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A MODEL FOR GLOBAL LOSS ESTIMATION IN EARTHQUAKES

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ABSTRACT

A new approach, which predicts the statistical distribution of the damage factor for a class of building in an inventory by using simulated time histories of ground motion coupled with a realistic structural model, is proposed to estimate building damage in earthquakes. While sensitive to the stochastic nature of the problem, the approach attempts to model the physical underpinnings of the process in a manner which permits quantitative assessment of the uncertainties in each phase of the modeling process and enables evaluation of the sensitivity of the final estimates to these uncertainties.

Case studies are also presented to compare the calculated building loss with damage data collected for wood-frame residential buildings in the City of Watsonville affected by the Loma Prieta earthquake and in the City of Los Angeles affected by the Northridge earthquake. The results show that the pattern of predicted building damage captures in a meaningful way the distribution of the building damage observed.

KEYWORDS

Building damage; insurance loss; ground motion; structural response.

INTRODUCTION

Recent earthquakes have shown that building damage and associated loss can be significant. Federal, state, and private agencies want to know how to mitigate the economic losses in earthquakes through preparedness; the insurance industry wants to know their expected loss in a certain time period to manage the potential risk; and homeowners want to know how to protect their properties from earthquakes. All of these factors call for reliable loss estimation methodologies.

There are three main components of the loss model from earthquake occurrence to structural damage. The first component involves the characteristics of the earthquake, including its magnitude, energy release level, fault rupture duration, frequency range, etc. The second is ground motion prediction, which depends upon the attenuation and local soil conditions. The third includes the structural response and quantification of damage due to the ground motion.

The earthquake loss estimation methodology suggested here is designed as a framework which combines the above modules. The modules are closely connected, but they can also be modified and replaced separately without reconstructing the whole methodology. The new method can therefore incorporate new knowledge and information, be adapted to other regions, and provide a better probabilistic insight into regional losses in earthquakes than existing methods. Here the framework, which includes ground motion generation, local soil amplification, structural dynamic response, and the building damage and loss calculation, is discussed. Two examples are then presented.

NEW LOSS ESTIMATION MODEL

There are two perceived advantages of using the model developed here over using other existing approaches:
1. Instead of using a number of single-parameter descriptors for building damage estimation, the new model estimates building damage by using all the available information in the path (such as ground motions which are able to fully represent the earthquake effect on buildings) from earthquake to building economic loss; and
2. because several key physical modules are used to calculate the building damage, uncertainty at each step can be incorporated into the model in a statistically consistent manner. Each module is be briefly discussed below.

Earthquake Occurrence

The assessment of the earthquake occurrence at a given location is the first step in building loss estimation. Potential earthquakes that affect a site can be determined from both seismological data and historic earthquake information (based on geographical location). There are commonly two kinds of probabilistic models used form temporal prediction of the earthquake after the potential faults are determined: The Poisson model and stochastic slip-prediction model. The parameters in these models are difficult to determine with confidence because of lack of sufficient earthquake occurrence data, and this component is not currently incorporated in the model.

Ground Motion Generation

Ground motion modeling is the primary link between earthquakes and above-ground structures. In conventional models for loss estimation, the Modified Mercalli Intensity (MMI) is used to represent the ground motion (Jones and Liu 1994). In the Northridge earthquake, however, it is evident that the relationship between maximum acceleration and MMI does not fit the real data collected (Liu and Jones 1996a). One of the reasons is that building technology is improving, and so therefore has the capacity of structures to resist earthquakes. Also, the qualitative nature of the MMI affects the consistency in relationships among building damage, maximum acceleration, and MMI.

Ground motion has been generated to act as an input to the structural model to estimate the potential loss. The procedure, which use physical models of the earthquake source release and wave transmission process to quantify the characteristics of strong seismic ground motion, has been developed by seismologists (e.g., Boore 1983). The effect of local soil conditions is also considered by using a frequency-dependent amplification factor based on the coda wave analysis at the site (Chin and Aki 1991). The principal goal is to match frequency content of accelerograms by controlling the power spectral density and to match amplitudes of accelerograms through application of temporal modulation functions.

Structural Modeling

Once a ground motion (or ensemble of records) at a candidate site is simulated using the above procedure, its effects on structures at the site can be modeled and calculated by using principles of structural dynamics. For multiple-degree-of-freedom structures, a simplified method is used to convert the structures into single-mode equivalents by effectively considering only their first modes. The model for structural response is able to incorporate a variety of structural and nonstructural failure types, such as soft-story failure in a structure, foundation failure, and chimney failure (Liu and Jones 1996a).

Building Damage

Physical damage to a building, which includes cracks in the wall, permanent deformation of structural elements, and collapse of the structure, is difficult to define and interpret except in two extreme cases: no damage and total damage. Therefore, a dollar loss for the building is often used simply because the definition of economic loss is more tangible. This is the reason that many methods avoid the assessment of physical damage and use an economic loss metric only to assess the damage to a building (ATC 1985). Here, the concept of physical damage to a building is still adopted together with an assessment of the associated economic loss because it is believed that both the concepts are useful descriptions of the damage level in building.

A damage factor is defined based on a modification of Park and Ang's original model as (Park and Ang 1985)

$$DF = k_\alpha \cdot \alpha \cdot \frac{D_m - D_y}{D_u - D_y} + \beta \cdot \frac{\int dE}{E_{\max}}$$

and

$$k_\alpha = (1 - \frac{k_2}{k_1}) + \frac{k_2}{k_1} \cdot \frac{D_m - D_y}{D_u - D_y}$$

where D_m is maximum deformation induced by the earthquake; D_u is the ultimate deformation under monotonic loading; dE is incremental absorbed hysteretic energy, and β is a strength deterioration parameter which has to be found experimentally. The model assumes a bilinear stiffness with initial stiffness k_1 and second stiffness k_2 . The first term in above equation: $1-k_2/k_1$ is necessary for the continuity of the structure displacement effect on the building damage factor (the change of ratio of post-yielding stiffness k_2 to original stiffness k_1), and the second term incorporates the continuity of the displacement effect from the yielding point to the ultimate (failure) point.

By using a few simple considerations, some basic relationships between building physical damage and economic loss can be hypothesized. Except for some critical points and slopes which have (more or less) physical meanings, there are few data to support the relationships. Replacement cost is used to represent the critical point for the structure replacement. Its mean and variance can be input by users using engineering and economic judgment.

Loss in the insurance context is the loss after applying the deductibles to the total loss. If the deductible da and coverage limit db ($0 \le da < db \le 1$) are assumed, the effective loss factor LF_{eff} for a structure will be

$$LF_{eff} = \min[\max(LF - da, 0), db - da]$$

Notice: $0 \le LF \le 1$ *and* $0 \le LF_{eff} \le db - da$.

Implementation Procedures

All the above components of loss estimation, from earthquake occurrence to building economic loss, are linked in a procedure to calculate the consequence of earthquakes due to structural failures. Due to the stochastic nature of the process, the exact economic loss cannot directly be calculated, but the properties of this randomly distributed loss can be broadly estimated by Monte Carlo simulation.

Almost all the parameters used to describe the geophysics, structure, and damage are treated as random variables in the model because of their uncertain nature. The simulation begins with defined earthquakes at specific faults. The loss estimation proceeds as follows:

1. Divide the fault into subruptures;
2. generate the power spectral density of ground motion for each subrupture;
3. modify power spectral densities to account for local soil amplification;
4. simulate the time history at the site for each subrupture;
5. modify the time history by a suitable temporal function;
6. obtain the ground motion at the site by adding all the time histories of subruptures;
7. modify the ground motion to account for the nonlinearity of local soil amplification;
8. apply the ground motion to a structure and calculate its dynamic response;
9. calculate the damage factor for the structure; and
10. estimate the economic loss to the structure.

Structural Inventory

In order to assess the building damage caused by earthquakes, it is important to know the structural and functional characteristics of the buildings exposed to the hazard. For instance, buildings with similar structural type should be grouped appropriately. If the number of the classifications is too detailed (too many classifications), the building quantity in each category will be too small to have any meaningful statistical interpretation. If it is too coarse, the representative characteristics of different building categories will be lost. Therefore, the quality of the building inventory strongly affects the quality of the building loss estimation.

It is very difficult to compile a good building inventory. This situation is gradually improving with more experience from mitigation activities in earthquakes. A building database is currently being developed which contains information on basic parameters for hundreds of buildings and provides some assistance in this regard (Khare and Jones 1996a, b).

Using current structure inventories, the uniqueness of each individual building can be modeled by the use of uncertain structural parameters in the new model. This model has a significant advantage in statistically estimating building damage and loss because it can treat uncertainties of all parameters simultaneously using Monte Carlo simulation. The precision of each parameter will ultimately define the precision of whole process. This type of simulation is efficient for this application as the loss distribution is bounded and extremes are not needed in detail.

CASE STUDIES

The new method, which uses state-of-the-art components at every step, was evaluated using recorded ground motion and real building loss data collected in the Loma Prieta earthquake, October 17, 1989 and the Northridge earthquake, January 17, 1994. In the City of Watsonville, basic damage information on 8,063 buildings was collected (Jones *et al.* 1995), and in the City of Los Angeles, a damage inventory on 1,373,605 buildings was collected (EQE and OES 1995).

To reflect the stochastic nature of the problem, an ensemble of one thousand cases was generated by Monte Carlo simulation of parameters associated with modeling of the earthquake, structure, and damage. The parameters are all chosen randomly to simulate a sense of the effect on the damage factor distributions. The principal task here is to compare simulated building losses with those recorded in these earthquakes and to study the pattern of building damage.

City of Watsonville in Loma Prieta Earthquake

Accelerograms for five sites at which ground motions were recorded during the Loma Prieta earthquake were first generated and compared with the recorded accelerograms at these sites. Table 1 shows the statistical characteristics of the seismological parameters used in the simulation of these ground motions. Some parameters, such as moment magnitude, are taken as pseudo-deterministic because of their clear definitions and/or measurements. Others are treated as random variables with mean values assigned based on a review of the literature, and their distributions and COVs assigned based on judgment and physical reasoning.

Table 1. Seismological and structural parameters for Loma Prieta earthquake.

Parameter	Distr.	Mean Value
Epicenter location	fixed	(37°2'N; 121°53'W)
Fault length	fixed	40 km
Fault width	fixed	13 km
Depth	fixed	11.5 km
Subruptures	fixed	5
Rupture Spread Velocity	fixed	2.4 km
Moment magnitude	fixed	6.9
Seismic moment	fixed	2.2×10^{26} dyne/cm
Stress drop	normal	100 bar
Average slip	fixed	141 cm
Cut-off frequency	fixed	8 Hz
Rock rigidity	fixed	3×10^{11}
Crustal density	normal	2.5 gm/cm^3
Wave velocity	normal	3.2 km/sec
Regional quality factor	normal	150.0
Story height	fixed	3.2 m
Floor mass	normal	5000 kg
Natural frequency	normal	2.5 Hz
Damping ratio	normal	0.05
Yielding displacement	normal	4.8 cm
Ductility	normal	4.0
Post-yielding stiffness	fixed	0.0
Displacement coeff.	fixed	1.0
Energy coeff.	fixed	0.05
Relationship between damage and loss	fixed	straight line

The accelerograms recorded at site ST31: Watsonville--Four-Story Commercial Building (ground floor) are shown in Fig. 1(a) (CSMIP 1989). The local site was described as "fill over alluvium". The detailed shear wave velocity information of the local soil was not available, so local soil effects are not considered at this site. Two generated accelerograms are shown in Fig. 1(b). It can be seen that the generated accelerograms are able to reasonably represent the real ground motions. Fig. 2 compares the average Fourier spectra of generated and recorded accelerograms at the site. From the figure, it can be seen that the spectrum of generated accelerograms matches the spectrum of recorded very well from 0 to 4 Hz. Above 4 Hz, simulated accelerograms seem to have a little richer high-frequency contents than recorded. The following building damage analysis is based on these generated accelerograms. The accelerograms, in general, can also be seen to be spectrally consistent (Liu and Jones 1996b).

Most wood buildings in the city are one- or two-story wood-frame residential buildings (predominantly one-story buildings), so the structures are modeled using a simple SDOF system. All the structural parameters for wood-frame class are listed in Table 1. Loss data collected in Watsonville and the simulated results using the ATC-13 based approach were compared to the results of the model and presented in other publications (Jones and Liu 1994; Liu and Jones 1996b). By comparing these data, it is clear that the "real" distribution of damage factors from the field data and the results of the new model match well. It is also apparent that the distribution of building damage is not a bell-like curve, not a Beta distribution.

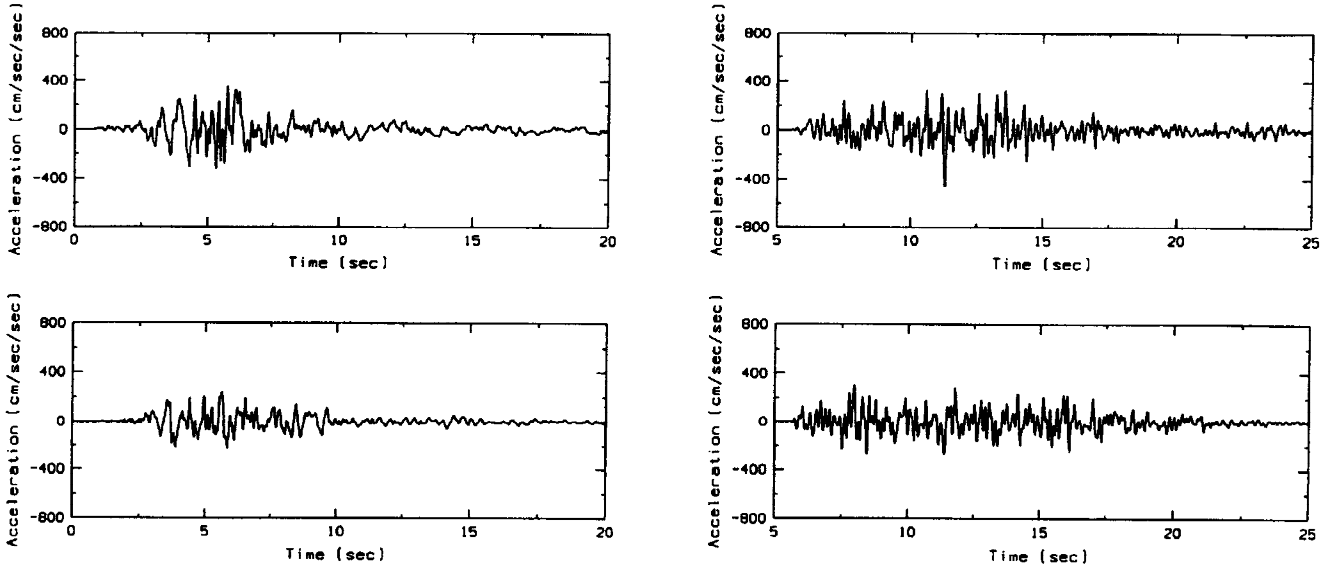

Figure 1. Recorded (a, left) and generated (b, right) accelerograms at Watsonville (ST31).

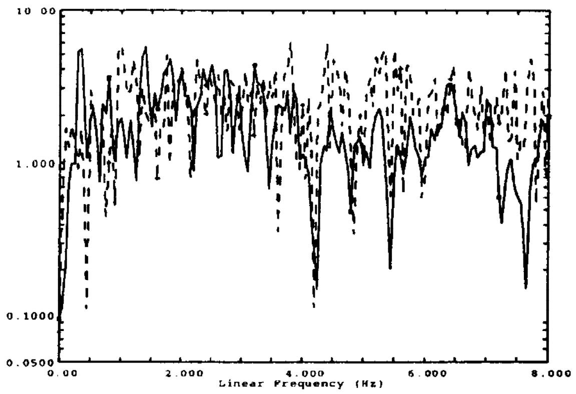

Figure 2. Fourier spectra of recorded accelerograms (solid line) and that of simulated (dashed line) at ST31.

City of Los Angeles in Northridge Earthquake

Here, one-story wood-frame buildings are again used as typical structures to show the damage and loss distribution of buildings in the earthquake, because most of the wood-frame single-family buildings are in the one-story range. The simulated results are compared with data collected from the field. The responses of two-story wood-frame buildings were also calculated. Although the damage to one-story and two-story buildings is simulated separately, their results should be considered together to get a complete picture of building damage in the Northridge earthquake.

Loss data collected in Los Angeles is compared to the simulated results of the new model (Table 2). The first column in the table shows the damage ranges. The loss distributions by age periods are shown from column 2 to 6, and the loss distribution of total wood-frame single-family buildings at soil sites is listed in the *All Bldgs* column. The results simulated by the new model are shown in last two columns (SDOF and 2DOF structural model).

It is apparent that the distributions of building losses of the collected data do fit well with the damage distribution calculated by the proposed model. Fig. 3 shows the histograms of three distributions of building losses, which are observed loss of wood-frame single-family buildings at soil sites (averaged over five construction periods) and the simulated losses using SDOF and 2DOF structure models. It is observed that the model captures the trends in the observed damage data very well.

Table 2. Distribution of damage factor of wood-frame building in Northridge earthquake.

Damage Range (%)	**<1941 Bldgs**	**1941-50 Bldgs**	**1951-60 Bldgs**	**1961-76 Bldgs**	**>1976 Bldgs**	**All Bldgs**	**SDOF Estimate**	**MDOF Estimate**
[0, 0.05]	96.16	98.03	96.31	94.60	96.56	96.33	95.70	94.50
(0.05, 0.3]	0.11	0.07	0.12	0.19	0.23	0.14	0.00	0.00
(0.3, 1.25]	0.63	0.37	0.65	1.01	0.78	0.69	0.10	0.50
(1.25, 3.5]	0.92	0.51	0.90	1.31	0.92	0.46	0.60	1.20
(3.5, 7.5]	0.82	0.45	0.86	1.21	0.62	0.40	1.10	0.90
(7.5, 20.]	1.05	0.46	0.95	1.22	0.69	0.86	1.30	1.00
(20., 65.]	0.25	0.10	0.17	0.37	0.22	0.22	1.10	1.40
(65., 100.]	0.08	0.01	0.03	0.09	0.06	0.05	0.10	0.50

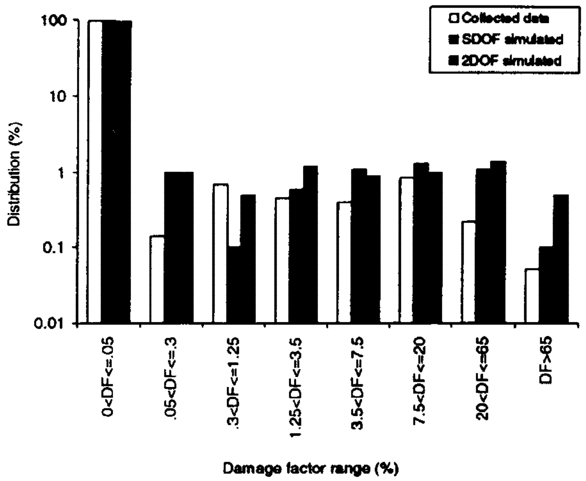

Figure 3. Histograms of simulated and collected damage factors for wood-frame single buildings.

CONCLUSIONS AND RECOMMENDATIONS

Instead of using single parameters for earthquake ground motions and other model components, which is common in existing procedures for building damage estimation, the model presented herein estimates building damage on a regional scale by modeling the path from earthquake to building economic loss based on physical models. Any new knowledge or information for any module can be easily incorporated by modifying that specific module instead of reconstructing the framework of the entire model. Because of the clear mechanisms in each part in the procedure, the variability of the modeling can be investigated properly and statistically.

After comparison with observations of past earthquake damage, the modified damage factor and loss estimation procedure appear to reflect the pattern of building damage and loss in low-rise wood-frame structures consistently. This new procedure can be extended to other types of structures with appropriate choice of parameters. The new model should also be able to make loss estimations for other events and regions by adjusting the values of parameters in the model to suitably reflect the regional differences in seismicity, geology, and building construction. It is also found that the usage of a SDOF structure is adequate for estimation of building loss for single-family wood-frame structures.

It is evident from this research that the quality of the structure inventory strongly influences the quality of building loss estimation in earthquakes. The existing structure inventory is still relatively immature compared to what is needed for different aspects of loss estimation. In addition to inventory data for structures, information on site-specific characteristics, such as local soil profiles and liquefaction potentials, is also required for reliable loss estimation.

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