A Review on
Earthquake Building Damage Functions

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Increasing Urban Resilience to Large Scale Disasters: The Development of a Dynamic Integrated Model for Disaster Management and Socio-Economic Analysis (DIM2SEA)

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Summary

This paper presents a primer for building damage function. It is written on behalf of the project DIM2SEA (Dynamic Integrated Model for Disaster Management and Socio-Economic Analysis). The first section sows a brief history of building damage models. Section two explains the points that should be considered to classify buildings based on their use, structural system, and level of performance. The building damage states are presented in section three. In section four the definition of fragility curves is discussed.

1. Introduction

Over time, urban regions have increase enormously and thus the risk against natural hazards, such as earthquakes, has increased. The main factor is that frequency of occurrence of earthquakes in urban areas is expected to increase in time. Therefore seismic risk analysis is playing an important role in the society. Risk analysis involves the evaluation of the hazard and vulnerability; however, for risk reduction it is important to monitor the vulnerability of the elements at risk, such as buildings. Building damage model studies were developed for regional loss estimation and building-specific loss estimation. Here, we will focus on building damage models for regional loss estimation being that our main target is evaluate urban resilience. In the early stage, the building damage estimation was a function of an intensity scale because of the lack of strong-motion instruments (**?**). **?** provided one of the first estimation of earthquake loss ratios for different types of buildings. **?** presented a summary of the earthquake loss estimation researches performed by insurance companies. **?** performed regional study of the San Francisco Bay Area and produced an estimated loss result from a major earthquake. One of the first researches on earthquake loss estimation from a probabilistic perspective was performed by **?**. Their study focused in dwellings located in the San Francisco Bay Area, U.S., which was classified in 24 classes. Considering the Modified Mercalli Intensities (MMI), a Matrix of 24x12 was produced. Each element of the matrix contains a damage ratio and a damage factor, which are the cost of repair as a percentage of replacement cost and the percentage of building that experienced this damaged ratio, respectively. **?** introduced the concept of damage probability matrix (DPM) and applied to buildings with stories greater than 5. Table 1 shows the format proposed, where a probability of damage is defined for each damage state under a specific intensity. The probabilities of damage for a specific intensity must sum to one (100%). Later, the Applied Technology Council (ATC) presented detailed information of DPMs for 78 classes of structures (**?**). Since the number of studies related to earthquake loss estimation increased considerably (**??**), a need for standardize a procedure emerged. **?** pointed out that the common methods for assessing physical vulnerability, vulnerability matrices, vulnerability curves (or fragility curves) and vulnerability indicators, are use in a conflicting way rather than in combination. Therefore, the HAZUS method for loss estimation was presented (**??**). One of the main modifications was to replace the MMI, a qualitative measure, to elastic spectral response, a quantitative measure.

2. Building classification

Buildings can be classified according to their use, type of material and structural system. The classifications based on the material and structural systems are important for building damage estimation. On the other hand, classification based on their use is important for economic loss estimation. Usually it is difficult to gather information related to the structural system and the material of existing buildings. There are several reasons,

Table 1: Format of damage probability matrix proposed by Whitman et al. (1973)

Damage state	Structural damage	Non-structural damage	Damage ratio (%)	Intensity of earthquake V	VI	VII	VIII	IX
0	None	None	0-0.05	x	x	x	x	x
1	None	Minor	0.05-0.3	x	x	x	x	x
2	None	Localized	0.3-1.25	x	x	x	x	x
3	Not noticiable	Widespread	1.25-3.5	x	x	x	x	x
4	Minor	Substantial	3.5-7.5	x	x	x	x	x
5	Substantial	Extensive	7.5-20	x	x	x	x	x
6	Major	Nearly total	20-65	x	x	x	x	x
7	Building condemned		100	x	x	x	x	x
8	Collapsed		100	x	x	x	x	x

Table 2: Summary of building damage in Nada Ward due to the Kobe earthquake (Yamazaki and Murao, 2000)

Type of buildings		Heavy	Moderate	No/slight	Total
Wood-frame (W)	-1951	5,032	1,636	1,138	7,806
	1952-61	2,897	936	992	4,825
	1962-71	2,588	928	1,126	4,642
	1972-81	1,006	764	1,128	2,988
	1982-94	384	542	1,523	2,449
	Subtotal	11,907	4,806	5,997	22,710
Reinforced concrete (RC)		354	532	2,928	3,814
Steel (S)		532	462	1,179	2,173
Light Gauge Steel (LS)		272	164	865	1,301
Others		133	89	324	546
Total		13,198	6,053	11,293	30,544

such as the fact that the finishing construction covers the structural system and makes it difficult to recognize it by visual inspection. In developed countries extensive information can be found in most cases, while in developing countries the lack of information is usual. For those cases where there is no data-base or is not updated, a field survey is necessary. Thus, considering the required time, a common practice is to choose a representative building for a specific area, such as urban block. The availability building inventory data not only play an important role in the estimation of building damage during earthquakes, it also allows quantifying the buildings that have damage after real earthquakes. Inventory of buildings damage are crucial to produce empirical fragility curves. For instance, Table 2 shows the association of building damage with building inventory, where specific level of damage is associated with a structural material and in the case of wood-frame to a specific construction period.

3. Building damage states

Damage state is a key issue because it is necessary to define it under a standard criterion in order to share and compare damage building data between the research communities. Thus, a proper definition of damage states must be established in order to reduce the errors from subjective judgments of the evaluator when a field survey of damaged buildings is carried out. Several institutions have spent efforts on defining damages states and proposing guidelines for post-earthquakes investigations (**??**). However, despite the effort to unify the damage states, there is not a unique classification of damage. Here the most common classification schemes are introduced. The European Macroseismic Scale 1998 (**?**) define six level of damage for masonry and reinforced concrete buildings, as shown in Table 3. EM-98 provides some details that an evaluator must consider when a classification of damage state is

Table 3: Classification of damage according to EMS-98

Damage level	Description
Grade 0	No damage
Grade 1	Negligible to slight damage (no structural damage, slight non-structural damage)
Grade 2	Moderate damage (slight structural damage, moderate non-structural damage)
Grade 3	Substantial to heavy damage (moderate structural damage, heavy non-structural damage)
Grade 4	Very heavy damage (heavy structural damage, very heavy non-structural damage)
Grade 5	Destruction (very heavy structural damage)

intended. For instance, Grade 2 for reinforced concrete building shows cracks in columns and beams of frames and in structural wall. The Japanese government adopted four level of damage (**?**): No damage, moderate damage, heavy damage and major damage.

One obstacle to unify damage states is the limitation of information from different source. For instance, remote sensing technology has been used widely to detect building damage (**???**). However, remote sensing provide information of the surface only (i.e., roof and some side of the buildings) and cannot have a close look on structural damage. Thus, two or three levels of damage are commonly used for damage detection from this technology (low, moderate and heavy).

4. Fragility curves

Fragility curves represent the relationship between a ground intensity measure (i.e., PGA, PGV, MMI) and the likelihood that a structure would experience or exceed certain level of damage. Fragility curves are mostly represented as a lognormal cumulative distribution function:

$$\begin{aligned} F_d(x) &= P[D \geq d|X = x] \quad d\epsilon\{1, 2, ..., N_D\} \\ &= \Phi\Big(\frac{ln(x/\theta_d)}{\beta_d}\Big) \end{aligned} \tag{1}$$

where $F_d(x)$ is the fragility function for damage state at d evaluated at x. $P[A|B]$ is the probability that A is true given that B is true. D is the uncertain damage state and any specific value of it is represented by d. N_D is the number of possible damage states. The ground intensity parameter is quantified by the variable X, and any specific value of it is represented by a lower-case x. $\Phi(s)$ is the standard normal cumulative distribution function evaluated at β_d and θ_d are the median and the logarithmic standard deviation, respectively. The lognormal distribution is used because it fits a variety of damage data well, either structural or non-structural components. Additionally, the lognormal distribution has zero probability density at values lower than or equal to zero EDP; and it can be defined by the median and standard deviation (**?**). A statistical approach is used for building damage function because the source of variabilities. Ground motions with the same intensity produces different demand on the same structure. Furthermore, buildings with the same structural system and built with the same design code have different capacity. Thus, in order to use a fragility function for a given structure, a calibration of equation (1) is required. In other words, we need to estimate θ_d and β_d. Such estimations are based on observed data, which can be based on field survey or analytical structural analysis. There are two common methods to estimate the parameters from the observed data: the method of moments and the method of maximum likelihood. However, as mentioned from **?**,

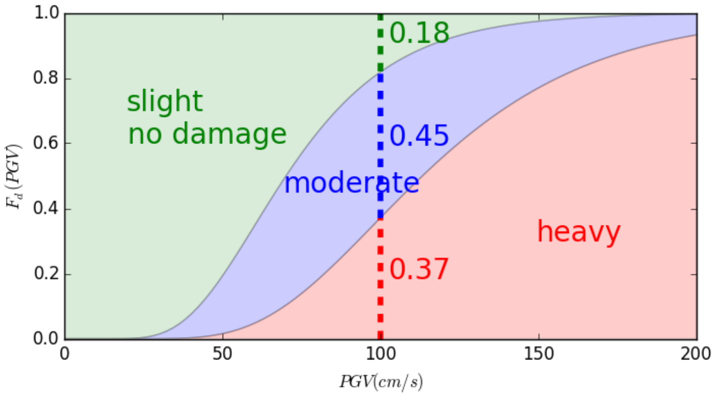

Figure 1: Fragility functions of wood-frame (left) and reinforced concrete (right) for moderate (green line) and heavy damage (blue line)

independent of the procedure, the parameter should be unbiased (i.e., the estimated parameters do not overestimate or underestimate the true parameters value), efficient (i.e., with small variance), and consistent (i.e., the estimated parameters converge to the true values when the observed data goes to infinity). A set of fragility functions for the same type of buildings with the same construction period can be used to delimit the region of each damage states. Figure 1 depicts the fragility curves for wooden buildings with construction period of 1972-81. The set of fragility functions delimits the region of each damage state. For instance from Figure 1 a building with a demand of 100 cm/s as PGV has a probability of 0.18, 0.45, and 0.37 for slight/no damage, moderate, and heavy damage, respectively. Recall that when the demand (PGV) increases, the probability of heavy damage increases as well, while the probability of slight/no damage reduces. The probability of each damage state from the set of fragility functions are expressed as follow:

$$
\begin{aligned}
P[D = d|X = x] &= 1 - F_1(x) && d = 0 \\
&= F_d(x) - F_{d+1}(x) && 1 \leq d \leq N \\
&= F_d(x) && d = N
\end{aligned}
\tag{2}
$$

5. Empirical Methods

Empirical fragility curves are based on field surveys of buildings damaged during earthquakes. First, buildings are classified according to its damage level. Then, buildings with different structural material and construction period (i.e., built with the same design code) are separated. For the next step, the distribution of the strong motion (i.e., PGV, PGA) must be estimated. The estimation of strong motion distribution is a crucial step because it is necessary to determine the ground motion intensity in each building. However, the distribution strong motion devices are in the order of some tens of kilometers in the best case. For instance, the Japanese strong motion network K-NET (Aoi et al., 2004) has stations distributed every 20 km. However, for building damage function purpose, it is necessary a greater resolution of the strong motion. Thus, it is necessary to perform an interpolation of the strong-motion record considering an attenuation law. **?** refined the distribution of the strong-motion of the

1995 Hyogoken-Nanbu (Kobe) earthquake by employing fragility curves previously constructed using recorded strong-motions and building damage data from the field survey by the Architectural Institute of Japan (AIJ) and the City Planning Institute of Japan (CPIJ) in other districts of Kobe. After each building surveyed is associated with its strong motion intensity, such as PGA or PGV, the damage ratios of buildings are calculated and used to calibrate a lognormal cumulative distribution function. Depending on the available data set, several methods for the fitting process have been published (**??**).

6. Analytical Methods

To obtain fragility curves based on analytical methods, the building structure must be idealized. The building capacity is reflected by its material properties, structural configuration, and geometrical properties. The idealization process involves considerable judgment (**?**). After the structure is idealized, a family of recorded strong motion is applied to the structure model by a structural analysis and the structural response, such as rift story, is measured. Then, the structural response is then related to a damage state. Finally, pairs of data set (i.e., ground motion intensity and damage state) are used to calibrate the lognormal cumulative distribution function, as mentioned in the previous section. Different structural analysis methods have been proposed to estimate the structural response. The most relevant methods is summarized further in this section.

6.1. Capacity spectrum method

The CSM evaluates the performance of a structure by comparing the capacity with the demand of the structure. Basically, the performance of the structure is estimated as the intersection of the capacity spectrum curve and response spectrum curve (**?**). The capacity spectrum is determined from the capacity curve, which is the relation between the applied force and the developed deformation. Usually, the applied force is measured as the shear at the base and the deformation as the displacement at the top. Then, the shear vs displacement is transformed to acceleration spectra (SA) vs displacement spectra (SD) (i.e., the capacity spectrum curve). In order to consider the hysteretic behavior and the increment of the fundamental period during the inelastic deformation; viscous damping factors are applied to the linear-elastic response spectrum. As an illustration, Figure 2 shows the procedure to estimate the performance point (i.e., the intersection between the spectrum capacity and the response spectrum). The figure shows several response spectrum curves obtained from different damping value, where each damping value is related to a specific effective ductility. Here, ductility refers to the ratio of inelastic-to-elastic deformation. It might also be noted that in the capacity spectrum curve there are some points for specific ductility. Thus, the objective is to search for the response spectrum curve of ductility μ that cross the capacity spectrum curve in a point that produce the same ductility value μ. From Figure 2, the performance point has a ductility of 2.5.

6.2. The coefficient method (CM)

The CM method is defined in FEMA-356document (**?**) and later modified by **?**. The CM uses the displacement obtained from a response of a linear elastic, single-degree-of-freedom (SDOF) model, which is modified by multiplying by a series of coefficients to estimate the displacement of the structure at a specific target. Thus, the displacement represents the performance point, which is related with certain level of damage.

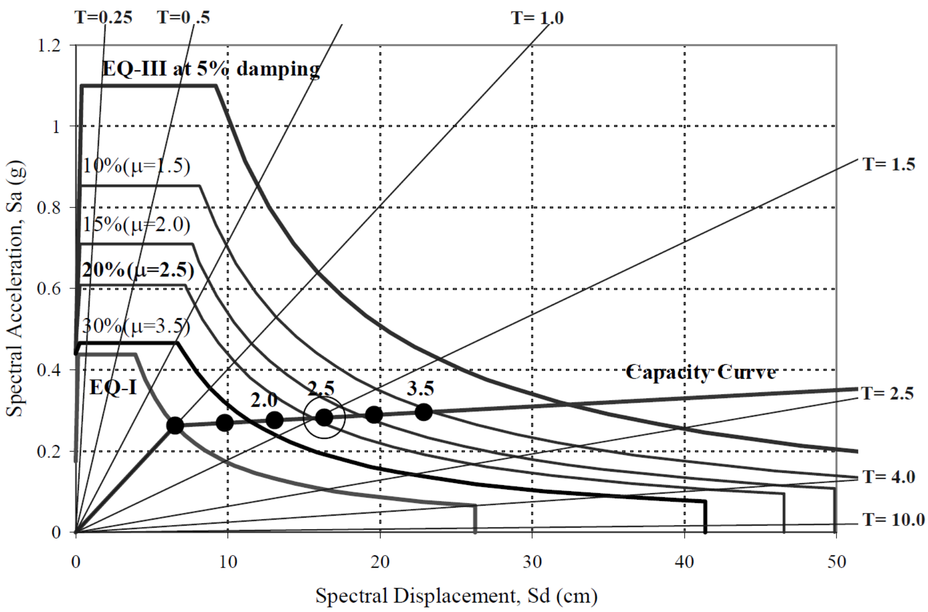

Figure 2: Capacity spectrum method (Freeman, 2004)

7. Conclusions

This paper was motivated to be used as a reference during the implementation of building damage scenarios due to erthquakes for the project DIM2SEA. The paper has aimed to illustrate the concepts and database necessary to built fragility functions.

Three main parts of the general framework can be drawn. Firstly, the building inventory database. Information regarding tructural system, building material, period of construction and a georeference are required. Secondly, the estimation of the engineering demand parameter for each building, which can be represented by the peak ground velocity (PGV) or peak ground acceleration (PGA). Thirdly, the relationship between the engineering demand paramter and the damage state. Here, generally two different approach can be chosen: an empirical and an analytical relationship. Empirical relationship is based on field surveys of a damaged area due to an earthquake. Meanwhile, analytical relationship is based on numerical simulation of the structure against strong ground motion due to earthquakes.

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