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Estimation of Earthquake Losses to Buildings

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This paper describes methods for estimating building losses that were developed for the FEMA/NIBS earthquake loss estimation methodology (Whitman et al., 1997). These methods are of a new form and represent a significant step forward in the prediction of earthquake impacts. Unlike previous building loss models that are based on Modified Mercalli Intensity, the new methods use quantitative measures of ground shaking (and ground failure) and analyze model building types in a similar manner to the engineering analysis of a single structure. Direct economic losses predicted by these new methods for typical single-family homes compare well with observed losses to Los Angeles County residences damaged by the 1994 Northridge Earthquake.

INTRODUCTION

Past earthquakes have shown that economic and social losses are primarily a function of damage to buildings. This is true for two very basic reasons: (1) buildings are the predominant kind of facility in the built environment and (2) buildings are vulnerable to earthquake damage. Buildings meet a variety of needs of society: providing shelter for people, whether at home or at work, housing commercial and industrial operations, and serving as essential facilities, such as schools and hospitals. Accurate prediction of building damage and loss is at the heart of reliable estimates of earthquake impacts.

This paper describes building loss functions developed as part of the FEMA/NIBS earthquake loss estimation methodology. This methodology has many components, or modules, as described in the paper by Whitman, et al. (1997) in this *Spectra* issue. The flow of the methodology between those modules related to building damage and loss is illustrated in Figure 1. Inputs to the estimation of building damage include ground failure, characterized

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by permanent ground deformation (PGD) due to settlement or lateral spreading, and ground shaking, typically characterized by response spectra, or, for those few buildings that are components of lifeline systems, by peak ground acceleration (PGA).

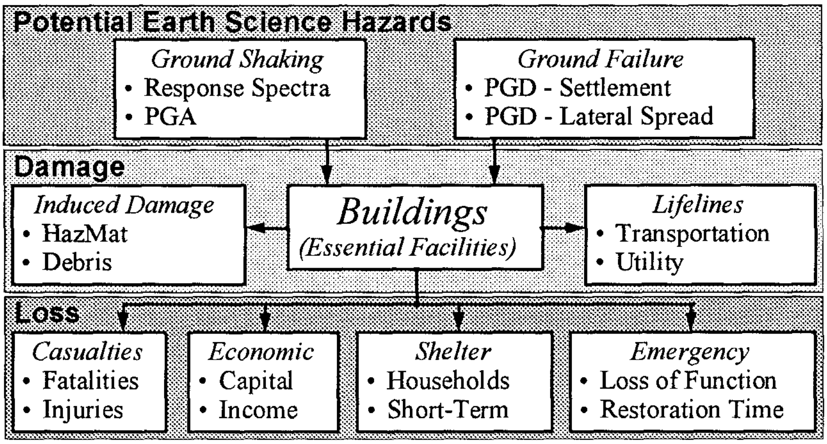


Figure 1. Building-related modules of the FEMA/NIBS methodology

Estimates of building damage are used as inputs to other damage modules (e.g., debris generation), and as inputs to transportation and utility lifelines that have buildings as a part of the system (e.g., airport control tower). Most importantly, building damage is used as an input to a number of loss modules, including the estimation of casualties, direct economic losses, displaced households and short-term shelter needs, loss of emergency facility function and the time required to restore functionality.

The FEMA/NIBS building damage functions have two basic components: (1) capacity curves and (2) fragility curves. The capacity curves are based on engineering parameters (e.g., yield and ultimate levels of structural strength) that characterize the nonlinear (pushover) behavior of 36 different model building types. For each of these building types, capacity parameters distinguish between different levels of seismic design and anticipated seismic performance. The fragility curves describe the probability of damage to a model building's (1) structural system, (2) nonstructural components sensitive to drift and (3) nonstructural components (and contents) sensitive to acceleration. For a given level of building response, fragility curves distribute damage between four physical damage states: Slight, Moderate, Extensive and Complete. A companion paper by Kircher et al. (1997) in this *Spectra* issue provides a more thorough description of the FEMA/NIBS building damage functions.

Earthquake loss due to building damage is based on the physical damage states that are the most appropriate and significant contributors to that particular type of loss. Deaths are heavily influenced by the number of buildings in the Complete damage state, which includes the kind of partial and complete collapse most likely to cause fatalities. In contrast, direct economic loss (e.g., repair/replacement cost) is accumulated from significant loss contributions in all states of structural and nonstructural damage.

The balance of this paper begins with a historical perspective on building loss estimates and its importance to the FEMA/NIBS methodology. The paper then summarizes methods for the estimation of direct economic loss to buildings (assuming that estimates of building damage have already been made). Methods for calculating other types of loss and detailed documentation of all of the topics covered in this paper may be found in the *Technical Manual* (NIBS, 1997). The paper closes with a comparison of predicted and observed economic loss to buildings using data for Los Angeles County residences damaged by the 1994 Northridge Earthquake.

HISTORICAL BACKGROUND

When considered in historical context, it is clear that in some ways the FEMA/NIBS methodology draws on previous work and represents a gradual evolutionary development, while in other respects it introduces major innovations that depart from past work.

INTENSITY AS A DAMAGE PREDICTOR

The FEMA/NIBS methodology uses quantitative definitions of ground motions rather than intensity. This is perhaps the single most useful topic to discuss in this historical context for three reasons. First, in and of itself, the way in which a loss estimation method incorporates a strong motion seismology module and defines and predicts ground shaking is of obvious importance. Second, the concept of intensity, with its long history, provides a convenient means of framing a very condensed review of some previous loss estimation methods. Third, knowing that the FEMA/NIBS methodology does not rely on intensity provides a subtle foreshadowing of the fact that damage is not predicted by graphs that relate loss to an intensity scale, but rather by means of a set of calculations that closely mimic the quantitative engineering evaluation of a single building.

If one were to update Charles Davison's 1927 book, *The Founders of Seismology* (Davison, 1927), in which he reviewed intensity scales developed since the 1780s, one would need only add to his lists the current versions of the Modified Mercalli Intensity (MMI), Japanese Meteorological Agency (JMA), Medvedev-Sponheur-Karnik (MSK) and a few others. It would not be necessary to describe the present generation of scales as a separate breed, that is, definitions have been tightened up, but the essential concept, for loss estimation purposes, of a graph or table relating damage to the number on an intensity scale still pertains. Hugo Benioff (1934) tantalizingly suggested the goal of characterizing ground motion in the title of his paper, "The Physical Evaluation of Seismic Destructiveness." This paper describes the basic approach of relating destructiveness to the "pendular spectrum" (or the response spectrum, constructed by calculating "the maximum deflections of a small finite number of pendulums"). Intensity scales have in some instances (e.g., the MSK Scale) incorporated parallel cross-referenced quantitative scales for peak ground acceleration or peak ground velocity, but incorporation of response spectra has remained elusive.

PREVIOUS LOSS ESTIMATION METHODS

John Freeman (1932) discusses early twentieth century loss estimation in the classic book, *Earthquake Damage and Earthquake Insurance*, whose title indicates the primary use of loss estimation at that time. Further developments in loss estimation in this country until about the 1970s remained largely confined within the insurance industry. The work of the Insurance Services Office (ISO) was especially influential, as discussed in Steinbrugge (1982). For insurance purposes, the prediction of physical damage is not of interest in itself; only the dollar cost of repairing the damage is desired.

With the publication in 1972 of *A Study of Earthquake Losses in the San Francisco Bay Area* (Algermissen et al., 1972), the federal government began to produce comprehensive estimates of the effects of major earthquakes on large urban regions. Direct economic losses, casualties, essential facilities' functionality, and some lifeline impacts were estimated. By the mid-1980's, these studies, produced by teams assembled by the National Oceanic and Atmospheric Administration and later the United States Geological Survey, had forecast losses for about a dozen metropolitan areas in the United States. (See NRC, 1989 and FEMA, 1994).

A program of studies at MIT, Seismic Design Decision Analysis, was begun after the 1971 San Fernando Earthquake and was directed by Robert Whitman (Whitman et al., 1974). This work popularized a new way to relate ground motion to loss, the damage probability matrix (Whitman, Reed, and Hong, 1973). Explicit recognition of the probabilistic nature of the underlying loss phenomenon became a reality that subsequent loss estimation methods could no longer overlook.

An influential study in 1985, *Earthquake Damage Evaluation Data for California*, (Applied Technology Council, 1985), commonly called ATC-13, used the Whitman damage probability matrix as its central framework. It also introduced several other notable advances in large-scale loss estimation, such as using expert opinion in a well-documented and systematic way, devising intensity-damage relations for a large number of buildings and structure types, predicting a greater variety of losses than had been previously done, and developing what might be called synthetic inventories by inferences relating structural type to building occupancy.

When the National Research Council's Panel on Earthquake Loss Estimation convened in the mid-80's, it noted that "more complex representations of ground shaking, for example, through a filtered 'effective' peak motion, a single-degree-of-freedom linear response spectrum, a nonlinear spectrum, a time history of motion, and the duration of strong shaking, have the ability to be more accurate predictors of damage and loss. There is less agreement, however, on how to estimate these functions for a future earthquake, how to quantify the single or multi-dimensional hazard associated with them, and how to derive an accurate predictor of damage from them." (NRC, 1989).

It is precisely the challenges defined by the Panel's 1989 report that the FEMA/NIBS methodology addresses, by using spectral response curves, capacity curves, and push-over analyses that parallel procedures used in the engineering design and evaluation of actual buildings to predict damage and loss. In this sense, these new methods follow the spirit of the recommendations of the National Research Council's Panel on Earthquake Loss Estimation and accomplishes in the field of large-scale loss estimation what Hugo Benioff and others of the 1930s could envision but not yet produce.

BUILDING LOSS FUNCTIONS

Building loss functions of the FEMA/NIBS methodology may be thought of as the second part of an integral two-step process in which estimates of building damage (i.e., probability of damage state) are transformed into estimates of various types of loss. The companion paper by Kircher, et al. (1997) in this *Spectra* issue describes the first step of this process and should be referred to for estimation of building damage and description of model building types, design levels, and other building parameters.

The building loss functions are typically complex and a full description of the background and theory is beyond the scope of this paper. The reader is directed to the *Technical Manual* (NIBS, 1997) for additional information. The balance of this section provides a summary description of direct economic loss functions for buildings.

DIRECT ECONOMIC LOSS FUNCTIONS

Direct dollar loss is defined in the FEMA/NIBS methodology as either capital-related or income-related. Capital-related losses for buildings include costs for repair and replacement of damage to the structural system, nonstructural components and building contents (including business inventory for commercial facilities). Income-related losses for a building include rental income loss, relocation expenses, and other losses directly caused by damage to the building, and while these losses are included in the methodology, they are not within the scope of this paper.

Direct economic losses depend on both building occupancy class (e.g., single-family residences) and model building type (e.g., light-frame wood, W1). Inventory information defines the floor area of each model building type used for each occupancy class in each area (i.e., census tract or group of census tracts) of the region being studied.

The FEMA/NIBS methodology provides default values for building repair and replacement cost (expressed in terms of dollars per square foot) for each combination of model building type and occupancy class. While it can be argued that the true cost of buildings damaged or destroyed is their loss of market value, replacement cost provides an immediately understandable picture of the community building loss. Furthermore, disaster assistance and most insurance is based on replacement cost. Market value is by no means constant in relation to replacement cost. For example, typical estimates of market value include lot value, which is not included in the replacement cost of a building and may cause market value to greatly exceed replacement cost.

Default values of repair and replacement costs are specified separately for the structural system, nonstructural drift-sensitive components and nonstructural acceleration-sensitive components of the building. The relative percentage of total building cost allocated to structural and nonstructural systems is derived from *Means* (Jackson, 1994) component data for each building occupancy class. For most classes, the nonstructural portion of the cost is about 75% of the total. In addition, adjustment factors based on *Means* data are used to reflect differences in construction cost for different regions of the United States. Contents value is expressed as a percentage of structural and nonstructural replacement cost for each occupancy class in a manner similar to that of *ATC-13* (ATC, 1985), but with different (lower) rates.

The costs of Slight, Moderate, Extensive and Complete structural and nonstructural damage are defined as fractions of full replacement cost of the building. These fractions are similar in concept to the central damage factors of ATC-13 (ATC, 1985), but are calibrated to better reflect observed earthquake losses. Damage to contents follows the same approach as that of the building, except that only 50% of all contents are assumed to be susceptible to earthquake damage, even in the case of Complete damage. The relationship between damage state and replacement cost is summarized in Table 1 for the structural system, nonstructural components, and contents.

Table 1. Direct economic loss as a percentage of building replacement cost by damage state

Damage State	Structural System	Nonstructural (Drift Sensitive)	Nonstructural (Acceleration Sensitive)	Contents
Slight	2%	2%	2%	1%
Moderate	10%	10%	10%	5%
Extensive	50%	50%	50%	25%
Complete	100%	100%	100%	50%

The process for determining direct economic capital-related loss to all buildings in a given study region is illustrated by the logic tree shown in Figure 2.

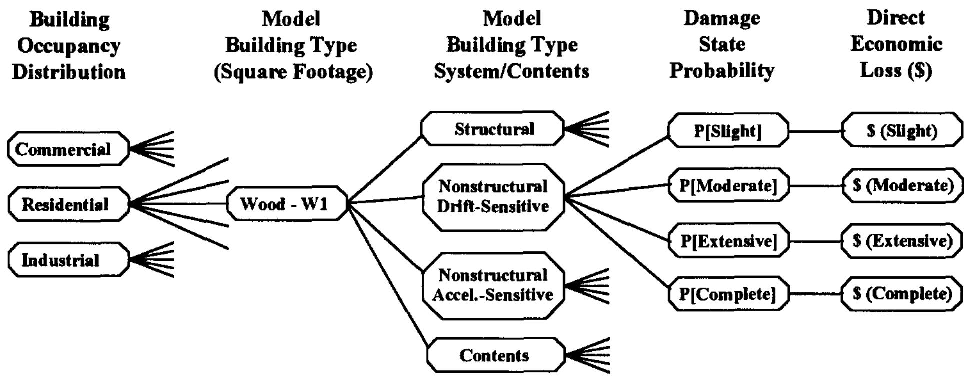


Figure 2. Logic tree for calculation of direct economic loss to buildings

Equation (1) illustrates the calculation of direct economic loss due to structural damage for a given model building type (e.g., single-family residential, light-frame wood building):

$$\$\text{Loss (Structural)} = \text{Square Footage}\left(\sum_{i}^{\text{damage-states}} P_i[SD]\,\$R_i[SD]\right) \tag{1}$$

Structural system loss rates, $\$R_i[SD]$, and nonstructural component and contents loss rates are given in Table 2 for a typical California, single-family residence. The term, $P_i[SD]$, in Equation (1) represents the probability of structural damage of damage state i. Similar equations are used to calculate losses due to damage to nonstructural drift-sensitive components, nonstructural acceleration-sensitive components, and contents.

Table 2. Typical loss rates for single-family residences of light-frame wood construction located in California (dollars per square foot)

Damage State	Structural System	Nonstructural (Drift Sensitive)	Nonstructural (Acceleration Sensitive)	Total Building	Contents	Building Plus Contents
Slight	$0.38	$0.80	$0.43	$1.60	$0.40	$2.00
Moderate	$1.88	$2.00	$2.13	$8.00	$2.00	$10.00
Extensive	$9.38	$20.00	$10.63	$40.00	$10.00	$50.00
Complete	$18.75	$40.00	$21.25	$80.00	$20.00	$100.00

Total loss to this particular building type and occupancy class is the sum of structural, nonstructural and contents losses. The total loss to all residences is the sum of the individual losses to each type of building used for residential construction. Total loss to all buildings is the sum over all occupancy classes.

PREDICTED AND OBSERVED LOSS - 1994 NORTHRIDGE EARTHQUAKE

As part of the development of the FEMA/NIBS methodology, loss functions were calibrated by comparing predicted loss with observed loss due to previous earthquakes, including the 1994 Northridge Earthquake. For the 1994 Northridge Earthquake, predictions of damage and loss were based on response spectra of ground shaking records. These comparisons either verified that building loss functions could reasonably replicate observed impacts, or in certain cases, loss functions were revised to achieve better correlation between predicted and observed losses.

Los Angeles County was selected as the study area for comparison of predicted and observed losses of the 1994 Northridge Earthquake. Los Angeles County is large (over 1,600 census tracts) and includes most of the populated areas that felt strong ground shaking. Losses were evaluated for individual census tracts, and aggregated results were used for calibration of loss functions.

To permit comparison with other loss estimation methods (and to simplify results for this paper), Los Angeles County census tracts are grouped into five regions of common Modified Mercalli Intensity (MMI). Intensity data was taken from the MMI map of Dewey (reproduced in the California Governor's Office of Emergency Services report on the 1994 Northridge Earthquake, OES, 1995). Figure 3 shows MMI shaking regions superimposed on top of the distribution of building value (i.e., replacement cost per square mile) of Los Angeles County residences.

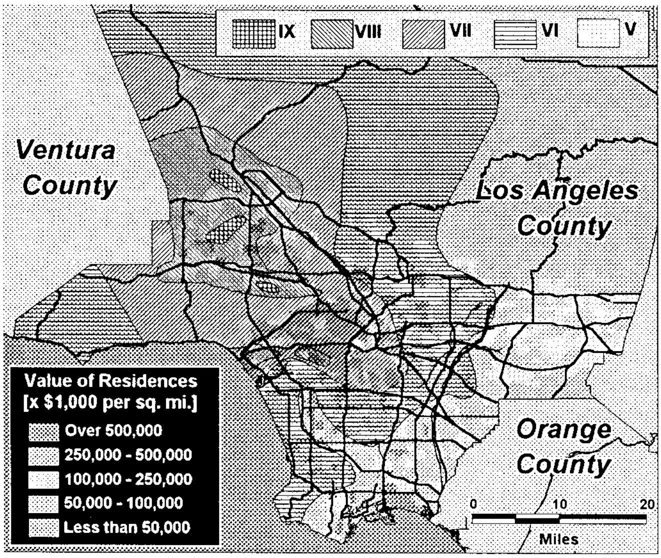


Figure 3. Map of Los Angeles County residential building value and MMI shaking regions of the 1994 Northridge Earthquake. *In color:* see plates following p. 738.

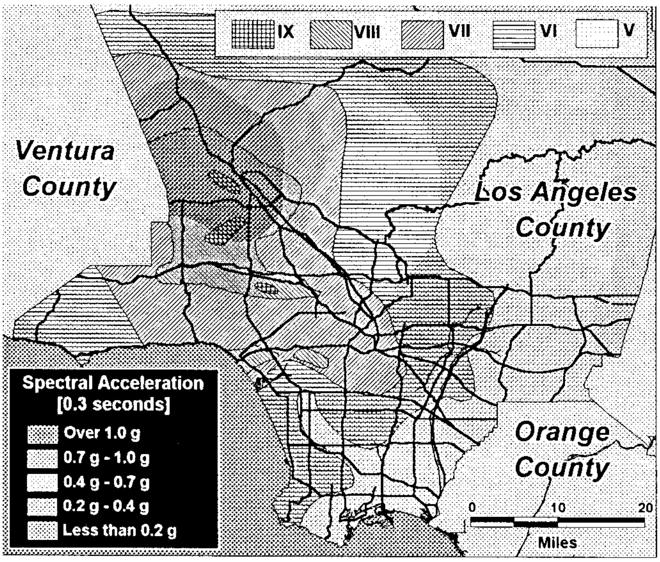
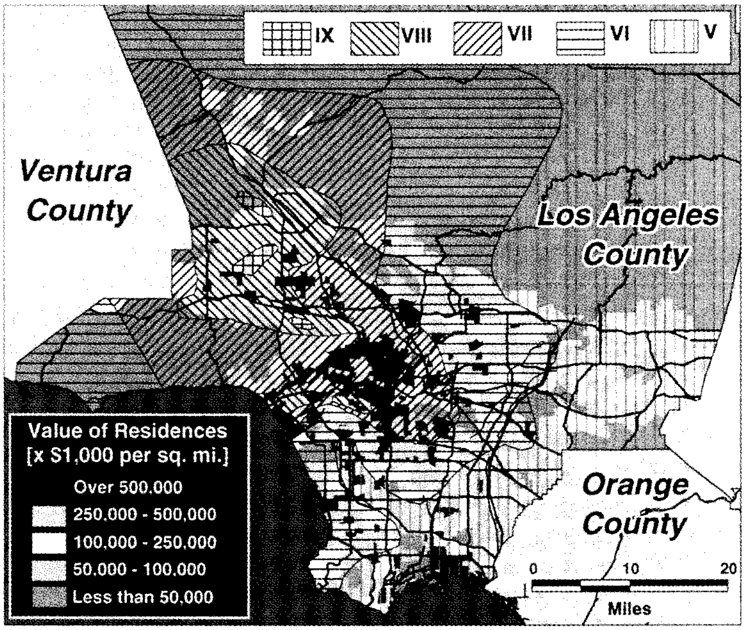
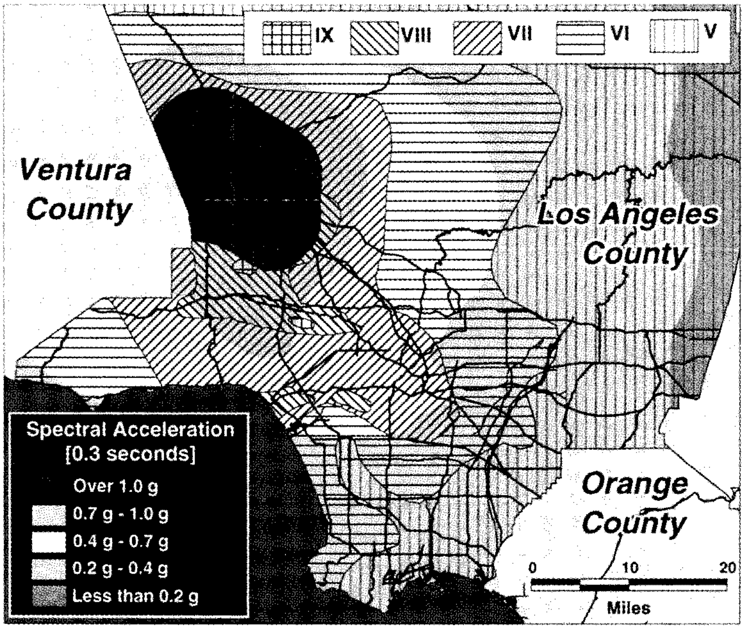


Figure 4. Map of Los Angeles County comparing 0.3-second spectral acceleration response and MMI shaking regions of the 1994 Northridge Earthquake. *In color:* see plates following p. 738.



8) Map of Los Angeles County residential building value and MMI shaking regions of the 1994 Northridge earthquake. From Kircher et al., p. 710.



9) Map of Los Angeles County comparing 0.3-second spectral acceleration response and MMI shaking regions of the 1994 Northridge earthquake. From Kircher et al., p. 710.

Representative ground response spectra (5% damping) are developed for each of the five regions of MMI shaking intensity. These spectra are based on weighted averages of individual census tract spectra of each MMI shaking region. Spectra are weighted by building floor area (since all census tracts do not have the same quantity of buildings). Individual census tract spectra are based on the spectral contour data developed by Somerville for the SAC Joint Venture investigation of steel moment frame structures (SAC 95-03, 1995). Figure 4 shows MMI shaking regions superimposed on top of 0.3-second spectral acceleration data used to define short-period earthquake demand.

The spectral contour data are based on recorded ground motion smoothed to eliminate local effects. Spectral demand (and corresponding loss predictions) for an individual census tract may not be valid, since smoothed spectral contour data may overpredict (or underpredict) actual ground shaking at an individual tract. Average spectral demand produces valid results, provided there are a sufficient number of census tracts in each group to determine a reliable estimate of ground shaking. All MMI shaking regions have a large number of census tracts, except MMI IX which does not contain a sufficient number of census tracts to produce a reliable estimate of typical ground shaking. Ground shaking for the MMI IX shaking region is estimated as 1.5 times the shaking for MMI VIII. This level of ground shaking is slightly above the calculated average, but well within the scatter of spectral contour values for census tracts of the MMI IX shaking region.

Figure 5 shows a plot of the ground response spectra (5% damping) developed for each of the five MMI shaking regions. The response spectrum for the MMI VIII shaking region is about 80% of the response spectrum required by the *Uniform Building Code* (ICBO, 1997) for design of buildings located in Seismic Zone 4 on stiff soil (Site Class D) at least 10 km from active sources. This level of ground shaking is not expected to cause life-threatening damage to modern buildings designed for earthquakes, but is sufficiently strong to cause some amount of structural and nonstructural damage.

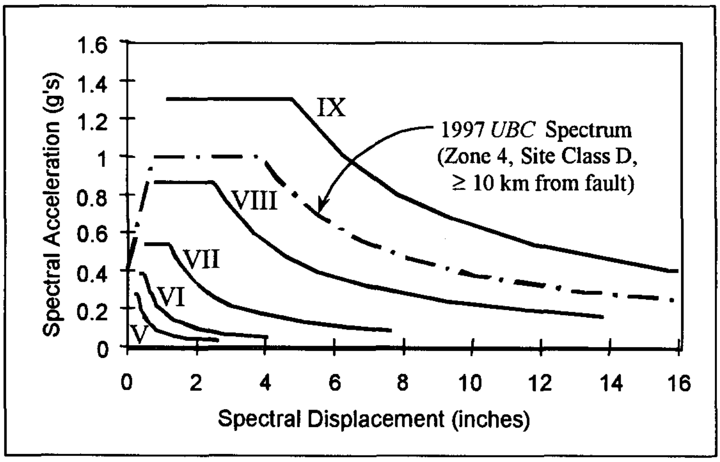


Figure 5. Average 5%-damped response spectra of the 1994 Northridge Earthquake for MMI shaking regions V - IX

LOS ANGELES COUNTY STUDY REGION

Population and building inventory data for Los Angeles County are based on census data provided with the FEMA/NIBS methodology, and on tax assessor data. Key information on population and building inventory, including the number, value (replacement cost), age, and construction of residences, is summarized in Table 3 for Los Angeles County as a whole, and as distributed among each of the five MMI shaking regions.

Table 3. Los Angeles County population and building inventory data by MMI shaking region

Population or Building Inventory Item	MMI Shaking Region - Los Angeles County					
	All	V	VI	VII	VIII	IX
Population ($x10^3$)	8,863	2,628	2,545	2,590	1,007	92
Number of Buildings (x 10^3)	2,254	745	682	526	272	28
Number of Residential Buildings and Living Units						
All Residences (x 10^3)	2,023	670	614	460	254	26
Single-Family Units (x 10^3)	1,740	578	548	386	206	23
Multi-Family Units (x 10^3)	1,334	288	301	555	180	10
Mobile Homes (x 10^3)	55.4	31.1	13.7	5.0	5.6	0.0
Replacement Cost of Residential Buildings - Dollars in Billions						
Building without Contents	$340B	$99B	$95B	$102B	$40.5B	$3.5B
Contents (50% of Building)	$170B	$49B	$48B	$51B	$20.5B	$1.5B
Building plus Contents	$510B	$148B	$143B	$153B	$61B	$5B
Building plus Contents (%)	100%	29%	28%	30%	12%	1%
Age and Construction of Residential Buildings						
Pre-1941 Residences (%)	29%	17%	32%	50%	14%	22%
1941-1976 Residences (%)	65%	62%	56%	36%	68%	68%
Post-1976 Residences (%)	16%	21%	12%	14%	18%	10%
Wood Residences (%)	99.2%	99.5%	98.4%	98.4%	99.3%	99.6%
Brick Residences (%)	0.5%	0.4%	0.4%	0.7%	0.4%	0.3%

Based on building value (defined as the replacement cost of the building, excluding land value), only about 12% of all residential construction is located in the MMI VIII shaking region, and just over 1% of all residential construction is located in the MMI IX shaking region. This distribution of building value is illustrated in Figure 6, which also shows the relative amount of replacement cost for the structural system, nonstructural drift-sensitive and acceleration-sensitive components, and building contents. Direct economic loss to residences due to damage in the MMI IX shaking region was not a significant portion of total residential loss, simply because only a small fraction of all residences are located in this region of shaking intensity.

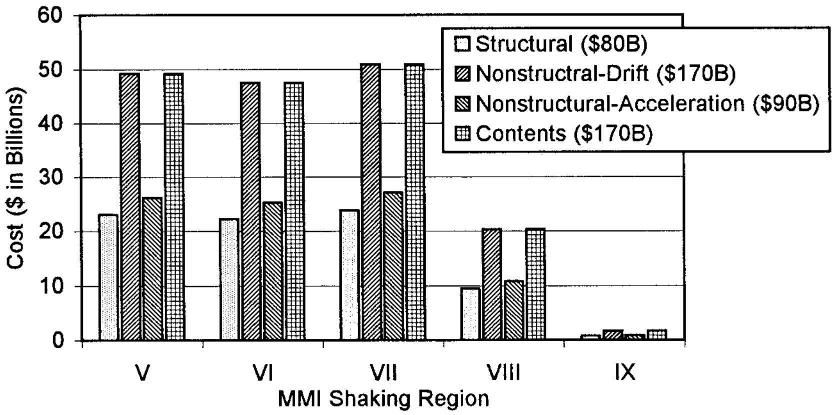


Figure 6. Replacement cost of Los Angeles County residences by MMI shaking region

Los Angeles County has a total population of 8.86 million people and an inventory of 2.25 million buildings. About 90% (over 2 million) of all buildings are residential. In terms of the replacement cost (based on floor area), residences represent about 75% of the total value of all buildings. Residences in Los Angeles County have a replacement cost (without contents) of $340 billion, or about $510 billion with contents.

Over 99% of all residences are wood construction (excluding mobile homes). This percentage applies to single-family residences, which are the most common type of residence. Multi-family residences are primarily wood construction, but also include about 5% steel, concrete or masonry buildings. There are 1.74 million single-family living units (residences) and 1.33 million multi-family living units (in about 230,000 buildings). In rough numbers, single-family residences represent about 75% of the total residential value. These data indicate that light-frame wood buildings (i.e., model building type W1 of the FEMA/NIBS methodology) are by far the most common type of residential building.

By age, about 29% of all residences in Los Angeles were built before 1941, about 65% were built between 1941 and 1976 and about 16% were built after 1976. These data indicate that residences were typically built to the seismic requirements of the *Uniform Building Code*, but before modern seismic-code criteria were adopted (i.e., Moderate-Code design level of the FEMA/NIBS methodology). In general, damage to residences built before 1941 (i.e., Pre-Code design level), such as wood buildings with cripple walls without bracing, or unreinforced masonry (URM) buildings, is expected to be much higher than that predicted by Moderate-Code buildings. However, the number of particularly vulnerable buildings is relatively small, and hazard reduction programs, such as Los Angeles City's Division 88 program to retrofit URM buildings, have helped reduce losses in these types of buildings (SSC, 1995).

To illustrate the loss estimation process, this paper predicts economic loss to residences based on a single model building type and design level (i.e., W1 buildings of Moderate-Code design). If a more realistic mix of residential building type and design vintage was used, then higher losses would be predicted. Since most residences are light-frame wood (W1) buildings of 1941 – 1973 (Moderate-Code) design vintage, losses predicted using a more realistic mix would likely not be more than 50% higher than those predicted using the W1 model building type of Moderate-Code design as typical of all residences.

OBSERVED ECONOMIC LOSS - 1994 NORTHRIDGE EARTHQUAKE

Estimates of the total cost of the 1994 Northridge Earthquake vary from $25.7 billion (Comerio et al., 1996) to more than $40 billion (Eguchi et al., 1996). The $25.7 billion estimate includes direct economic (i.e., capital-related) loss to public and private property, but does not include indirect economic loss and some amount of direct loss not covered either by insurance or governmental programs. About one-half, $12.7 billion, of $25.7 billion of total recovery and reconstruction funds is associated with residential building reconstruction. The spatial distribution of the $12.7 billion of residential loss is not known and insurance industry data is used to distribute this estimate of "observed" loss among MMI shaking regions.

Private insurance has provided most of the funds for post-Northridge reconstruction. As of June 1996, the California Department of Insurance estimates that the state's private insurance companies have paid a total of about $12.3 billion for Northridge-related claims, of which approximately $9.5 billion, or 78%, has been for residential claims. Insurance claims include four types of coverage: (1) primary structures (Type A), (2) appurtenances (Type B), (3) contents (Type C) and (4) loss of use (Type D). Loss of use (Type D) is not considered a capital-related loss by the FEMA/NIBS methodology. Type D losses account for only 5.6% of insurance claims and are not a dominant portion of observed loss.

The spatial distribution of observed residential loss by MMI shaking region is estimated based on a sample of insurance coverage and claims paid (RMS, 1996). Information on about 85,000 claims was sorted by MMI shaking region to establish the distribution of exposure (policy limits), the number of claims and the amount of "ground-up" losses. Ground-up loss reflects actual claims paid, plus an estimate of losses not covered by policy deductibles. Dividing ground-up loss by exposure provides an estimate of the insured loss ratio for each MMI shaking region. This information is summarized in Table 4.

The $12.7 billion of residential building loss appears to be low, considering that insurance companies paid about $9 billion for residential claims (excluding deductible losses) and that only about one-half of all residences were covered by insurance. The $12.7 billion amount for residential recovery and reconstruction should be considered a lower bound on direct economic loss. If the insured loss ratios of Table 4 were applied to all residences in Los Angeles County, then the estimate of residential loss would be over $20 billion (if all damage was repaired and all uncompensated out-of-pocket expenses were paid).

The $12.7 billion estimate of observed residential loss (building plus contents) is distributed by MMI shaking region in proportion to insured loss ratios. Observed loss ratios are calculated for each MMI shaking region by dividing observed loss by residential value (i.e., the replacement cost of residential buildings and their contents). Observed losses and the corresponding loss ratios are summarized in Table 4.

A total of about $10.5 billion, over 80% all residential loss, is attributed to MMI shaking regions VII and VIII. These shaking regions have both relatively large inventories of buildings and damaging levels of shaking intensity. In contrast, only about $740 million, less than 6% of all residential loss, is attributed to MMI shaking region IX. Although the loss ratio is high for this region, the inventory of buildings is relatively small.

Table 4. Insured and observed economic loss to residences by MMI shaking region – 1994 Northridge Earthquake

Insurance/Observed Loss Item	MMI Shaking Region - Los Angeles County Study Area					
	All	V	VI	VII	VIII	IX
Insurance Loss Data – Dollars in Billions (RMS, 1996)						
Number of Claims	84,983	164	5,288	22,625	32,214	4,692
Exposure (Policy Limits)	$52B	$1.35B	$17.0B	$19.6B	$12.2B	$1.62B
Ground-Up Loss	$3.7B	$0.006B	$0.21B	$1.05B	$2.03B	$0.41B
Insured Loss Ratio		0.41%	1.25%	5.4%	16.6%	25%
Observed Loss Data – Dollars in Billions						
Replacement Cost	$510B	$148B	$143B	$153B	$61B	$5B
Observed Loss	$12.7B	$0.35B	$1.03B	$4.72B	$5.81B	$0.74B
Observed Loss Ratio		0.23%	0.72%	3.1%	9.5%	15%

PREDICTED ECONOMIC LOSS

Predictions of damage and direct economic loss are made for single-family residences of light-frame wood (W1) construction and older (Moderate-Code) design vintage using the response spectra shown in Figure 5. Peak earthquake response of the structure, the corresponding probability of structural damage, and the resulting losses to the structural system and the building as a whole, are summarized in Table 5 for each MMI shaking region. Predicted losses for the Los Angeles County study area assume all residences to be the same model building type (i.e., W1 buildings of Moderate-Code design). Figure 7 illustrates the distribution of predicted residential losses between MMI shaking regions for the structural system, nonstructural components and contents, respectively.

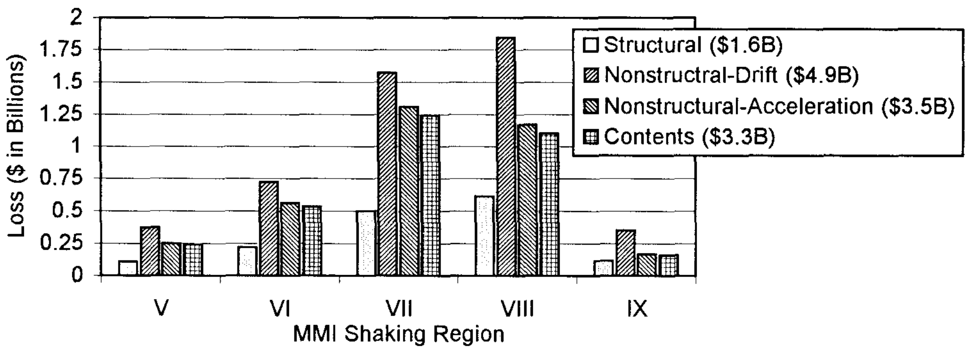


Figure 7. Direct economic loss predicted by the FEMA/NIBS methodology for Los Angeles County residences by MMI shaking region - 1994 Northridge Earthquake

Table 5. Damage and direct economic loss predicted by the FEMA/NIBS methodology for Los Angeles County residences by MMI shaking region - 1994 Northridge Earthquake

Peak Response, Damage or Loss Parameter	MMI Shaking Region - Los Angeles County Study Area					
	All	V	VI	VII	VIII	IX
Peak Response of W1 Buildings (Moderate-Code Design)						
Peak Displacement (in.)		0.21	0.29	0.42	0.70	1.25
Peak Acceleration (g)		0.17	0.25	0.35	0.54	0.70
Probability of Structural Damage to W1 Buildings (Moderate-Code Design)						
P[No Damage]	65.9%	85.3%	73.9%	57.3%	26.7%	8.9%
P[Slight Damage]	24.5%	12.8%	21.4%	31.9%	40.7%	31.0%
P[Moderate Damage]	8.7%	1.83%	4.5%	10.2%	28.2%	44.7%
P[Extensive Damage]	0.74%	0.04%	0.15%	0.55%	3.4%	11.3%
P[Complete Damage]	0.23%	0.01%	0.04%	0.15%	1.0%	4.2%
Predicted Loss to Residences – Dollars in Billions						
Replacement Cost	$510B	$148B	$143B	$153B	$61B	$5B
Structural System Loss	$1.56B	$0.11B	$0.22B	$0.50B	$0.61B	$0.12B
Building plus Contents Loss	$13.1B	$0.96B	$2.03B	$4.61B	$4.72B	$0.79B
Predicted Loss Ratio		0.65%	1.4%	3.0%	7.8%	16%

Peak displacement and acceleration response of single-family residences (i.e., W1 buildings of Moderate-Code design) and the corresponding probabilities of structural damage are calculated using the building damage functions described in the companion paper by Kircher et al. (1997) in this *Spectra* issue. Peak displacement and acceleration values represent average response within each MMI shaking region, since they are based on the average 5%-damped response spectra of each MMI shaking region (Figure 5).

Damage state probabilities shown for "All" MMI shaking regions reflect the combination of individual MMI shaking region probabilities weighted by building value. The "All" probabilities provide an overall picture of the earthquake's effect on residences of the study area. For example, some amount of structural damage is predicted for about 1/3 of all residences in the study area, although less than one-quarter of 1 percent of all residences are predicted to have Complete, and potentially life-threatening, structural damage.

Direct economic loss is calculated for the structural system using the probabilities of each damage state given in Table 5 and the loss rates summarized in Table 2. Similar calculations are performed for nonstructural components and building contents. Building plus contents losses shown in Table 5 are the sum of the individual calculations of structural, nonstructural and contents losses. As illustrated in Figure 7, the structural system contributes only a small fraction to total building loss. Nonstructural components and contents, which are more valuable, dominate the calculation of direct economic loss. Predicted loss ratios for each MMI region are calculated by dividing buildings plus contents loss by residential value (i.e., the replacement cost of residential buildings and their contents).

COMPARISON OF PREDICTED AND OBSERVED ECONOMIC LOSS

FEMA/NIBS predictions of residential loss ratios for MMI shaking regions are compared in Figure 8 with ratios derived from observed residential losses (distributed by MMI based on insurance claims data). Also shown in Figure 8 are loss ratios taken from Steinbrugge (1982) for Class 1D buildings and loss ratios derived from ATC-13 damage probability matrices (ATC, 1985) for low-rise wood buildings.

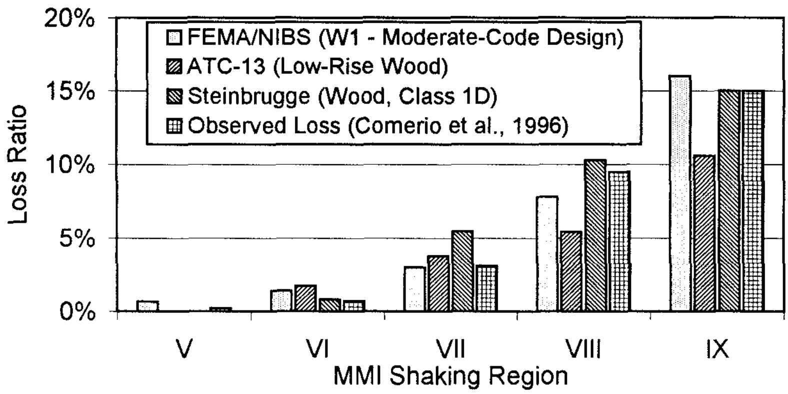


Figure 8. Comparison of loss ratios of various predictive methods and observed loss ratios for Los Angeles County Residences by MMI shaking region - 1994 Northridge Earthquake

FEMA/NIBS predictions of residential losses for MMI shaking regions are compared in Figure 9 with losses derived from observed residential losses (distributed by MMI based on insurance claims data) and with predictions based on the loss ratios of Steinbrugge and ATC-13, shown in Figure 8. To permit uniform comparison of losses predicted by different methods, Steinbrugge and ATC-13 predictions are based on the same replacement cost of residential buildings and their contents as those of the FEMA/NIBS methodology (i.e., $510 billion for the Los Angeles County study area). This approach is not entirely consistent with the definition of ATC-13 and Steinbrugge loss ratios, which apply to residences whose replacement cost does not include an additional 50% increase for contents. If contents were excluded, the predictions of ATC-13 and Steinbrugge would be 33% lower.

Figure 9 indicates a good comparison between residential losses predicted by the FEMA/NIBS methodology and observed losses for MMI shaking regions VII and VIII, the two regions that dominate direct economic loss for the 1994 Northridge Earthquake. The ATC-13 method tends to underpredict observed loss in the MMI VIII shaking region, and the Steinbrugge method tends to overpredict observed loss in the MMI VII shaking region. However, all three predictive methods provide reasonable estimates of observed loss to residential buildings of Los Angeles County damaged by the 1994 Northridge Earthquake.

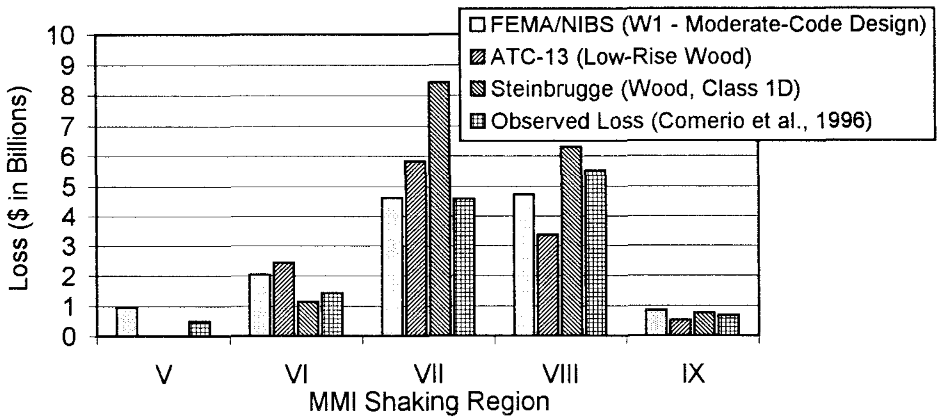


Figure 9. Comparison of predicted and observed direct economic loss for Los Angeles County residences by MMI shaking region - 1994 Northridge Earthquake

CONCLUSION

This paper has described the building economic loss methods of the FEMA/NIBS earthquake loss estimation methodology and compared predicted losses to residences using these methods with those observed for the 1994 Northridge Earthquake as well as with losses predicted by the methods of ATC-13 and Steinbrugge.

Building loss functions (and related damage functions) are of a new form and represent a significant step forward in the prediction of earthquake impacts. Previous methods, such as those of ATC-13 and Steinbrugge, are based on MMI. The new functions are based on quantitative measures of ground shaking (and ground failure) that analyze groups of buildings in urban regions in a manner similar to that used for the seismic design of new buildings and rehabilitation of existing ones.

The FEMA/NIBS methodology now permits loss estimation to incorporate important ground shaking characteristics, including site/soil amplification effects and shaking duration. Further, the methodology explicitly considers differences among buildings based on their seismic design level and vintage, and anticipated performance, explicitly considering nonlinear inelastic response, and its effects on the structural system, nonstructural components, and contents of the building.

Direct economic losses predicted for Los Angeles County residences compare well with those observed for the 1994 Northridge Earthquake and are consistent with existing MMI-based predictions based on ATC-13 and Steinbrugge methods. In future studies of earthquake loss, the FEMA/NIBS methodology would be expected to provide more reliable estimates of building loss, since quantitative measures (response spectra) provide a more meaningful description of ground shaking than MMI intensity. Improvements in the prediction of ground shaking (response spectra) can be incorporated directly into the estimation of building losses.

The FEMA/NIBS methodology opens the way for quantitative evaluation of building losses and mitigation alternatives that previously could only be judged in a qualitative manner. With these tools, engineers and planners can now develop strategies for earthquake hazard mitigation that combine both elements of pre-event action and post-event response and recovery in a more rational manner.

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Freeman, John R., 1932. *Earthquake Damage and Earthquake Insurance: Studies of A Rational Basis for Earthquake Insurance, also studies of Engineering Data for Earthquake-Resisting Construction.* (New York: McGraw-Hill). Disaggregation of results is a feature of a loss estimation study that is frequently desired. Freeman, by contrast, advocated portraying an earthquake's damage at the most aggregate of scales which usefully illuminates the subject from a different angle. He calculated ratios of total damage to all buildings in a large urban district to their total value, e.g. "the average percentage of earthquake damage to sound value within any district of say 5 square miles covering the region most seriously affected, has seldom amounted to more than 5 per cent" (p. 622).

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