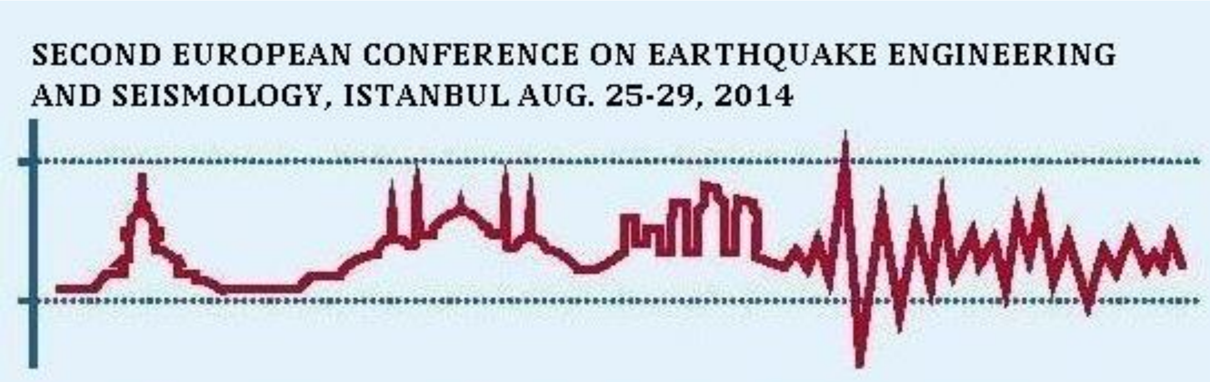

USING REPRESENTATIVE SUITES OF INDEX BUILDINGS TO MODEL THE SEISMIC VULNERABILITY OF AN ASSET CLASS

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A central challenge to modelling building exposure and vulnerability in a community is the proper probabilistic conditioning of building classes. Building classes in community loss models are often defined in terms of structural material, lateral force resisting system, height range, and use. To truly understand what an asset class comprises, the analyst needs to know which building features matter most to the uncertain seismic performance of a specimen of the class, must have an estimate of the joint probability distribution of those features within each class in the community of interest, and most importantly, must know that the vulnerability model for that class mimics that joint probability distribution. The present work focuses on how to construct a probabilistic seismic vulnerability function for an asset class that accounts for that joint probability distribution.

In work for the Willis Research Network and the Global Earthquake Model, we developed and pilot tested a procedure that (1) identifies the important features of an asset class, (2) quantifies their joint distribution, (3) generates a small suite of particular building models called index buildings, (4) produces an analytical vulnerability model for each such index building, and (5) probabilistically combines them to produce a probabilistic vulnerability function for that asset class.

Important features are selected by meta-analysis, by reviewing the features that prior respected works identify as mattering greatly to seismic performance of the class. Features most often cited are taken to be the ones that matter most. For example, in US publications, given structural material, lateral force resisting system, and height range, the features most commonly cited as important to performance are design era, number of stories, vertical and plan irregularities, redundancy, pounding, openness, and captive columns. Design base shear is indirectly captured by reference to design era.

The joint distribution of these features is estimated by a survey of buildings within the community of interest. Sampling procedures were developed for the Global Earthquake Model to efficiently select buildings that can be shown to approximate the population of each asset class in question. Once the sample is selected, survey instruments and software, also developed by the Global Earthquake Model, can be used to observe and record the relevant features in the survey sample. The survey results in a joint probability distribution of the features considered to matter most.

It can be shown that a small suite of sample values of the important features can efficiently approximate the distribution of those features among the population. This is done by a process called moment matching: a sample is selected and each is assigned a weight so that the first several moments of the features (mean, variance, skewness, etc.) of the sample match the same moments of the population (as represented by the survey observations). If we identify k variable features within each class that matter most to the vulnerability of the class, a sample set of $2k + 1$ particular buildings can match the first 5 moments of the joint distribution. This fact will be important later when the samples are analysed and combined into a model of the class. Higher moments can be captured with more

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samples, e.g., $4k + 1$ can match the first 9 moments of the joint distribution. The features do not need to be monomodal or independent for the sampling procedure to work.

Each sample is then represented by a particular building model, called an index building after Reitherman and Cobeen (2003). Each model is defined in fine detail: its geometry, material properties, structural and nonstructural component inventory, replacement cost, and the fragility and local repair costs of its damageable components. To do so, we suggest using local construction cost manuals. To limit the amount of effort required, the inventory can be limited to the building components that contribute to construction cost new. Vulnerability results will later be scaled up to account for the components not included in the inventory. A structural model of each index building is also created.

We developed a procedure for the Global Earthquake Model to estimate the seismic vulnerability of each index building. It employs incremental dynamic analyses to capture record-to-record variability in structural response. Each structural analysis is input to a stochastic model of component damage and repair cost to estimate building-level repair cost. Monte Carlo simulation is employed to generate a probabilistic repair cost as a function of ground motion intensity. The analysis slightly simplifies the procedures developed for FEMA P-58 (Applied Technology Council 2012). The simplification avoids the principal component analysis used by PACT, which, while it can generate an infinite set of properly correlated structural response vectors from a finite set of structural analyses, imposes lognormality on each structural response measure. The procedure generalizes FEMA P-58 by allowing the analyst to specify local costs that may differ from FEMA's US-centric values. A companion work in these proceedings by Vamvatsikos et al. details the structural analysis.

Finally, the probabilistic seismic vulnerability function for the class is calculated as a weighted mixture of the vulnerability functions for the index buildings. As shown by Cho and Porter (2014) and earlier works discussed there, by matching the first *p* moments of the distribution of the *k* key features, the mean vulnerability function for the class is accurate to p^{th} order as well and the coefficient of variation is accurate to $\lfloor p/2 \rfloor$ order. Thus, with 3 key features and 7 index buildings we generate a vulnerability function for the class that is accurate in the mean to 5^{th} order and in the coefficient of variation to 2^{nd} order, already superior to first-order-second-moment approaches.

We exercised this methodology for highrise (7+ story) reinforced concrete moment-frame office buildings designed to the International Building Code, i.e., with microzonation. This class has not experienced strong earthquake motion so empirical performance data is unavailable, even if one were to broaden the class to include older buildings that experienced the fairly modest levels of shaking in the Loma Prieta, Northridge, and Nisqually earthquakes. From a review of ASCE-7, ACI 318, FEMA 154 and several other relevant documents, we selected three features that seem to matter most to the seismic performance of this building class: number of stories, degree of vertical irregularity, and design ground motion. (We also varied component fragility.) We compiled statistics of these features from a survey of 263 commercial buildings in 4 urban and suburban California communities. They appear to be uncorrelated. The distribution of S_{D1} was calculated using the December 2008 US National Seismic Hazard Map at the locations of 1,865 highrise buildings in the Emporis database that are located in areas with $S_{D1} \geq 0.2$g. Moment matching produced the samples listed in Table 1.

Table 1. Index building features

Index building	Stories	h_2/h_1	S_{D1}, g	T_1, sec	Weight
Baseline	12	1.74	0.60	2.14	0.147
7 story	7	1.74	0.60	1.61	0.096
20 story	20	1.74	0.60	2.85	0.079
Low vertical irregularity	12	1.15	0.60	2.02	0.315
High vertical irregularity	12	2.74	0.60	2.42	0.042
Low design base shear	12	1.74	0.26	2.14	0.170
High design base shear	12	1.74	0.97	2.14	0.150

Building components and quantities were selected to match RSMeans' (2012) M.480 model. Detailed types (accounting for seismic installation conditions and other aspects of fragility that distinguish finer differences than appear in RSMeans' UNIFORMAT II numbering) were selected by Porter's judgment from the PACT database. Incremental dynamic analysis was used to estimate structural response at each of many levels of $S_{agm}(T_i,5\%)$, where T_i denotes the geometric mean of the small-amplitude fundamental period of vibration of the 7 index buildings, approximately 2.2 sec, and S_{agm} denotes the geometric mean of two orthogonal horizontal directions' damped elastic spectral acceleration response. (No distinction is made here between pseudo-spectral acceleration response and spectral acceleration response, since at 5% damping there is virtually no difference.) At each level of Sa, 1000 Monte Carlo simulations were applied to simulate component damage and repair costs. Structural response is randomly selected from one of the 44 ground motion time history structural analyses. For simulations with collapse in the IDA, repair cost is taken as 100% of the replacement cost new. For non-collapsed simulations, all identical components on a single story or floor are assumed to have perfectly correlated damage, and independent (conditioned on structural response) of damage to similar components at other levels. Repair costs for non-collapsed simulations were factored up by the fraction of value represented in the partial inventory, which in this analysis was 0.59. When repair costs reach approximately 60% of replacement cost new, the building is assumed to be a total loss. (We took constructive total loss—an insurance concept—as normally distributed with mean of 0.6 and coefficient of variation 0.1.)

We collected statistics and calculated mean and standard deviation of building repair cost at each level of S_{agm}. We repeated the simulation at many levels of S_{agm} and constructed a vulnerability function for each index building. We performed the process for each of three variants of each index building: a poor-quality variant with generally fragile components, typical quality with a mix of fragile and rugged components, and superior quality with more rugged components. The vulnerability functions shown in Figure 1 are equally weighted averages of the three variants. The vulnerability function labeled "Asset class MDF" is taken as the weighted average of the 7 index buildings, using the weights in Table 1. The coefficient of variation (COV in the figure) is calculated from the probabilistic mixture of the vulnerability functions from the 21 variants just described.

This appears to be the first analytical derivation of a seismic vulnerability function for a building class in which all major contributors to uncertainty are deliberately selected, quantified and propagated. This asset class has not yet experienced strong motion, so no empirical analog is available.

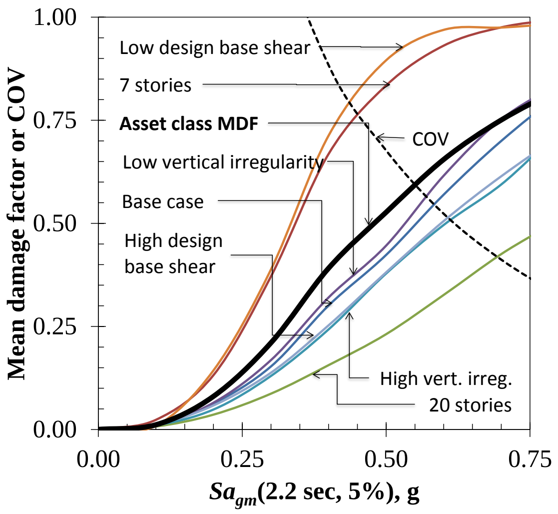

Figure 1. Analytically derived seismic vulnerability function of IBC-conforming 7+ story RC moment frame office building in seismic design category D.

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