classes of buildings, and so in principle, can be regarded as a better approach than HAZUS where the displacement capacities are estimated with engineering judgement. Maximum displacements that the structure can undergo at various threshold damage limit states are determined using geometrical and material properties of the structure. The displacement limits are converted to roof drifts of equivalent single degree of freedom models of the structure (i.e. spectral displacements). Fragility functions are expressed as cumulative lognormal distribution functions using median spectral displacement values at the thresholds of damage states and dispersion associated with demand spectrum, capacity of the structure and uncertainty associated with the median spectral displacement at every threshold state. In this study, the capacities of different structural systems are estimated using the procedure developed by Priestley et al. [5].

4. Proposed Displacement-based Methodology

In the proposed methodology, buildings are represented as equivalent single degree of freedom (SDOF) oscillators. Limit states for various levels of damage are defined in terms of the spectral displacement capacities, Sd(capacity) of SDOF systems. Once the building deforms and enters into the damage states domain, the equivalent (secant) period of the SDOF system is assessed and used to obtain the spectral displacement demand from the ground motion displacement spectrum, i.e. Sd(demand). For a given damage limit state, if the demand exceeds the capacity corresponding to that damage state, the building is considered to be in that damage state. The steps involved are: (i) simulation of building's initial parameters from geometrical and material properties; (ii) determination of displacement capacity at various damage limit states; (iii) determination of effective period at a given damage limit state; (iv) prediction of spectral displacement demand at the effective period; and (v) verification for failure criteria. Note that at every step, the variability and uncertainty components are addressed.

4.1 Simulation of Building Characteristics

In each building group, as listed in Table 1, the properties (geometrical and material) of each individual building are unlikely to be the same. Hence, it is appropriate to define a 'typical' building which can represent the building group. The building characteristics are identified in terms of structural parameter variables that affect the displacement capacity and initial period of a building; for example, number of storeys (N_s), storey height (S_h), beam length (L_b) and yield strength and strain of steel (f_y ,ε_y). The ranges of values for each variable that can vary within a building group are assigned based on engineering judgement. A typical set of values assigned for concrete moment resisting frame (Post 1980) is given in Table 2 [6]. The notations used to identify the variables are also given and are referred in following sections. The 'effective height coefficient' is the ratio of the height of the effective mass of the single degree of freedom model to the total height of the actual building. U[ ] refers to uniform distribution and N[ ] refers to normal distribution.

Table 2: Structural parameters for concrete moment resisting frame (CMRF) structures

Structural Parameters	Low-rise	Medium-rise	High-rise
Number of storeys, N_s	U [1,3]	U [4,7]	U [8,16]
Storey height (m), S_h	U [3.4, 3.8]	U [3.4, 3.8]	U [3.4, 3.8]
Beam length (m), l_b	U [4.0, 6.0]	U [5.0, 7.0]	U [6.0, 8.0]
Beam depth (m), h_b	U [0.45, 0.65]	U [0.5, 0.7]	U [0.65, 0.85]
Steel strength (MPa), f_y	N [325,35]	N [325,35]	N [325,35]
Concrete strength (MPa)	35	35	35
Effective height coeff, *efh*	0.64	0.64-0.0125*(Ns-4)	0.64-0.0125*(Ns-4)
Maximum Ductility , μ	4~6	4~5	3~4

Given a building group, a Monte-Carlo procedure is adopted to simulate the geometrical and material property variables of every possible building within that group. A uniform distribution is assumed for each uniform variable and a random number between 0 and 1 is generated during every simulation step to determine the building characteristics. From each simulation two initial parameters such as yield displacement (D_y) and initial period (T_y) are obtained using the geometrical and material properties of the simulated building. From the simulations of Dy and Ty, median and variance of Dy and Ty (i.e. $median\_D_y$, $median\_T_y$ and β_D_y , β_T_y as noted in the following sections) are calculated to represent the characteristics of the building group.

4.1.1 Estimation of Initial Parameters for Period and Displacement

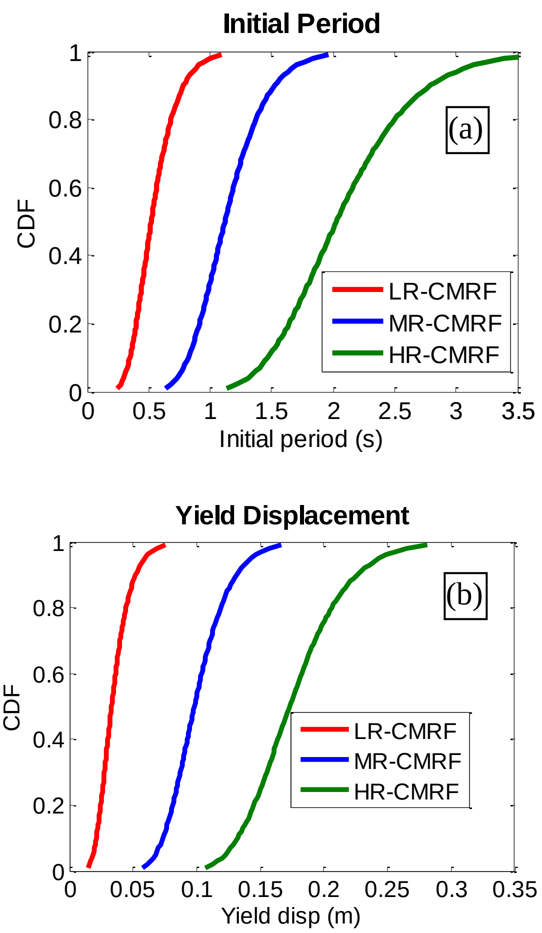

Figure 2 Cumulative distribution functions (CDF) for initial parameters for CMRF structures

First, the initial period is computed based on the recommendations from NZS1170.5 commentary code [7]. The building periods based on code recommendations are usually conservative for estimating design base shear and less than the 'actual' value. The median initial period is estimated on the higher side, considering a reasonable amount of variation from the initial period recommended for design purposes.

The displacement capacity at yield is computed at the effective height level of the structural system using established empirical relationships. In this study, expressions proposed by Priestley et al. [5] are used for appropriate building groups. For example, the yield displacement for concrete moment resisting frame is computed using (1);

$$D_y = 0.5 \quad efh.N_s.S_h \;\; \varepsilon_y l_b / h_b \tag{1}$$

in which the range of values used for randomly generating the variables are listed in Table 2. The distribution of yield displacement and initial period for low, medium and high rise concrete moment resisting frames are shown in Figure 2.

4.2 Damage Limit States

Five damage limit states are described for every building class: (i) None DS(0); (ii) Slight DS(1); (iii) Moderate DS(2); (iv) Extensive DS(3) and (v) Complete DS(4). The description damage states differ depending on the structural system under consideration. The descriptions are qualitative and can be interpreted in similar lines to those referred in HAZUS technical manual. For damage state DS(0) there is no damage. Damage state DS(1) is usually associated with the yield displacement limit. However, considering the importance of the serviceability limit state, it is important to verify the displacement limits corresponding to the damage of non-structural components including infill panels, doors and windows. The non-structural displacement is related to 0.5% drift.

4.3 Spectral displacement Capacity at Damage States

The median displacement capacity for a damage limit state (*Lsi*) is related to median ductility level at the chosen damage state ($median\_\mu_{Lsi}$) and median yield displacement (2).

$$median\_D_{Lsi} = median\_\mu_{Lsi} * median\_D_y \tag{2}$$

Note that the median and dispersion limits for the various ductility levels are based on engineering judgement. Assuming that ductility, μ and yield displacement, D_y are lognormally distributed and independent, the dispersion in the displacement capacity is computed as the square root of the sum of squares of dispersions of yield displacement and ductility (3).

$$\beta\_D_{Lsi} = \sqrt{\beta\_\mu_{Lsi}{}^2 + \beta\_D_y{}^2} \tag{3}$$

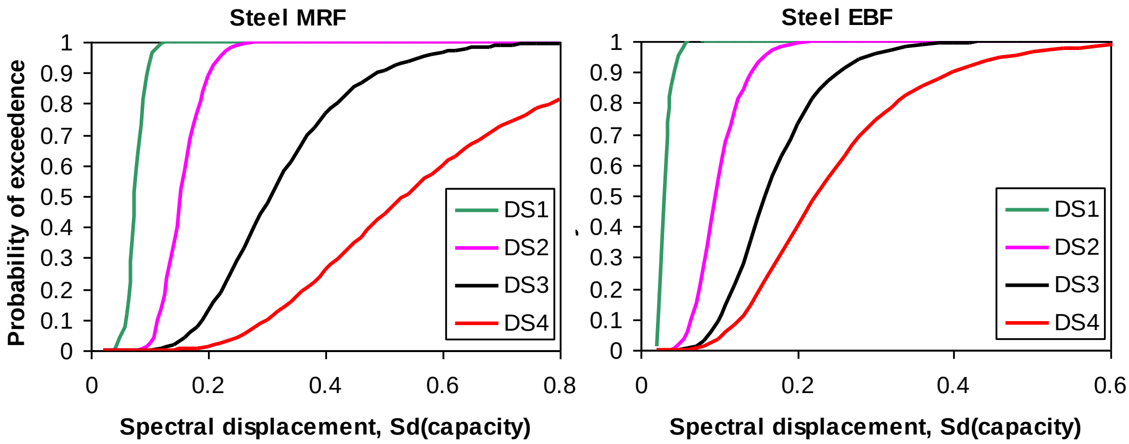

Figure 3: Capacity fragility functions for moment resisting frames and eccentrically braced frames of steel structures

For illustrative purposes, the displacement capacity fragility functions generated for steel buildings with two types of structural system are shown in Figure 3.

4.4 Effective Period of Building at Damage States

The median and dispersion in effective (secant) period (T_{Lsi}) at various damage states is expressed as in (4) and (5).

$$median\_T_{Lsi} = \sqrt{median\_\mu_{Lsi}} * median\_T_y \tag{4}$$

$$\beta\_T_{Lsi} = \sqrt{0.25\ \beta\_\mu_{Lsi}{}^2 + \beta\_T_y{}^2} \tag{5}$$

4.5 Seismic Displacement Demand

Given the location, soil type, source to site distance and other earthquake related parameters including magnitude and fault properties, attenuation models can be used to estimate the seismic demand related to a given site period. Note that in the simplified formulation used it is assumed that the uncertainty in the capacity and demand arising from the uncertainty in initial period, T_y, are uncorrelated. While this is strictly not correct it allows an uncoupling of the capacity and demand relationships, which is desirable from both a practical and computational point of view, and is consistent with other simplifying assumptions made in the methodology.

For a given damage state, the site period is assumed to be equal to the building effective period to simulate the maximum impact. Attenuation models [8] provide median and dispersion of spectral acceleration, S_a, corresponding to the site period. The spectral displacement demand is obtained using spectra reduction factor, ψ_{eff} which could be derived from damping reduction factor and equivalent damping ration for the building system under consideration [4]. The spectral displacement demand is given as (6):

$$S_{d\ demand} = \psi_{eff}\, S_a\, g / \left(2\pi / T_{Lsi}\right)^2 \tag{6}$$

Note that in (6) $S_{d\ demand}$ is conditional on period; to make it unconditional, a linear variation approximation of spectral displacement with period is assumed. The central difference method is used to estimate the gradient of variation. The median $S_{d\ demand}$ is directly obtained from the median spectral acceleration using (6) at a given period, T_{Lsi}. The dispersions of $S_{d\ demand}$ unconditioned on period T_{Lsi} is given by combining two parameters: (i) the dispersion of $S_{d\ demand}$, which is conditioned on period, is same as the dispersion of S_a; and (ii) the dispersion of the period, T_{Lsi}, accounting for the gradient as given in (7):

$$\beta\_S_{d\ demand} = \sqrt{\beta\_S_{d\ T} + \left[\frac{\partial\ S_{d\ T}}{\partial\ T}\right]^2 * \beta\_T_{Lsi}^2} \tag{7}$$

5. Probability of failure

The probability of being in a damage state is determined by comparing the spectral displacement demand with spectral displacement capacity as given in (8) and (9) (where, as noted previously the demand and capacity are independent because the dependence between T_y is neglected) .

$$Z = \left(\frac{ln\ median\_D_{Lsi} / median\_S_{d\ demand}}{\sqrt{\beta\_D_{Lsi}^{\ 2} + \beta\_S_{d\ demand}^{\ 2}}} \right) \tag{8}$$

Using standard normal cumulative distribution function, the cumulative probability of being in a given damage state can be computed as in (9):

$$P_f = \Phi\ -z \tag{9}$$

From a cumulative probability of failure function, the probability of failure for a lower damage state DS(2), (say Pf(2)) will be higher than probability of failure for a higher damage state DS(3) (say Pf(3)). The probability of being in a particular damage state, say DS(1) to DS(4) is given in (10),

$$\begin{aligned} P\ DS\ 4\ &= P_f\ 4 \\ P\ DS\ 3\ &= P_f\ 3 - P_f\ 4 \\ P\ DS\ 2\ &= P_f\ 2 - P_f\ 3 \\ P\ DS\ 1\ &= P_f\ 1 - P_f\ 2 \end{aligned} \tag{10}$$

5.1 Illustrative Example

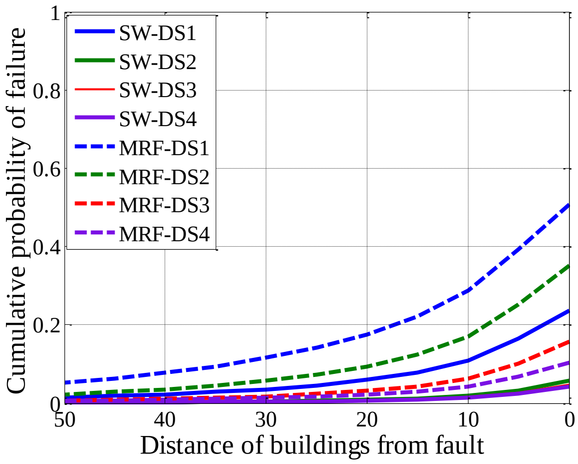

Figure 4: Performance of concrete shearwall and moment resisting frame structures

For illustrative purpose, the proposed methodology is used to obtain the probabilities of four damage state failures for two predominant building types in New Zealand, viz. concrete shear wall and moment resisting frames as shown in Figure 4. The results are generated for magnitude 7, strike-slip faulting and for site class C with typical shear wave velocity of 400 m/s. It is clear from the Figure 4 that the probabilities of failure of moment resisting frame structures are higher than those of shear wall structures; this feature is observed for all the site distances and for all damage states. Further details on the other building classes with regard to their capacities are available elsewhere [6].

6. Summary

A simplified probabilistic displacement-based framework is proposed to derive fragility functions for buildings in a regional portfolio. A building classification scheme is developed based on building material, structural system and their height. The variability in structural and material parameters of buildings is considered within the framework. A practical approach is suggested to deal with uncertainties, particularly with ground motion demands. Thus in a regional loss model, for a given building group spread over a region, the probabilities of being in various damage states can be estimated.

At this stage, the displacement capacities at various limit states are based on engineering judgement. The framework can adopt improved quantitative measures as and when they become available. In this paper, the procedure has been illustrated for a scenario event. It should be noted that the framework is flexible to be integrated within a probabilistic loss assessment tool.

7. Acknowledgements

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