Extending the USGS National Seismic Hazard Maps and ShakeMaps to Probabilistic Building Damage and Risk Maps

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Abstract

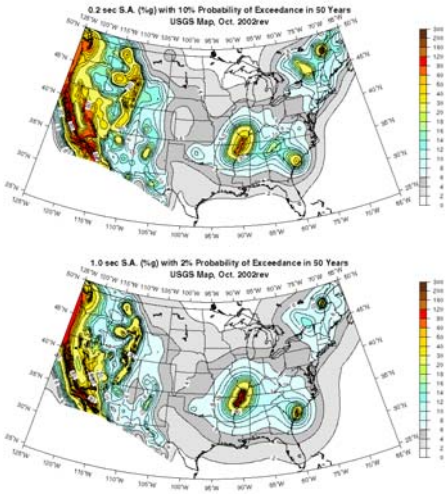
By combining hazard curves from the USGS National Seismic Hazard Mapping Project (http://earthquake.usgs.gov/research/hazmaps/) with building capacity and fragility curves from FEMA's HAZUS-MH earthquake model for loss estimation (http://www.fema.gov/plan/prevent/hazus/), we have developed preliminary maps of the seismic risk to structures hypothetically located at grid points across the conterminous U.S. In their primary form, the risk maps show the mean annual frequencies (MAFs) of exceeding different structural damage states (none, slight, moderate, extensive, and complete) for each of thirty-six different generic building types (e.g., wood light frame, mid-rise concrete shear wall, or high-rise steel frame) designed to different code levels (high-, moderate-, low-, and pre-code). Note that the HAZUS default values of direct economic losses corresponding to each of the five structural damage states (enumerated above) are 0%, 2%, 10%, 50%, and 100% of the building's replacement cost, respectively. In this way, the risk maps also provide information about the probability distributions of losses (including, and beyond, average annual losses) for different types of buildings designed to different code levels at different geographic locations in the U.S.

The risk maps are computed via an application of the theorem of total probability that integrates the product of (i) the differential of the appropriate seismic hazard curve at each grid point of the National Seismic Hazard Maps and (ii) each of the HAZUS-based but "revamped" building fragility curves that we have developed for this purpose (Karaca and Luco, 2006). Recall that a seismic hazard curve generally provides the MAFs of exceeding various ground motion spectral acceleration (*SA*) values, and a building fragility curve typically provides the conditional probabilities of exceeding a specified damage state for various *SA* values (or structural response values, as is the case in HAZUS). Each of the fragility curves we have developed reflects (i) uncertainties in the building capacity (or "pushover") curve, (ii) variabilities in the building response across different ground motion waveforms with the same *SA* value, and (iii) variabilities in the observed damage state for a given level of building response. The first and third of these uncertainties/variabilities are extracted from HAZUS. Additionally, we quantify the waveform-to-waveform variability in building response by conducting inelastic time-history analysis of a single-degree-of-freedom model of each generic building type subjected to ground motions from the Pacific Earthquake Engineering Research (PEER) Next Generation Attenuation (NGA) Strong-Motion Database (http://peer.berkeley.edu/nga/). The result is fragility curves that include the appropriate uncertainties/variabilities (and are in terms of consistent *SA* parameters) for combination with the seismic hazard curves.

Along the same lines, we also combine (a subset of) the derived building fragility curves with USGS ShakeMaps of the best estimates of and uncertainties in the ground motions generated by the 1994 Northridge earthquake, as an example (http://earthquake.usgs.gov/eqcenter/shakemap/). The result is a map of damage-state probabilities (pre-reconnaissance) for each of the generic building types and code levels at each grid point on the ShakeMaps. Note that these damage-state maps reflect uncertainties in the actual ground motion *SA* values for the earthquake (lowest at and near ground motion recording stations, higher elsewhere), in addition to the three fragility-curve uncertainties/variabilities included in the risk maps described above.

Motivation

Although the USGS National Seismic Hazard Maps themselves (e.g., those shown below; Frankel *et al*, 2002) do not convey the risk of damage to structures, they do provide the ground motion hazard information needed to do so.



(Source: http://earthquake.usgs.gov/research/hazmaps)

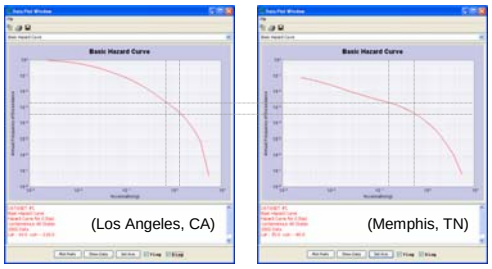
Approach

For each building type (see table below), seismic design level (high-, moderate-, low-, pre-code), structural damage state (none, slight, moderate, extensive, complete), and grid point on the USGS National Seismic Hazard Maps:

$$\lambda[DS > ds] = \int_{sa} P[DS > ds \mid SA = sa] \; |\mathrm{d}\lambda[SA > sa]|$$

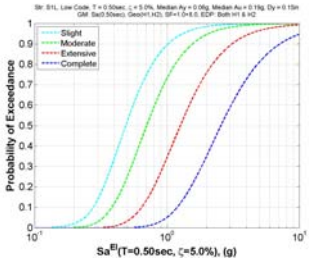
where

$\lambda[SA > sa] \equiv$ Mean Annual Frequency (MAF) of exceeding a Spectral Acceleration (*SA*) of *sa* (i.e., a seismic hazard curve), e.g., …

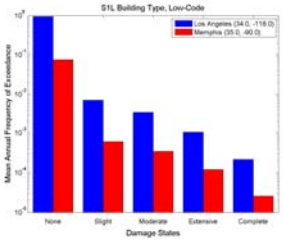


(Source: http://earthquake.usgs.gov/research/hazmaps/design/)

$P[DS > ds \mid SA = sa] \equiv$ Conditional probability of exceeding the Damage State *ds* given an *SA* of *sa* (i.e., a building fragility curve), e.g., …



$\lambda[DS > ds] \equiv$ MAF of exceeding the Damage State *ds*



Bldg. Types from HAZUS®MH Technical Manual

Table 3.1: Building Structure (Model Building) Types

No.	Label	Description	Height Range Name	Height Range States	Height Typical States	Height Typical Feet
1	W1	Wood, Light Frame (≤5,000 sq. ft.)		1 - 2	1	14
2	W2	Wood, Commercial and Industrial (> 5,000 sq. ft.)		All	2	24
3	S1L	Steel Moment Frame	Low-Rise	1 - 3	2	24
4	S1M		Mid-Rise	4 - 7	5	60
5	S1H		High-Rise	8+	13	156
6	S2L	Steel Braced Frame	Low-Rise	1 - 3	2	24
7	S2M		Mid-Rise	4 - 7	5	60
8	S2H		High-Rise	8+	13	156
9	S3	Steel Light Frame		All	1	15
10	S4L	Steel Frame with Cast-in-Place Concrete Shear Walls	Low-Rise	1 - 3	2	24
11	S4M		Mid-Rise	4 - 7	5	60
12	S4H		High-Rise	8+	13	156
13	S5L	Steel Frame with Unreinforced Masonry Infill Walls	Low-Rise	1 - 3	2	24
14	S5M		Mid-Rise	4 - 7	5	60
15	S5H		High-Rise	8+	13	156
16	C1L	Concrete Moment Frame	Low-Rise	1 - 3	2	20
17	C1M		Mid-Rise	4 - 7	5	50
18	C1H		High-Rise	8+	12	120
19	C2L	Concrete Shear Walls	Low-Rise	1 - 3	2	20
20	C2M		Mid-Rise	4 - 7	5	50
21	C2H		High-Rise	8+	12	120
22	C3L	Concrete Frame with Unreinforced Masonry Infill Walls	Low-Rise	1 - 3	2	20
23	C3M		Mid-Rise	4 - 7	5	50
24	C3H		High-Rise	8+	12	120
25	PC1	Precast Concrete Tilt-Up Walls		All	1	15
26	PC2L	Precast Concrete Frames with Concrete Shear Walls	Low-Rise	1 - 3	2	20
27	PC2M		Mid-Rise	4 - 7	5	50
28	PC2H		High-Rise	8+	12	120
29	RM1L	Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms	Low-Rise	1-3	2	20
30	RM1M		Mid-Rise	4+	5	50
31	RM2L	Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms	Low-Rise	1 - 3	2	20
32	RM2M		Mid-Rise	4 - 7	5	50
33	RM2H		High-Rise	8+	12	120
34	URML	Unreinforced Masonry Bearing Walls	Low-Rise	1 - 3	2	15
35	URM		Mid-Rise	3+	3	35
36	M	Mobile Homes		All	1	10

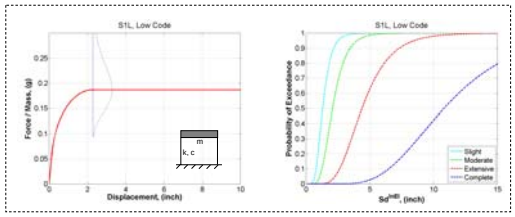
Building Fragility Curves

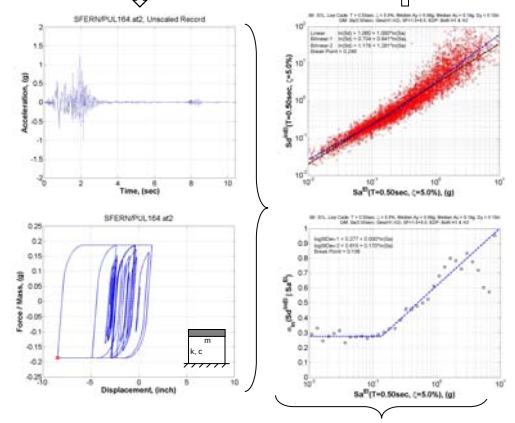
(i.e., $P[DS > ds \mid SA = sa]$**)**

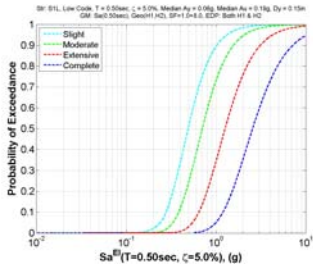
Since HAZUS does not provide building fragility curves that are functions of the scalar[1] elastic spectral acceleration parameters used for the USGS National Seismic Hazard Maps, we have developed them using the building capacity curves (and associated structural properties) and building fragility curves (in terms of inelastic spectral displacement) defined in HAZUS. We relate elastic spectral acceleration to inelastic spectral displacement via inelastic time-history analysis, in lieu of the Capacity Spectrum Method (e.g., ATC-40) used in HAZUS.

[1] See the Future Work section of this poster for a comment on the use of vector ground motion intensity measures.

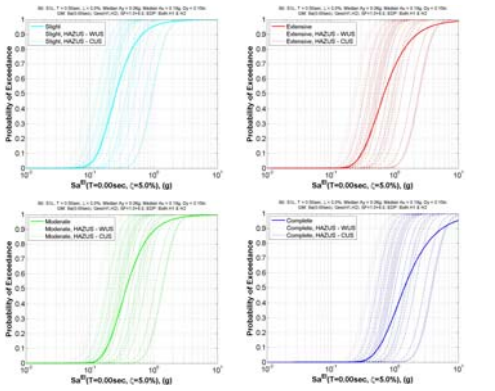
From HAZUS®MH







Comparison with HAZUS for PGA



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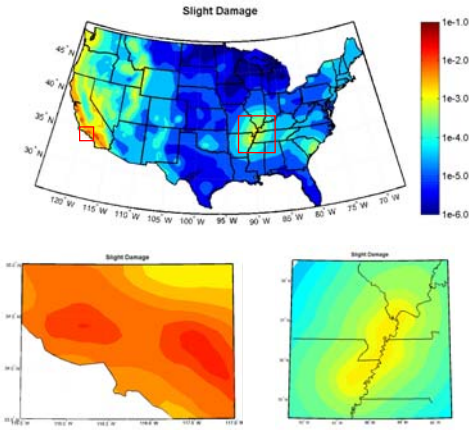
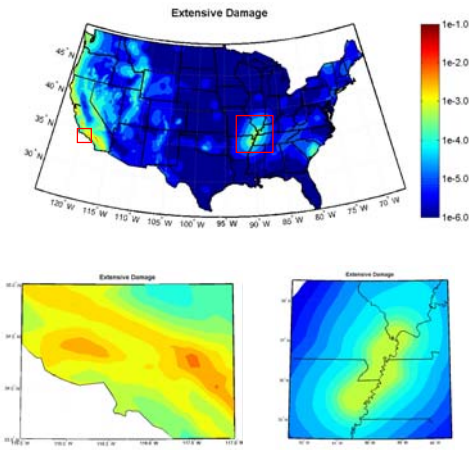
Example Risk Maps

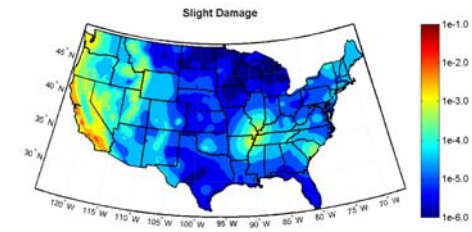
(i.e., $\lambda[DS > ds]$)

Low-Rise Steel Moment-Frame Building, Low-Code





Low-Rise Steel Moment-Frame Bldg., High-Code



Example Damage Maps

The approach we use to compute Damage Maps based on ShakeMaps of the best estimate of the ground motion *SA* and its uncertainty (e.g., see below) is analogous to that used for the Risk Maps, i.e., …

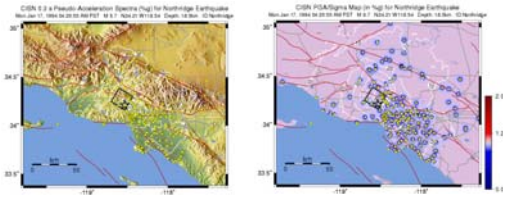
$$P[DS > ds] = \int_{sa} P[DS > ds \mid SA = sa]\; f_{SA}(sa)\, \mathrm{d}sa$$

where

$$f_{SA}(sa) \equiv \text{Probability density function of } SA \text{ (based on ShakeMaps and the lognormal assumption)}$$

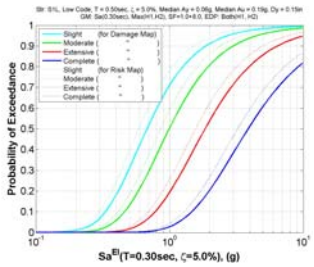
Here *SA* is the maximum value between the two horizontal components of ground motion (i.e., the ShakeMap *SA*), as opposed to the geometric mean *SA* used for the Hazard/Risk Maps.

1994 Northridge Earthquake ShakeMaps

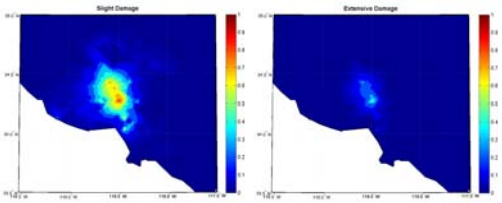


(Source: http://earthquake.usgs.gov/eqcenter/shakemap/)

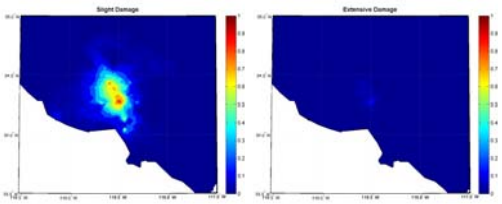
Building Fragility Curves for ShakeMaps



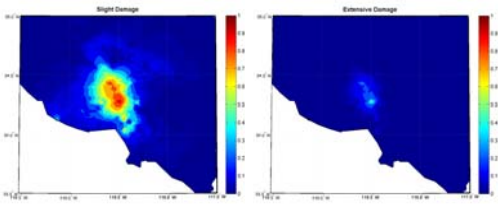
Low-Rise Steel Moment-Frame Building, Low-Code



Light-Frame Wood Building, Low-Code



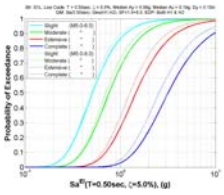
Low-Rise Unreinforced Masonry Bldg., Low-Code



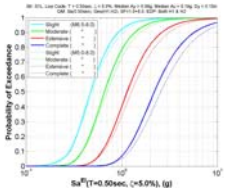
Future Work

Though widely used, elastic spectral acceleration at or near the fundamental building period (*SA*) has been demonstrated to be an "insufficient" ground motion intensity measure with respect to inelastic displacement response (e.g., Luco & Cornell, 2006). As a result, the building fragility curves we have developed are not always independent of the earthquake magnitudes (*M*) and source-to-site distances (*R*) of the ground motion waveforms used, as demonstrated in the figures below. To remove this dependence, we plan to develop building fragility *surfaces* that are functions of both *SA and* ground motion epsilon (ε ; Baker & Cornell, 2005) or *M* and *R*. In either case, the corresponding seismic hazard information in terms of the vector ground motion intensity measure, which is needed to compute the Risk Maps, will incorporate (e.g., *ala* Bazzurro & Cornell, 2002) USGS deaggregations for each geographic location. Alternatively, we may develop building fragility curves that are a function of *SA* alone, but that vary with geographic location and the associated deaggregation information (e.g., *ala* Shome & Cornell, 1999).

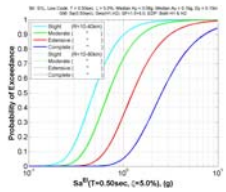
Magnitude, M5.0-6.5



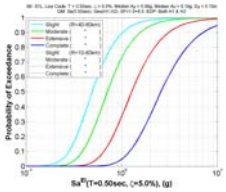
Magnitude, M6.5-8.0



Distance, 10-40km



Distance, 40-80km



Other plans for future work include an extension to direct economic losses that takes into account the variability in loss for a given damage state.

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