A Scenario Case Study to Evaluate Methods of Seismic Loss Assessment for Communities of Buildings

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ABSTRACT: The study assesses economic losses for the estimated building stock of concrete frame buildings in and around downtown Los Angeles, due to a M_w 7.8 rupture scenario on the San Andreas Fault. The study begins by making a "Benchmark" prediction of earthquake-induced losses in this building stock using state-of-the-art ground motion simulations, structural analyses, and loss assessment techniques. The Benchmark loss prediction is compared to estimates from two other methods. These methods are representative of current regional loss estimation procedures, which rely on ground shaking intensity to predict losses. Comparisons of the results demonstrate the strengths and weakness of different regional loss estimation techniques. The results highlight the importance of accounting for spatial correlations in ground shaking intensity and building response for dealing with uncertainty in the regional loss assessment.

1 INTRODUCTION

The development of performance-based earthquake engineering methods has been primarily concerned with the assessment of earthquake-induced losses and collapse risk in individual buildings. While beneficial for examining design or retrofit alternatives for specific structures, this unit of analysis is problematic for making policy decisions about seismic design and mitigation, because the metrics of building performance obtained through such methods, *i.e.* individual buildings, are decoupled from the unit of decision, *i.e.* communities or regions. Tools for predicting seismic losses in a geographically-distributed building inventory are in need of further refinement.

1.1 *Methods of regional seismic loss assessment*

This article is concerned with probabilistic methods for estimating earthquake-induced losses in a region. Here, the term "regional loss" refers to the total seismic loss experienced by all of the buildings comprising a building stock (or portfolio of buildings) that are located in a specified geographically proximate area. The distribution of possible losses for a region or building portfolio may be estimated by performing the following steps:

1. Identify all relevant faults and the distributions of potential earthquake magnitudes and rupture locations.
2. Use a Monte Carlo simulation approach to generate a suite of realizations of possible earthquake scenarios that is consistent with the distributions of potential magnitudes and earthquake locations.
3. For a given scenario, use a ground motion prediction equation (GMPE) to compute the expected (mean) ground motion intensity measure (IM) at each site and the dispersion (logarithmic standard deviation) in this prediction.
4. Generate realizations of IM values at each site, based on the mean and standard deviation of IM defined in *(3)*. *Step (4)* creates a map representing one possible realization of ground motion intensities in the region for the earthquake scenario.
5. Compute the loss for each building using a predefined damage function (DF) for the building or class of buildings of interest. A DF is a relationship between an input parameter and the expected loss for a building. The input parameter may be the site IM or a measure of structural response, known as an engineering demand parameter (EDP). The DF can also define the uncertainty in the loss (conditioned on either IM or EDP).
6. Sum the losses from each building to compute the total expected loss for the building portfolio.
7. Repeat *(3)-(6)* for multiple Monte Carlo realizations of each potential scenario.

A common metric for presenting risk-based regional seismic loss estimations is via mean rates of exceedance (MRE). MREs represent the temporal rates (frequencies) at which earthquake-induced losses are expected to exceed a set of threshold (dollar) values. By combining the results from all of the scenario earthquakes, and loss realizations associated with each of these scenarios, MREs for various loss thresholds are computed.

Note that this probabilistic approach, as it is described above, results in estimates of direct economic earthquake-induced losses for the building stock only *(i.e.* costs to repair or replace buildings). Indirect losses, such as fatalities and revenue losses due to downtime, would require extension of the methodology and are not considered here.

1.2 *Recent advancements in regional seismic loss assessment*

In the last decade, a number of contributions have been made to the probabilistic regional loss estimation procedure that is described in Section 1.1. Some of these studies (Bazzurro and Luco 2005, Lee and Kiremidjian 2007, Park *et al.* 2007, Goda and Hong 2008a) demonstrate that consideration of spatial correlations in ground shaking intensity has a large influence on the probabilistic distribution of losses predicted for a regionally distributed building stock. In particular, large, rare losses are underestimated when spatial correlation in ground motion intensities between closely spaced sites is ignored in generating maps of ground shaking intensity (*e.g.*, in *(4)* in Section 1.1). Large losses occur when ground shaking intensity is above average all throughout a region, which occurs as a result of site-to-site correlations of the intensity. Several models have been developed for simulating maps of ground shaking intensities that represent the spatial correlations that may exist between closely spaced sites (*e.g.* Wesson and Perkins 2001, Wang and Takada 2005, Goda and Hong 2008b, Jayaram and Baker 2009, Loth and Baker 2012). Considering these spatial correlations is important for capturing large rare losses, or, in other words, for capturing the variance in regional losses.

Fewer researchers have examined correlations in building response or losses that stem from these correlations in ground motion intensity. These authors observed that spatial correlation patterns of structural responses (*i.e.* EDP) are similar to those of IM (DeBock *et al.* 2013). In particular, we showed that the relationship between IM and EDP at a particular site is correlated with the relationship between IM and EDP at other sites. Neglecting this source of correlation may lead to underestimation of the variance of regional losses for the same reason that ignoring spatial correlations in ground shaking intensity leads to underestimation of the variance of regional losses.

1.3 *Overview of the scenario case study*

This study evaluates regional loss estimation methods in the context of a case study of a large, high consequence, scenario event in Los Angeles. Three methods are used to estimate the regional losses for a "test stock" of buildings in a small area of Los Angeles. The characteristics of these three methods are selected to interrogate the impacts of neglecting or including spatial correlations in IM and EDP on regional loss estimates. Each of these methods essentially represents *(3)-(6)* in the list above, but with different sets of assumptions. Losses are predicted for a test stock consisting of the estimated inventory of reinforced concrete (RC) frame buildings in a region of Los Angeles, south of downtown. Comparisons between the different methods can be used to improve the current state-of-the-art in regional seismic loss estimation.

2 EARTHQUAKE EVENT CASE STUDY

2.1 *The ShakeOut earthquake scenario*

The case study examines earthquake-induced losses for the stock of RC frame buildings due to the ShakeOut earthquake scenario, which is a M_w 7.8 south-to-north rupture along the southern San Andreas fault. Graves *et al.* (2008) predicted ground motion time histories throughout the southern California region using physics-based simulations of the rupture and seismic wave propagation from source to site. Graves *et al.* (2008) provide ground motion time-histories for a large number of sites that are uniformly spaced at 2 km intervals over a region encompassing Los Angeles and the surrounding area.

2.2 *Building stock and modeling*

The case study examines seismic-induced losses for RC frame buildings in and around downtown Los Angeles (zip codes 90071, 90013, 90014, 90015, 90021). Figure 1 displays the approximate boundaries of the zip codes, along with the building site locations that are used in the subsequent analyses.

The inventory of RC frame buildings is estimated for each zip code and categorized by (1) occupancy type, *i.e.*, residential (apartments or condos), hospitality (motels and hotels), and commercial (office space), (2) year of construction (representative of non-ductile or ductile detailing), and (3) height (low-rise, mid-rise, or high-rise). The building inventory in the case study test region is composed of 178 RC frame structures, with a total gross area of approximately 6.8 million sq. ft., as summarized in Figure 2. These estimates are based on data from HAZUS (FEMA 2003), Comerio and Anagnos (2012), and Google Streetview. All of the buildings are randomly assigned to sites in Figure 1 within their respective zip codes to create a test building stock for the purpose of the scenario analysis. Due to the high density of buildings in the area, more than one building may be assigned to the same site.

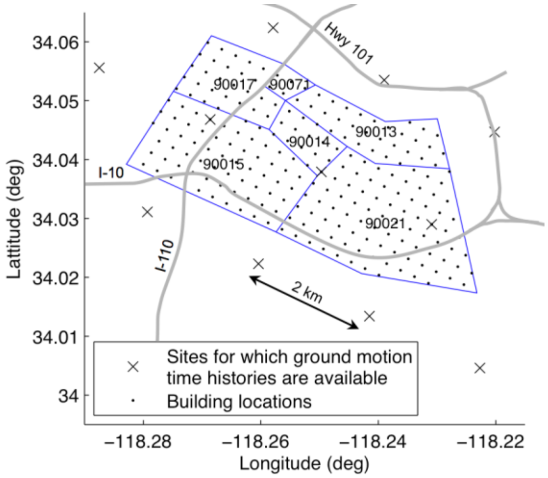

Figure 1. Map of test region showing possible building sites and zip code boundaries.

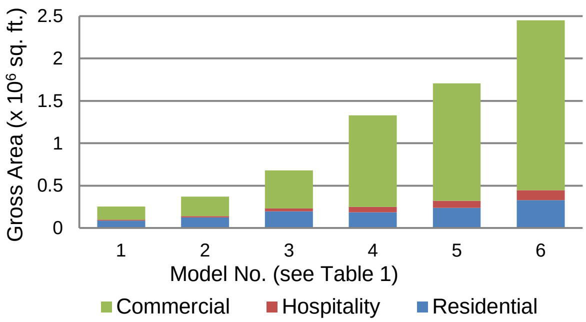

Figure 2. Summary of test building stock of RC buildings.

Each RC frame building in the building stock is represented by one of a group of six robust multiple-degree-of-freedom nonlinear simulation models that is most similar to the structure of interest. These model buildings include both ductile and non-ductile moment resisting frames and range in height from 2 to 8 stories. Each model building is represented in 2D in *OpenSees* (PEER 2013), accounting for material and geometric nonlinearities (Liel *et al.*, 2011). Material nonlinearities are represented by lumped plasticity beam and column elements that are capable of capturing both cyclic and in-cycle flexural degradation and inelastic joint shear springs. Table 1 lists the characteristics of the model buildings.

Table 1. Model RC frame buildings

	Model No.	No. of stories	T_1*
Modern (ductile)	1	2	0.60
	2	4	0.91
	3	8	1.81
Older (nonductile)	4	2	1.03
	5	4	1.92
	6	8	2.23

*Building periods (T_1) are determined from eigenvalue analysis, assuming cracked concrete sections

The building models have been analyzed for each of the ShakeOut ground motions in the test region using a method similar to that described by Lynch *et al.* (2011). Each 2D model is analyzed twice to account for the two orthogonal horizontal ground motion time-histories per site. Structural response is characterized by EDPs, such as interstory drift ratio (IDR) and peak floor acceleration (PFA), for each nonlinear dynamic time-history analysis.[1] The response of a model building at a given site is characterized by the maximum IDR and PFA that occur at any time in the dynamic analysis, in any story, due to either of the two orthogonal horizontal ground motion components. The IM used to quantify ground shaking intensity is the spectral acceleration at the building's fundamental period of vibration, $Sa(T_1)$.[2]

2.3 *Estimation of losses for individual buildings*

Damage functions (DF) are used to predict losses for individual buildings at each site in the case study region. Two types of DFs are used for loss analysis here: (1) DFs that employ $Sa(T_1)$ as the input variable (referred to as IM-based DFs), and (2) DFs that take IDR as the input variable (EDP-based DFs).

For each model building and occupancy category, IM-based and EDP-based DFs are computed by first performing nonlinear dynamic time history analysis on the building model with ground motion time histories with a range of characteristics. For this part of the study, we subject the buildings to the FEMA (2009) far-field ground motions, with each record scaled to several intensity levels.

The nonlinear dynamic time history analysis results are imported into the Performance Assessment Calculation Tool (PACT), a product of the FEMA P-58 project (ATC 2011a). PACT is intended for estimating earthquake-induced losses in an individual building. The inventory of the building's structural and nonstructural components and contents of the building are also inputted into PACT. This inventory depends on the size of the building and the building's occupancy. Each component has an associated fragility function, which defines probability distributions of cost for repair or replacement, based on demand from structural analysis (measured from different EDPs, depending on the component of interest). Due to limitations in available fragility information, not every component in a building can be represented in PACT, but those that have been shown to contribute the most to the losses in buildings, such as wall partitions and structural elements (Beck et al. 2002), are included. Losses obtained from PACT have been validated through comparison to past research on building losses (ATC 2011b).

Pairs of IM-Loss or EDP-Loss data for developing DFs are generated by PACT through a probabilistic

[1] IDR is the peak relative displacement between two adjacent floors, normalized by the story height. PFA is the maximum absolute acceleration experienced by a floor diaphragm.

[2] $Sa(T_1)$ is used here to refer to the geometric mean of the $Sa(T_1)$ of the two orthogonal horizontal components.

approach. PACT predicts loss realizations at varying levels of ground motion intensity by generating random realizations of damage-states for each of the building components. The probabilities of reaching damage states are determined from pre-defined fragility functions and depend on the EDP values from structural analysis results. Repair/replacement costs for each component are generated randomly from distributions of probable costs that are associated with each of the damage states. The total loss for the building, in dollar terms, is the sum of the losses of its components.

IM-based DFs are computed by regressing the building loss data from PACT with $Sa(T_1)$, where $Sa(T_1)$ is the independent variable, as shown in Figure 3. EDP-based DFs are computed by regressing the building loss data with IDR. Both types of DFs are obtained through local polynomial regression (Fan and Gijbels 1996) based on 4,000 loss realizations of each model building. Local polynomial values are predicted at each point by computing a local weighted regression, for which the weights of surrounding realizations are inversely proportional to their distance from the point of interest. Local polynomials can be fit to complicated data sets for which standard regression techniques may fail to satisfy homoscedasticity, normality, and other conditions (Fan and Gijbels 1996).

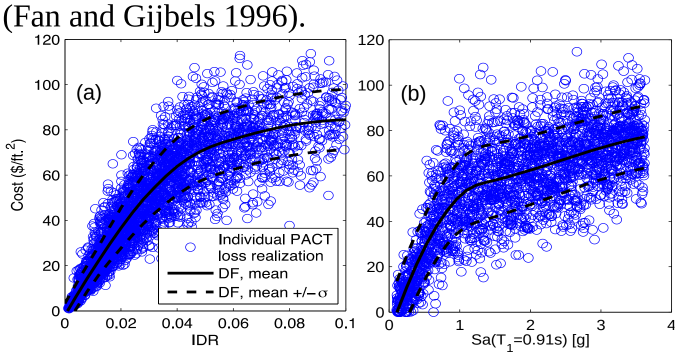

Figure 3. (a) EDP-based and (b) IM-based DF for model No. 2 with residential occupancy, conditioned on no collapse.

There are other well-documented methods for developing building-specific DFs (*e.g.*, FEMA 2003 and Ramirez and Miranda (2009)). The PACT-based method used for developing DFs in this study is not necessarily superior to other methods, but, rather, is selected because IM and EDP-based DFs are computed in the same way. Therefore, any differences that are observed between regional loss estimation methods which employ the two different types of DFs will result only from differences inherent to the methods themselves, but not from the procedures or source data that are used to develop the DFs.

2.4 *Collapse and building replacement*

DFs are only used for computing losses if the building has not collapsed. If collapsed, the building loss is taken as equal to the building's replacement cost. In this study, replacement costs are estimated to range from $160 to $200 per gross square foot (RSMeans 2009) depending on the building height and occupancy type. Replacement costs are assumed to be lognormally distributed about their expected values, with a logarithmic standard deviation of 0.3 (Ramirez and Miranda 2009).

Each of the three loss estimations methods described in Section 3 employ different methods to predict building response. If building response is predicted by nonlinear dynamic time-history analysis, then collapse can be simulated directly. Otherwise, whether or not a building has collapsed is determined from its collapse fragility function, which is reported in Table 2. Collapse fragilities are predetermined for each of the building models and quantified through incremental dynamic analysis (IDA) with the FEMA (2009) far-field ground motion set. IDA is conducted by analyzing the response of a nonlinear building model to a ground motion time-history at increasing scale factors, until the ground motion causes the building to collapse, as illustrated in Figure 4. Collapse occurs when a small increase in ground-shaking intensity causes a large increase in response (*i.e.* sidesway collapse). Here, collapse is defined as the point ($IDR_{collapse}$, $Sa_{collapse}$) on the IDA curve at which the slope decreases to less than 20% of its initial value. The median collapse capacities in Table 2 are based on statistics obtained from collapse during each of the ground motion records.

Table 2. Parameters defining model building collapse fragility functions

Model No.	T_1 (sec)	$Sa_{Collapse}$ (T_1)		$IDR_{Collapse}$	
		Median	β*	Median	β*
1	0.60	2.42	0.50	0.068	0.20
2	0.91	1.52	0.43	0.071	0.17
3	1.81	0.57	0.41	0.050	0.20
4	1.03	0.37	0.35	0.033	0.11
5	1.92	0.25	0.32	0.059	0.26
6	2.23	0.22	0.42	0.042	0.23

*Logarithmic dispersion from 22 IDA analyses, which only accounts for record-to-record collapse dispersion

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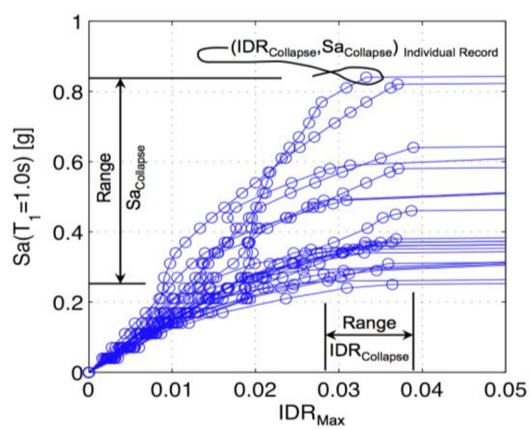

Figure 4. IDA results for the 2-story nonductile RC building (model number 4) with the FEMA far-field ground motion set.

3 LOSS ESTIMATION METHODS

Regional losses are computed by three different methods. The first method, termed the "Benchmark" method is based on physics-based simulations of ground shaking and structural response. As such, it includes a realistic level of correlation in IM and EDP for the test stock, and represents a "best" estimate that considers both of these sources of correlation. Comparisons are made against two other methods. The so-called "Pre-2005" and "Post-2005" methods represent the losses that could be computed from *steps 3-6* of the loss assessment procedure with varying assumptions. As the name implies, the Pre-2005 method is intended to represent the state-of-the-art in regional loss estimations before about 2005 (*i.e.* neglecting consideration of spatial correlations of IMs in *step 4* of the loss estimation procedure). The Post-2005 method is intended to represent the estimate that could be obtained by *steps 3-6* of the loss estimation procedure, if spatial correlations of IMs are considered, but not spatial correlations of EDPs. Comparisons of the losses resulting from the three methods provide valuable insights about the effectiveness of current regional loss estimation tools.

3.1 *Benchmark regional loss assessment method*

The Benchmark method estimates the loss for the building stock through nonlinear time-history analysis results. For each building, EDPs are determined from nonlinear dynamic time-history analysis with a ShakeOut ground motion time history. Recall, however, that the ShakeOut earthquake simulation produced ground motion time-histories at 2 km intervals, but the building sites are positioned at 250 m intervals. Therefore, not all of the buildings are located at sites where nonlinear dynamic time history analyses are available. Buildings sites where ground motion time histories are not available are termed "intermediate sites." EDPs of buildings at intermediate sites are determined by interpolation of EDPs that are obtained at neighboring sites for which ground motion time histories are available. Collapse at the simulated sites is a direct output of the nonlinear time history analysis. Whether or not collapse has occurred for buildings at intermediate sites is determined by first, computing the probability of collapse based on the performance at neighboring simulated sites and, second, generating a binary random variable to represent collapse or no collapse.

The loss for each building is determined from its structural response (*i.e.* IDR) and the corresponding EDP-based DF. To account for dispersion in the DF, a random value of loss is generated which is consistent with the mean and standard deviation of the DF for that level of EDP. Variability of the replacement costs for collapsed buildings is addressed by generating a random realization of replacement cost. The regional loss is the sum of the losses for each of the individual buildings.

The regional loss computed depends on the variation of underlying parameters, including loss predicted by DFs, the occurrence of collapse at intermediate sites, and building replacement costs, that affect the losses computed for individual buildings. Therefore, 1000 realizations of the regional loss are computed, in order to obtain an expected value and distribution of the regional loss in the scenario event. A summary of the Benchmark method is shown in Table 3.

3.2 *Pre-2005 regional loss assessment method*

In the Pre-2005 method, losses are based on site-specific predictions of ground motion intensity obtained from a GMPE and an IM-based DF. At each site, a random value of $Sa(T_1)$ is generated from the expected value and logarithmic dispersion that are computed by the Boore and Atkinson (2008) GMPE. A random realization of a binary random variable is used to determine whether or not the building is collapsed, based on $Sa(T_1)$ at its site and the collapse fragility defined by $Sa(T_1)_{Collapse}$ for the appropriate model building. Random loss realizations for each building are generated from the expected loss and its standard deviation from the corresponding IM-based DF; losses for collapsed buildings are randomly generated from the expected building replacement cost and its dispersion. Like the Benchmark method, 1000 realizations are performed and results are averaged. As shown in Table 3, this method accounts for variability in the ground motion intensity and loss without consideration of spatial correlation.

3.3 *Post-2005 regional loss assessment method*

With the Post-2005 method, regional losses are estimated from the $Sa(T_1)$ values of the ShakeOut earthquake ground motion time histories. Losses for individual buildings are determined from the probability distributions defined by the DF (conditioned on $Sa(T_1)$) and replacement costs and random number generation. The results are based, again, on 1000 realizations. As shown in Table 3, this method accounts for ground motion intensity directly, but additional sources of correlation that may be present in the distribution of EDPs are neglected.

3.4 *Summary of regional loss assessment methods*

This study compares three regional loss assessment methods, as summarized in Table 3. The Benchmark method is considered to be the most complete estimate. The Pre-2005 method is intended to represent regional loss estimation procedures that do not consider spatial correlations among IMs. The

Post-2005 method represents the current state-of-the-art loss estimation procedures, *i.e.* those that employ robust models for simulating spatially correlated IMs.

Since the Post-2005 method uses the IM values that are actually produced by the ShakeOut event, it represents the accuracy that can be achieved with methods that involve robust simulations of IMs (*i.e.* those that consider spatial correlations), but do not consider correlations in EDPs. If a robust spatial distribution of IMs is sufficient for estimating regional loss, then the regional loss that is computed by this method will be similar to that which is computed from the Benchmark method.

Methods akin to the so-called Pre-2005 approach have been previously shown to underestimate large rare losses (e.g. Bazzurro and Luco 2005, Lee and Kiremidjian 2007, Park *et al.* 2007, Goda and Hong 2008a). Since the ShakeOut earthquake scenario produces larger than normal ground shaking intensity (given its magnitude and location) in the downtown Los Angeles area, this method is expected significantly under-estimate the regional losses for the case-study scenario.

Table 3. Summary of the case-study regional loss estimation methods

Parameter	Benchmark method	Pre-2005 method	Post-2005 method
Earthquake Scenario	ShakeOut earthquake, 7.8 M_w south-to-north rupture along the San Andreas fault.		
Prediction of IM or EDP	EDPs are simulated from nonlinear simulation models, using ground motion time-histories produced by Graves *et al.* (2008).	IMs computed from a GMPE, assuming no spatial correlation.	IMs are computed directly from ground motion time-histories produced by Graves *et al.* (2008).
Losses	EDP-based DF.	IM-based DF.	

4 RESULTS

4.1 *Comparison of methods*

The regional losses for the case-study building stock, computed by the three methods, are reported in Table 4 and Figure 5. Each of the three loss estimations produces significantly different results, which demonstrates that these methods of dealing with the major sources of uncertainty and correlations (*i.e.*, uncertainty and correlation in IM and EDP) are not equivalent. In particular, we note that the Benchmark method results in larger predicted losses than the Pre-2005 and Post-2005 methods (300% and 40% higher, respectively).

Table 4. Regional loss estimations

Method	Model building (results summed for all buildings of each type over all occupancies) 1	2	3	4	5	6	Entire stock
Benchmark							
$\$ (x 10^6)$[1]	3.3	2.8	70	106	311	403	**897**
COV[2]	0.33	0.23	0.16	0.08	0.07	0.08	0.05
Collapse[3]	0%	0%	53%	24%	98%	98%	46%
Pre-2005							
$\$ (x 10^6)$	4.8	3.6	9.4	52	63	79	**221**
COV	0.41	0.46	0.48	0.23	0.31	0.42	0.19
Collapse	0%	0%	2%	13%	11%	13%	9%
Post-2005							
$\$ (x 10^6)$	4.6	3.0	20	31	257	321	**639**
COV	0.39	0.42	0.30	0.15	0.12	0.15	0.09
Collapse	0%	0%	4%	2%	71%	75%	25%

[1]Expected value of losses in scenario event in 2009 dollars, averaged over 1000 realizations.
[2]Coefficient of variation of the estimate of regional loss, based on 1,000 random realizations
[3]Percentage of the buildings that collapsed

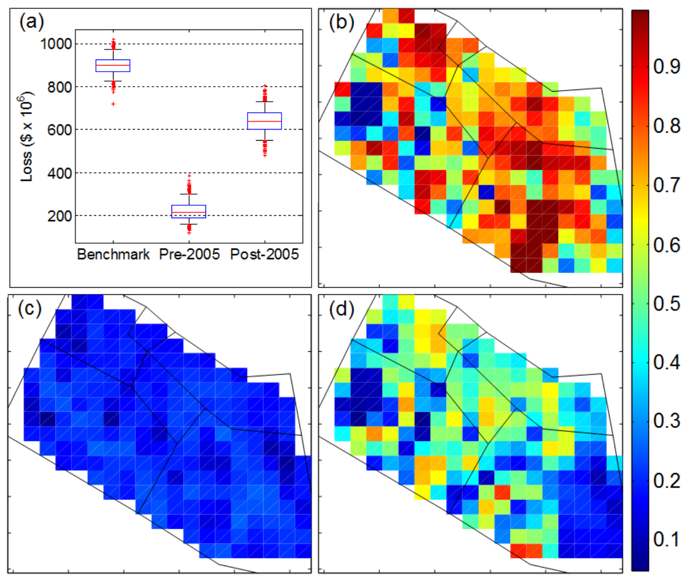

Figure 5. (a) Boxplots of regional losses for 1000 realizations. Average predicted loss as a fraction of replacement cost for (b) Benchmark, (c) Pre-2005, and (d) Post-2005 methods for the ShakeOut scenario.

The Benchmark is seen as the best estimate of regional loss, given the scenario event, because it relies on dynamic time-history analysis of nonlinear simulation models to compute building damage and losses. The Pre-2005 and Post-2005 methods do not account for structural responses (*i.e.* EDPs) directly.

As expected, the Pre-2005 method significantly underestimates the regional loss for the case-study building stock. The Pre-2005 method predicts lower losses than both other methods because results are based on maps of site IMs that are on average close to the expected values from a GMPE. However, the ground motion intensities from the ShakeOut scenario are above the expected value at virtually every site, as is characteristic of events that cause large losses. In particular, the ShakeOut ground motions have lots of energy at periods greater than 1.0 sec., which is the period range in which four of the six model buildings fall. As a result, the entire range of regional losses predicted by the Pre-2005 method severely under-estimates the losses for this event. The Pre-2005 method cannot capture these effects because it neglects spatial correlations in IM.

Recall that the Post-2005 method uses the IM values that are recorded directly from the ShakeOut simulation. It is expected that robust empirical models for generating ground-shaking intensity maps, *i.e.* those that consider spatial correlation, are capable of capturing distributions of IM like what is observed in the ShakeOut earthquake. Therefore, this method demonstrates the kind of loss that could be predicted by loss estimation procedures that implement such models. Overall, the Post-2005 method makes a much closer regional loss prediction to the Benchmark prediction than the Pre-2005 method. Obviously, using realistic ground motion intensity maps improves the estimate, but there is still a significant portion of the loss that is not explained by ground motion intensity.

A major source of the difference between the Post 2005 and Benchmark methods results from differences in buildings that are identified as collapsed, especially for model building Nos. 3-6. The Pre-2005 and Post-2005 methods consider collapse independently for each building, based on its collapse capacity distribution (conditioned on IM) and the IM at the site. However, model buildings 3-6 tend to have larger than typical structural responses to the ground motions, given IM, which results in higher collapse rates (and larger EDPs in general) for those buildings. These larger than average responses result from frequency content characteristics, *e.g.* long period energy, of the ShakeOut earthquake that tend to be particularly damaging for buildings. In the context of regional loss assessment, these higher than expected EDP values reflect site-to-site correlations in the relationships between IM and EDP.

The observations above describe the patterns in total losses for the entire test stock in the scenario event. Note, however, the patterns of loss for the subset of the building stock represented by model buildings No. 1 and 2 are an exception. These model buildings have fundamental periods of 0.6 sec. and 0.91 sec., respectively. At periods less than 1.0 sec., the ShakeOut scenario produces average level shaking (*i.e.* similar to the expected values from GMPEs) in the case-study region. Therefore, the Pre-2005 method predicts regional losses similar to the losses predicted by the Post-2005 method (10% different) for those buildings, because the $Sa(T_1)$ values from the geophysical simulations (Post-2005) and the GMPE (Pre-2005) are similar.

The distribution of the losses, as indicated by the COV, serves as further comparison between the three different methods. In this scenario loss assessment, the distribution of loss realizations from the Benchmark method overlaps significantly with the distributions of the loss realizations from the Post-2005 and Pre-2005 methods for buildings that are represented by model buildings 1 and 2. This indicates that the Pre-2005 and Post-2005 methods may be capable of capturing the same losses as more robust methods, *e.g.* those that directly consider spatial correlations of EDPs, for this subset of buildings. However, a side-study was conducted for which ten times as many low and mid-rise ductile buildings (*i.e.* those represented by model buildings 1 and 2) were included in the building stock. Due to the larger number of buildings, the sum of their losses had a stronger central tendency, such that the losses had smaller coefficients of variation (Montgomery and Runger 2007). With the larger building stock, the Pre-2005 and Post-2005 methods predicted different regional losses than the Benchmark method for model buildings 1 and 2, and the distributions of their loss realizations no longer overlapped. It was concluded with greater than 95% confidence that IM-based methods (*e.g.* Pre-2005 and Post-2005) do not capture the regional loss that is computed with the Benchmark method for the larger building stock.

The significant differences between the regional loss estimations that are produced by the Post-2005 method and the Benchmark method suggest that ground-shaking intensity, even when it is precisely known (or robustly simulated), is not sufficient for making accurate regional loss predictions. Regional losses that are predicted from building responses (*i.e.* EDPs) are much different than those that consider only ground motion intensity, and all else equal. Therefore, it is likely that current procedures for regional loss assessment can benefit from a robust method for simulating structural response (i.e. spatially correlated EDPs), such as that proposed by DeBock *et al.* (2013).

4.2 *Limitations*

One limitation is the use of only six building models to represent all of the RC frame buildings in Los Angeles. In reality, every building is different, and should be represented by its own unique model. Such an approach, however, is computationally prohibitive. By representing every building in the test stock with one of six model buildings, we may be overestimating correlations in structural response. However, since this limitation applies to all three loss estimation methods, its impact on the relative comparisons between them is expected to be small.

A second limitation stems from the scarcity of available building stock data. The test stock is a rough estimate based on available information and may be substantially different than the actual Los Angeles RC frame building stock. More detailed building stock information does exist (Comerio and Anagnos 2012), but it is not yet publicly accessible. Due to the large uncertainty in our estimations of the

Los Angeles RC frame building stock, the *absolute* values of the regional loss estimates in the case study may not be robust. However, since the same building inventory is analyzed for each of the regional loss estimation methods, errors in the building inventory information are not expected to affect *relative* comparisons between the different loss estimation methods.

Additionally, IM-based DFs and the probability distributions of collapse, given IM, are not conditioned on the spectral shape of the ground-motion as represented by the parameter epsilon. It is well-known that epsilon is a significant predictor of building response. Conditioning on epsilon reduces the variance of the Pre-2005 estimations and reduces the expected value of the Post-2005 estimations for this case study.

5 CONCLUSIONS

Probabilistic regional seismic loss analysis relies heavily on Monte Carlo simulation methods. Past research has shown that considering spatial correlations of ground motion intensity is important for capturing the effects of large rare losses. In this case study, seismic-induced losses to the downtown Los Angeles RC frame building stock, due to a M_w 7.8 rupture of the San Andreas Fault, are computed by three different methods.

The comparison of the three different assessment methods shows that robust techniques for simulating ground shaking intensity (*i.e.* those that consider spatial correlations of the intensity) are vital for simulating large rare losses. However, appropriate representation of spatial correlations in ground shaking intensity may not be sufficient. The results, particularly the limitations in the Post 2005 method to recreate the Benchmark results, indicate that current regional loss estimation techniques may need further refinement. Even if spatially correlated ground motion intensities are considered, the spatial correlations in buildings' EDPs are needed in order to fully capture the effects of large rare losses when performing probabilistic regional seismic loss analysis.

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