When the *Big One* Strikes Again—Estimated Losses due to a Repeat of the 1906 San Francisco Earthquake

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This paper presents interim results of an ongoing study of building damage and losses likely to occur due to a repeat of the 1906 San Francisco earthquake, using the HAZUS technology. Recent work by Boatwright et al. (2006) provides MMI-based ShakeMap estimates of spectral response accelerations derived from observations of intensities in the 1906 San Francisco earthquake. This paper calculates damage and loss estimates using those estimated ground motions, then compares the resulting estimates with those calculated using a method parallel with that of current seismic provisions of building codes for a magnitude M7.9 event on the San Andreas Fault, and contrasts differences in damage and loss patterns for these two scenarios. The study region of interest comprises 19 counties of the greater San Francisco Bay Area and adjacent areas of Northern California, covering 24,000 square miles, with a population of more than ten million people and about $1.5 trillion of building and contents exposure. The majority of this property and population is within 40 km (25 miles) of the San Andreas Fault. The current population of this Northern California region is about ten times what it was in 1906, and the replacement value of buildings is about 500 times greater. Despite improvements in building codes and construction practices, the growth of the region over the past 100 years causes the range of estimated fatalities, approximately 800–3,400 depending on time of day and other variables, to be comparable to what it was in 1906. The forecast property loss to buildings for a repeat of the 1906 earthquake is in the range of approximately $90–120 billion; 7,000–10,000 commercial buildings in the region are estimated to be closed due to serious damage; and about 160,000–250,000 households calculated to be displaced from damaged residences. Losses due to fire following earthquake, as well as losses to utility and transportation systems, would be in addition to these estimates. [DOI: 10.1193/1.2187067]

INTRODUCTION

The great earthquake of 18 April 1906 caused widespread damage to San Francisco and other Bay Area locales, ranging from as far north as Mendocino County to as far

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south as Monterey County. The literature for many years has reported approximately 700–800 deaths (see, for example, Freeman 1932, p. 8), although some recent studies (Hansen and Condon 1989) suggest the life loss may have been approximately four times greater. Direct economic losses to buildings in San Francisco were about $400 million (Steinbrugge 1982, p. 298). Most of these losses were due to the three-day conflagration following the earthquake that burned more than 500 downtown blocks.

In 1906, about 390,000 people lived in San Francisco, and less than one million people lived in the greater San Francisco Bay Area (U.S. Census Bureau 1995). Today the number of San Franciscans has more than doubled, and the Bay Area population has increased tenfold. In 1906, few buildings were over ten stories in height; ferryboats crossed the bay, and horses were still a viable means of transportation. Today, tall buildings and large bridges spanning the bay define the skyline of San Francisco. Over time, unreinforced masonry buildings and other highly vulnerable structures have been strengthened, or replaced, by more seismically resistive construction. However, considering the growth of the region, have improvements in seismic resistance been sufficient to offset increased risk due to a much larger population and greatly appreciated property value? This paper explores that question, and related seismic risk questions, by estimating damage and related losses likely to occur to the greater Bay Area due to a repeat of the 1906 San Francisco earthquake.

The damage and loss estimates presented in this paper are interim results (as of January 2006) of an ongoing ’06 earthquake loss study, and these estimates include preliminary values of direct damage to buildings due to ground shaking and ground failure, as well as economic and social losses due to this damage. While attention is often focused on the loss estimates of a study, it is important to document the methods and data used in calculating those losses. Thus this paper provides, within the limits of its allotted space in this 1906 earthquake centennial theme issue of Spectra, a relatively extensive discussion of how the study was conducted.

STUDY OBJECTIVE, SCOPE, AND APPROACH

The objective of this study is to comprehensively estimate potential losses to the greater Bay Area region due to a repeat of the 1906 San Francisco, considering direct damage to the region’s infrastructure caused by earthquake ground motions and ground failure, and induced (or secondary) damage caused by fire, inundation, hazardous material release, and debris generation. Infrastructure includes all buildings, essential facilities, and lifeline systems of the region. This study relies primarily on the “Earthquake Model” of the HAZUS technology (NIBS 1997, 2005; Kircher et al. 2006) to accomplish this scope, since the model provides the necessary methods for estimating earthquake damage and loss, and default inventory data describing the infrastructure and demographics of the region. For full appreciation of the discussion of approach and methodology used for this study, a general familiarity of the HAZUS Earthquake Model is necessary; this can be obtained from the references above.

Interim results presented in this paper are limited to estimates of direct damage to buildings due to ground motion and ground failure, and related losses. Building damage and loss methods are sophisticated in their consideration of building type and material, height, and design vintage in assessing seismic performance, provided these data are known or can be obtained (or inferred) from sources such as United States Census Bureau, Dun & Bradstreet (business-related information), or county tax assessor files. Default inventory databases of HAZUS are quite extensive but still have inherent limitations. For example, the demographics of a given census tract are known quite well from census data, and the use or occupancy and the exposure (i.e., value of buildings) are known reasonably well from census, Dun & Bradstreet, and Means cost data. However, the model building type, which defines the structural system, is typically not known.

Default inventory databases of HAZUS infer model building type from an assumed distribution by square footage of the different building types, given occupancy (referred to herein as the building mapping scheme), and are based largely on the occupancy-building–type relationships of Earthquake Damage Evaluation Data for California (ATC-13) (ATC 1995). Other key building performance properties that are not known, in general, include building height and seismic design level. The HAZUS default building-mapping scheme assumes all model building types to be of low-rise construction and to have a seismic design level based on a "generic" mix of buildings (based on an assumed "typical" distribution of building age). The assumption that all buildings are low-rise can cause very poor estimates of damage and loss (e.g., for tall buildings in downtown San Francisco). Likewise, the "generic" mix of buildings can also result in very poor estimates of damage and loss, if buildings (e.g., in the census tract of interest) are significantly older, or significantly newer, than that assumed by the typical age distribution. Further, default inventory data does not provide model building types for seismically retrofitted buildings.

A significant effort in this study is the improvement of default data describing building inventory of the 19-county study region. Specifically, the default mapping scheme is replaced by 22 custom mapping schemes that better describe actual combinations of model building type by height and seismic design level throughout the 19-county study region. These inventory improvements are based on evaluations of building age and density data by census tract and tax assessor data obtained from an ongoing study by Applied Technology Council for the Community Action Plan for Seismic Safety (CAPSS) of the City and County of San Francisco (ATC 2005). Default building properties are also modified to better represent damage and loss for the most vulnerable building types (e.g., unreinforced masonry, nonductile concrete, and soft-story buildings), and new retrofitted model building types are developed to estimate damage and loss for those model building types that have been seismically strengthened (e.g., unreinforced masonry buildings).

The study region inventory as well as loss results were reviewed for reasonableness in several ways. For example, in terms of inventory, do the distributions of building age and height reasonably match those of key study region counties? In terms of methods, do losses estimated by the model for 1989 Loma Prieta earthquake ground motions look reasonable with respect to actual losses for this event? In addition to height and age distributions, building inventory data are also checked for those few building types for which information is available. For example, the square footage of unreinforced masonry (URM) buildings is checked against information on these buildings available from the California Seismic Safety Commission (CSSC 2005). Finally, improvements are made to building square footage and exposure (i.e., replacement costs of buildings and contents), based on detailed exposure data compiled for the insurance industry by Risk Management Solutions in Newark, California.

Building damage and loss methods of HAZUS are quite complex and, in general, are used without modification. Exceptions include, in particular, improvements to damage functions for "soft-story" wood and "nonductile" concrete frame buildings and development of new damage and loss functions for retrofitted buildings (e.g., unreinforced masonry). Other improvements include adjustment to certain damage parameters and loss rates that better reflect actual damage and losses, e.g., examining those that occurred during the 1989 Loma Prieta earthquake. As a final check, this study "benchmarks" improved inventory and methods by estimating losses for the 1989 Loma Prieta earthquake and comparing these estimates with observed social and economic losses for this event (after appropriate modification to reflect 2006 population and property values).

EARTHQUAKE HAZARD

Earthquake hazards include ground motion, ground failure due to liquefaction or landslide, and surface fault rupture offset. Landslide and surface fault rupture hazards are beyond the scope of this paper. For the scenario study conducted here, their exclusion does not greatly affect overall losses, though in some earthquakes, landslides and surface faulting can cause major damage.

The HAZUS technology estimates building damage due to ground failure based on peak ground acceleration, which is one of four ground motion parameters in HAZUS, and the liquefaction susceptibility of the soil, which must be supplied by the user as a GIS map. For this study, a map of liquefaction susceptibility was obtained from the U.S. Geological Survey (USGS) report "Preliminary Maps of Quaternary Deposits and Liquefaction Susceptibility, Nine-County San Francisco Bay Region: A Digital Database" (Knudsen et al. 2000). Although this map does not cover the entire 19-county study region, it does include the most highly populated counties with the strongest ground motions. Ground failure–related damage and losses in other sparsely populated counties or counties with weaker ground motions are considered negligible.

The HAZUS technology includes fault location and other properties and a variety of attenuation functions that can be used to generate scenario earthquake ground motions for user-defined criteria (e.g., magnitude M7.9 on the segments of the San Andreas Fault near San Francisco), or it can accept user-specified ShakeMaps of ground motions. Both approaches are used for this study. The primary source of 1906 San Francisco earthquake ground motions is the recent work of the U.S. Geological Survey (USGS) described in "Using Modified Mercalli Intensities to Estimate Acceleration Response Spectra for the 1906 San Francisco Earthquake" (Boatwright et al. 2006, this issue). ShakeMaps are obtained from the USGS report "Modified Mercalli Intensity Maps for the 1906 San Francisco Earthquake Plotted in ShakeMap Format" (Boatwright and Bundock 2005). These maps (referred to herein as "1906 MMI" ground motions) currently

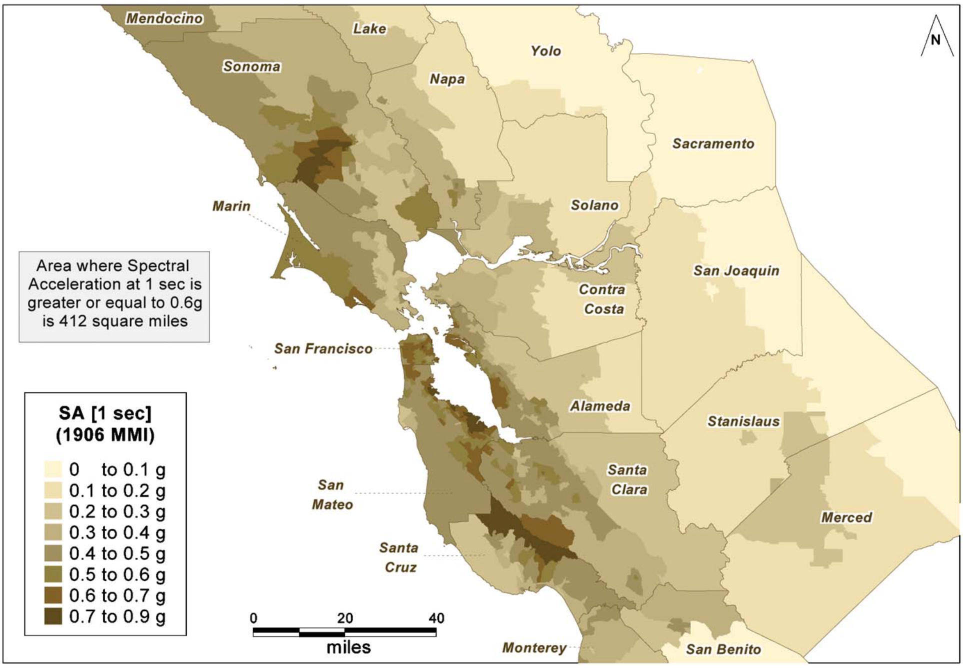

Figure 1. Map of study region showing one-second spectral acceleration ground motions of the 1906 San Francisco earthquake (based on Boatwright et al., 2006).

provide the best available estimate of 1906 San Francisco earthquake ground motions, showing areas of relatively weaker and stronger shaking for this event. Figure 1, a map of one-second spectral acceleration based on the 1906 MMI ground motions, shows strongest ground motions to be north (near Santa Rosa) and south of San Francisco, rather than in the city of San Francisco itself. While our study was predicated on an exact repeat of the 1906 earthquake, in all likelihood the next big earthquake on the San Andreas will generate a different pattern of ground motions.

This study develops a second, alternative, description of ground motions of an assumed magnitude M7.9 earthquake occurring on the segments of the fault that ruptured in the 1906 San Francisco earthquake. These ground motions are calculated using median predictions of western United States (WUS), shallow crustal, non-extensional, attenuation functions (i.e., average of four median predictions). These four functions are the same as those used by the USGS (Frankel et al. 2002) to make the ground motion hazard maps (for coastal California areas) of FEMA 450: NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures (FEMA 2004) and the American Society of Civil Engineers Standard, ASCE 7-05: Minimum Design Loads for Buildings and Other Structures (ASCE 2005). These ground motions, referred to in this paper as the “M7.9 motions,” incorporate site effects using the same site amplification factors as those found in the NEHRP Provisions and ASCE 7-05, and site

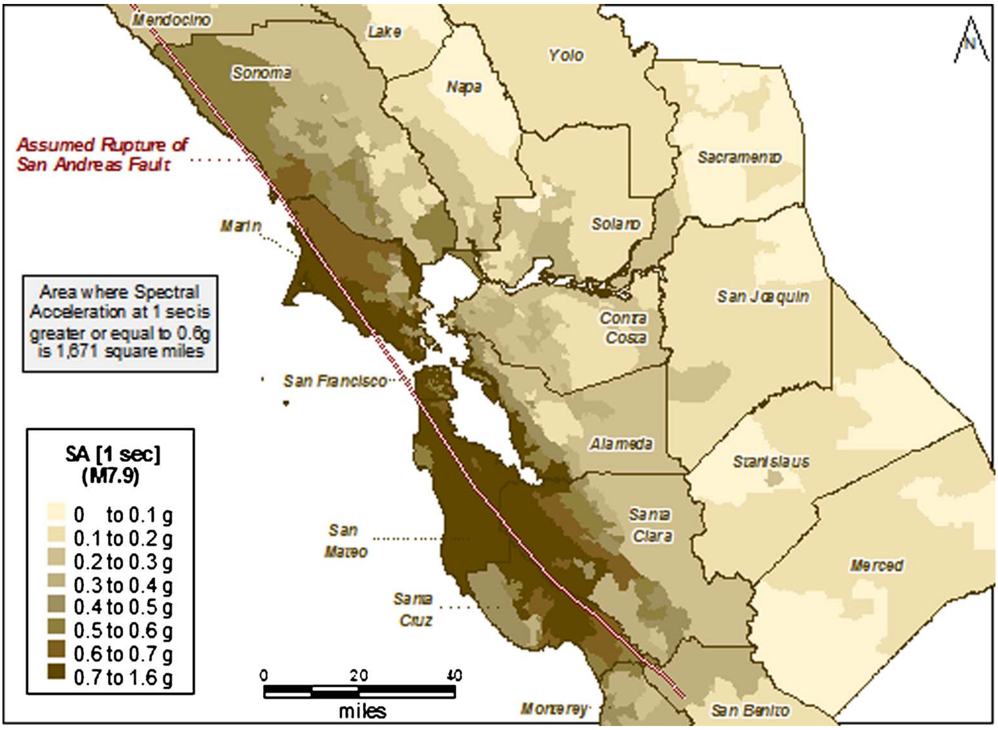

Figure 2. Map of study region showing one-second spectral acceleration ground motions for a magnitude M7.9 earthquake on the San Andreas Fault (near San Francisco).

class information described by a high-resolution soils map of northern California (PBS&J 2006).

The M7.9 ground motions, based on median values of the attenuation functions, are essentially the same as those of the design basis earthquake of the NEHRP Provisions and ASCE 7-05 for areas relatively close to the San Andreas Fault (areas within about 15 km of the fault) including most of San Francisco and San Mateo counties. These ground motions provide a basis to compare damage and losses due to 1906 MMI ground motions with damage and losses that could occur due to other large-magnitude earthquakes on the San Andreas Fault. Figure 2, a map of one-second spectra accelerations based on the M7.9 ground motions, shows a generally stronger trend in shaking throughout the region and, in particular, in San Francisco, but lacks the "hot spots" of 1906 MMI ground motions shown in Figure 1.

This study validates improved study region inventory and methods by comparing damage and loss estimates based on 1989 Loma Prieta earthquake ground motions with observed values of damage and loss. For these comparisons, 1989 Loma Prieta ground motions are obtained from a 1997 study, "Maps of Ground Motions from the 1989 Loma

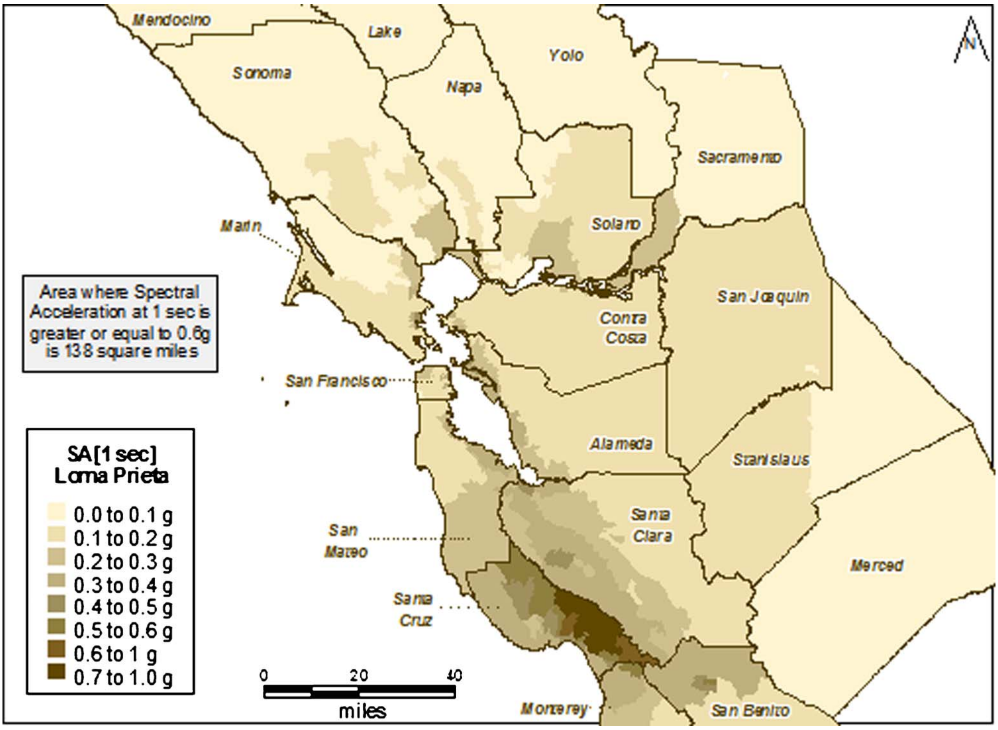

Figure 3. Map of study region showing one-second spectral acceleration ground motions for the 1989 Loma Prieta earthquake based on Pitarka et al. (1997).

Prieta Earthquake" (Pitarka et al. 1997). The 1997 study developed maps of 1989 Loma Prieta ground motions from instrumental records, which were used along with maps of other earthquake ground motions to calibrate the original HAZUS technology. Figure 3 is a map of one-second spectral accelerations of the Loma Prieta ground motions.

STUDY REGION

This study evaluates damage and loss for a large—19-county—region of Northern California. The region includes the 9 immediate San Francisco Bay Area counties that belong to the Association of Bay Area Governments (ABAG), plus Santa Cruz, San Benito, and Monterey counties (to the south), Mendocino and Lake counties (to the north), and Yolo, Sacramento, San Joaquin, Stanislaus, and Merced counties (to the east). Table 1 lists the 19 counties of the study region. Although ground shaking will be much less at inland locations distant from the San Andreas Fault, areas of high population and exposure, such as Sacramento County, are included in the study region to contrast damage and losses for these areas with high-impact coastal areas. Figure 4 is a map of the study

Table 1. Study region population, households, and building exposure, by county

			Building Exposure (dollars in millions)		
Country	Population	Households	Residential	Non-Residential	Total
Alameda	1,443,741	523,366	111,030	44,670	155,700
Contra Costa	948,816	344,129	82,392	20,415	102,807
Lake	58,309	23,974	3,872	924	4,796
Marin	247,289	100,650	26,772	9,278	36,050
Mendocino	86,265	33,266	5,561	1,723	7,285
Merced	210,554	63,815	10,450	2,451	12,901
Monterey	401,762	121,236	25,014	8,759	33,773
Napa	124,279	45,402	10,039	4,541	14,579
Sacramento	1,223,499	453,602	84,890	25,672	110,562
San Benito	53,234	15,885	3,424	712	4,136
San Francisco	776,733	329,700	62,296	37,882	100,179
San Joaquin	563,598	181,629	33,228	9,528	42,756
San Mateo	707,161	254,103	63,595	20,706	84,301
Santa Clara	1,682,585	565,863	135,520	47,793	183,312
Santa Cruz	255,602	91,139	21,349	7,034	28,383
Solano	394,542	130,403	28,071	6,749	34,820
Sonoma	458,614	172,403	38,724	12,134	50,858
Stanislaus	446,997	145,146	25,864	7,964	33,828
Yolo	168,660	59,375	10,531	3,948	14,479
All 19 Counties	10,252,240	3,655,086	782,621	272,883	1,055,503

region showing the 2,153 census tracts of the 19 northern California counties and areas of greater and lesser building density (i.e., total building square footage of each census tract, normalized by census tract area).

Table 1 summarizes population (2000 census data) and building exposure (2005 cost data) for each of the 19 counties. The total population of the study region is just over ten million people. There are an estimated three million buildings in the study region that have a total exposure of about $1 trillion (including their built-in nonstructural components) without contents, and about $1.5 trillion with contents. Building exposure is based on replacement cost of the structure, nonstructural systems, and contents, and does not include land value. Coastal counties with the largest populations and building exposures include San Francisco, San Mateo, and Santa Clara counties, representing about one-third of the study region's total population and building exposure. The majority of building exposure and study region population is within 40 km (25 miles) of the San Andreas Fault.

Northern California has grown considerably since 1906, with about a tenfold increase in population. Likewise, buildings have been constructed essentially in parallel with this growth. Table 2 summarizes population and Building Cost Index (BCI) (ENR

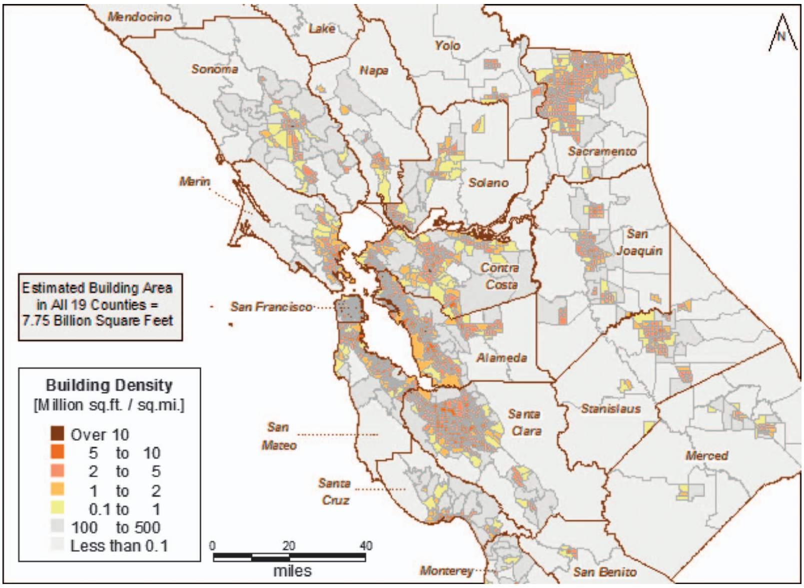

Figure 4. Map of study region showing 19 counties and areas of greater and lesser building density (i.e., total building square footage normalized by census tract area). In color: see plates following p. S68.

2005) data from 1990 to the present, and projections of these data through 2040. Trends in population and exposure growth, normalized to 2006 values, are also shown in the table. Building exposure is estimated as the product of population and the BCI, that is, the total square footage of buildings is assumed to increase in proportion to the population, and the cost (per square foot) is assumed to increase in proportion to the BCI. From 1906 to 2006, building exposure in the study region increased by about a factor of 500 (roughly a tenfold increase in population and a factor of 50 increase in the BCI). Figure 5 shows trends in population and exposure growth. As these trends show, over the next 30 years the population of the greater Bay Area study region is expected to grow by about 30%, and building exposure to increase by about a factor of 3.

By 1906, San Francisco was significantly developed and had a population of approximately 390,000, about one-half of the current population. Thus San Francisco building exposure has not increased as much as other, less developed, areas of the study region areas, but still by a factor of approximately 100 (i.e., population factor of 2 times BCI factor of 50). Reports of 1906 San Francisco earthquake losses include about $400 million, total loss including fire, and about $80 million, earthquake loss only (Steinbrugge 1982). In terms of current San Francisco building exposure, 1906 economic loss factored by 100 would correspond very approximately to $40 billion, total loss including fire; and $8 billion, earthquake loss only (i.e., ground motion and failure losses). Rela-

Table 2. Building cost index and study region population, 1900–2040, and normalized trends in population and exposure growth

Year	Building Cost Index[1]	Population[2,3]	Growth Trends Normalized to 2006	
			Population	Exposure[4]
1900	95	845,868	7.8%	0.173%
1906	95	1,048,521	9.7%	0.21%
1910	95	1,183,623	11.0%	0.24%
1920	207	1,531,848	14.2%	0.68%
1930	185	2,073,101	19.2%	0.82%
1940	203	2,353,359	22%	1.03%
1950	375	3,660,600	34%	2.9%
1960	559	5,067,984	47%	6.1%
1970	836	6,403,564	59%	11.5%
1980	1,941	7,431,035	69%	31%
1990	2,702	8,988,508	83%	52%
2000	3,539	10,252,240	95%	78%
2006	4,310	10,796,440	100%	100%
2010	4,758	11,127,739	103%	114%
2020	6,090	12,358,781	114%	162%
2030	7,796	13,726,012	127%	23.0%
2040	9,979	15,135,103	140%	325%

[1] Building Cost Index (BCI), 1915–2005, ENR (2005). BCI values before 1915 are assumed equal to 1915 BCI; BCI values after 2005 are based on 2.5% annual increase.
[2] Population, 1900–2000, U.S. Census Bureau (2005)
[3] Projected Population, 2010–2040, Counting California (2005)
[4] Exposure growth based on product of BCI and population.

tively modest losses due to earthquake ground motion and failure are consistent with observations that buildings in San Francisco generally withstood "earthquake shock" quite well (Freeman 1932).

Similarly, all else being equal, estimated present casualties would be expected to be twice that due to the 1906 San Francisco earthquake (due to a factor of 2 increase in population), or about 1,500 deaths, based on the figure of about 750 fatalities for 1906. Of course, all else is not equal. The fire following the 1906 earthquake was the dominant factor in casualties, as well as economic losses, so perhaps only 20% of all deaths, or about 300 deaths, would be expected due to building collapse, based on the current population of San Francisco. Further, building inventory has changed significantly since 1906. While building codes have improved, buildings added to the western half of San Francisco (largely undeveloped in 1906) are in closer proximity to the San Andreas Fault that is just offshore from the city, and are likely to experience stronger ground motions than buildings on the eastern half of San Francisco.

Over the period from 1906 to the present, seismic provisions of building codes (seismic codes) have evolved, and construction methods have improved, most notably in the

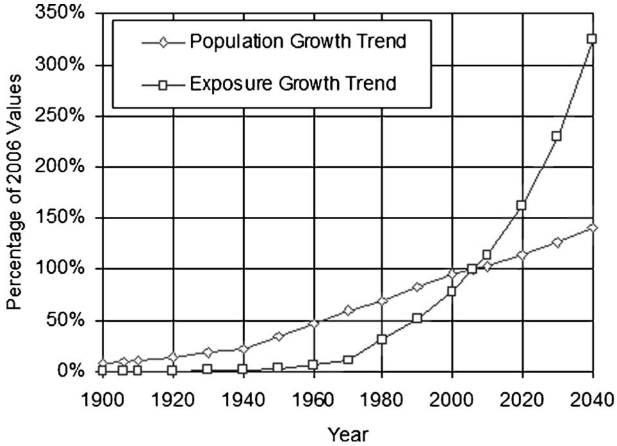

Figure 5. Trends in study region population and building exposure growth, 1900–2040, normalized to 2006 values.

San Francisco Bay Area, since about 1950. Newer buildings, designed to meet more stringent seismic code criteria are generally expected to perform better in earthquakes than older buildings, though there are exceptions. Since detailed, building-specific information is generally not available, this study infers seismic design and performance information from building vintage. Figure 6 is a map of the study region showing areas of older and newer residential buildings based on census data. The five age categories of this map differentiate between areas of predominantly pre-1950 construction (i.e., buildings likely designed to older seismic code requirements—if designed for earthquake loads at all) to areas of predominantly post-1974 construction (i.e., buildings likely designed to meet modern seismic code requirements). For example, most areas of San Francisco have predominantly older buildings. In contrast, other than the area around San Jose, most of the developed areas of Santa Clara County have predominantly newer buildings.

BUILDING INVENTORY DATA IMPROVEMENT

A number of significant improvements are made to default building inventory data in HAZUS, including (1) development of custom "mapping schemes" that better reflect the relationship of building occupancy to model building type, (2) adjustment of the square footage of the most seismically vulnerable model building types to better reflect actual square footage of these building types (when such information is known), (3) adjustment of building exposure (e.g., to better reflect actual exposure based on information developed by Risk Management Solutions for the insurance industry), and (4) adjustment of "time-of-day" populations to better reflect study region population. The following section provides an overview of these inventory improvements, recognizing that detailed description of the work (particularly for the development of custom mapping schemes) would be too lengthy for this paper.

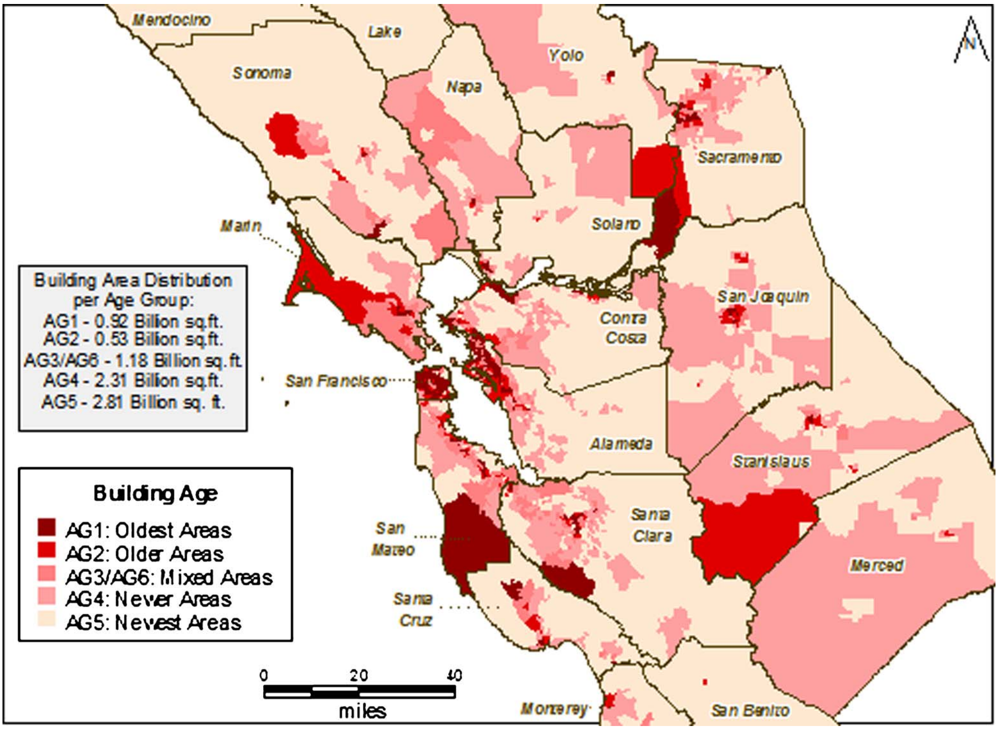

Figure 6. Map of study region showing 19 counties and areas of older and newer buildings (based on age of residential buildings).

CUSTOM BUILDING ATTRIBUTE MAPPING SCHEMES

The default mapping schemes of the HAZUS technology include only one scheme for coastal California counties (i.e., one scheme for all Uniform Building Code Seismic Zone 4 census tracts in California). This mapping scheme assumes that all buildings are low-rise and that the distribution of seismic design level is the same for all census tracts: i.e., by assuming that buildings have the same age distribution for all census tracts, 25% (pre-1950), 50% (1950–1974), and 25% (post-1974). This mapping scheme is inappropriate for census tracts with a significant percentage of mid-rise and/or high-rise buildings and for census tracts with a distribution of buildings by age that does not match the 25%-50%-25% age assumption. As shown in Figure 6, the distribution of building age, and hence the distribution of seismic design level, varies significantly from census tract to census tract. Key counties of the study region reflect these differences in building age. For example, Figure 7 shows that most buildings in San Francisco were built before 1950, but that less than 10% of buildings in Santa Clara County were built before 1950.

The HAZUS technology provides building damage functions for different building height ranges, identified as Low-Rise, Mid-Rise, and High-Rise, and for different seismic design levels and construction quality classes, identified as High Seismic Design/

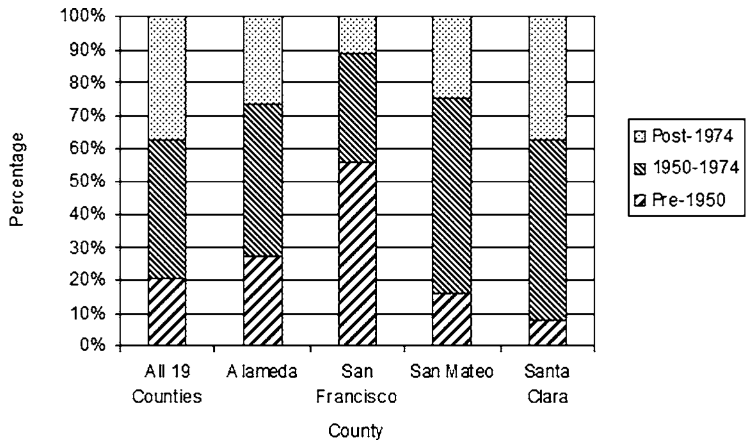

Figure 7. Distribution of buildings by age group for key counties and the study region.

Code Quality (High Code), Moderate Seismic Design/Code Quality (Moderate Code), Low Seismic Design/Code Quality (Low Code), and Low Seismic Code/Inferior Quality (Pre-Code). Building response models, based on height-dependent period, calculate very different demands for Low-Rise, Mid-Rise, and High-Rise buildings, respectively. Of even greater significance, building damage models calculate very different probabilities of structural and nonstructural damage for different seismic design levels for the same model building type.

This study develops 22 "custom" mapping schemes and uses these schemes in lieu of the single default mapping scheme typically applied throughout a HAZUS study region. These schemes are based on 11 combinations of three generic height distributions (labeled as HG1–HG3) and six generic age distributions (labeled as AG1–AG6), as defined in Table 3. Table 4 shows generic age distributions for each of the six age groups, and Table 5 shows generic height distributions for each of the three height groups used in this study. Further, two sets of these 11 (height/age) mapping schemes are developed, one set for San Francisco County and Alameda County (counties known to have a higher concentration of older soft-story wood residences), and one set for all other counties.

Each scheme follows the distribution of model building types, given building occupancy and age, as described in tables of Appendix 3A of the HAZUS Technical Manual (NIBS 1997), with two exceptions. First, model building type W2 (wood structures over 5,000 square feet) is used for larger multifamily wood residences (HAZUS Occupancies RES3C through RES3F), rather than W1. Second, relative fractions of unreinforced masonry model building types (URML and URMM) are increased for San Francisco and Alameda County mapping schemes to avoid underestimation of the square footage of URM buildings in these two counties. The tables of Appendix 3A of the HAZUS Technical Manual are an adaptation of the original work of ATC-13 (ATC 1985).

The most appropriate mapping scheme for each census tract is selected based on re-

Table 3. Eleven mapping schemes/combinations of building age and height groups used in this study, and relative use of age and height groups in the study region

Building Age Group (AG)	Building Height Group (HG) HG1	HG2	HG3	Fraction - All Height Groups
AG1		1	2	12%
AG2		3	4	7%
AG3		5	6	10%
AG4		7	8	30%
AG5		9	10	36%
AG6	11			6%
Fraction - All Age Groups	6%	17%	77%	100%

view of available height and age data. For San Francisco, building height information is taken from CAPSS data files (ATC 2005) and used to infer "target" height distributions for other counties. Evaluations of building density by census tract (e.g., building density data shown Figure 4) are made to determine which of the three generic height groups best represents building height for each census tract.

Building age information is taken from census data as found in the HAZUS demographics file that describes the age of residences, i.e., number of housing units constructed in various decades. These age data are assumed applicable to both residences and smaller, local commercial buildings (i.e., commercial buildings likely constructed in parallel with local residential growth). Evaluations of building age by census tract (i.e., correlations of the distribution of building square footage across various construction vintages, relative to assumed age category distributions given in Table 4) are made to determine which of the five age groups, AG1–AG5, best represents building age for each census tract. Age group, AG6, is used for census tracts with large (tall), primarily com-

Table 4. Six generic building age groups used in this study to develop mapping schemes

Age Group	Building Age Distribution Pre-1950	'50 – '74	Post-1974	Description of Buildings of Typical Census Tracts
AG1	0.7	0.25	0.05	Older, mainly pre-WW2, buildings
AG2	0.5	0.45	0.05	Older mix of pre-and post-WW2 buildings
AG3	0.3	0.45	0.25	General mix of buildings
AG4	0.05	0.7	0.25	Newer, primarily post-WW2, buildings
AG5	0.05	0.25	0.7	Newer, primarily post-1974, buildings
AG6	0.33	0.33	0.33	City center/tall buildings of major city

Table 5. Three generic building height groups used in this study to develop mapping schemes

Height Group	Building Height Distribution			Description of Buildings of Typical Census Tracts
	Low-Rise	Mid-Rise	High-Rise	
HG1	0.1	0.1	0.8	City center/tall buildings of major city
HG2	0.4	0.4	0.2	Commercial and dense urban residential buildings
HG3	0.95	0.05	0.0	Suburban, primarily residential buildings

mercial, buildings, found in financial districts and civic center areas of major cities (i.e., San Francisco, San Jose, Oakland, and Sacramento). For these census tracts, the distribution of building age is inferred from overall regional population growth, which is approximately the same for the three periods, 33% (pre-1950), 33% (1950–1974), and 33% (post-1974), as shown by the trend line in Figure 5.

A check for reasonableness of the custom mapping schemes is performed by comparing "as-built" building height and age distributions of key counties used in this study with "target" distributions of building height and age (and with default mapping scheme distributions of building height and age), as described in Table 6. This table shows such comparisons of building height and age distributions for Alameda, San Francisco, San Mateo, and Santa Clara counties, and for all 19 counties of the study region, respectively. In general, the distributions used in this study compare well with target distributions, indicating successful implementation of the custom mapping schemes. In general, these distributions do not compare well with the default distributions, indicating a need for improvement of building inventory data by using custom mapping schemes. Inventory improvements are most significant for census tracts of counties like San Francisco that have very different distributions of building height and age than those of the default mapping scheme.

SEISMICALLY VULNERABLE BUILDINGS

This study is especially concerned with inventory accuracy of certain building types known to be particularly susceptible to earthquake damage and collapse. Specifically, URM buildings, nonductile concrete frame buildings, and soft-story wood single-family and multifamily residences. The inventory (square footage) of these building types is either based on or checked against available data from other studies when such information was available. For example, the CAPSS program performed a citywide sampling, neighborhood-by-neighborhood, and found that about 50% of all San Francisco single-family wood residences and about 70% of all multifamily wood residences have a "soft story." So-called soft-story buildings are due to a variety of problematic geometries, including weak cripple walls (i.e., between the first floor and the foundation) and open first floors (e.g., narrow house over garage). The CAPSS program estimated that about 10% of single-family residences have been seismically retrofitted (e.g., strengthening of cripple walls).

Table 6. Comparison of HAZUS default values, target values, and the building height and age distributions used in this study

		Height Distribution			Age Distribution[1]		
County	Source	Low-Rise	Mid-Rise	High-Rise	Pre-1950	’50 – ’74	Post-1974
Alameda	Default	100%	0%	0%	25%	50%	25%
	Target[3]	79%	10%	11%	26%	40%	33%
	This Study	89%	6%	5%	26%	40%	34%
San Francisco	Default	100%	0%	0%	25%	50%	25%
	Target[2]	72%	12%	16%	52%	30%	17%
	This Study	77%	11%	12%	43%	36%	20%
San Mateo	Default	100%	0%	0%	25%	50%	25%
	Target[3]	84%	12%	4%	26%	47%	27%
	This Study	91%	7%	1%	25%	42%	32%
Santa Clara	Default	100%	0%	0%	25%	50%	25%
	Target[3]	78%	11%	11%	13%	48%	39%
	This Study	90%	6%	4%	18%	43%	39%
All 19 Counties	Default	100%	0%	0%	25%	50%	25%
	Target[3]	81%	11%	8%	20%	42%	38%
	This Study	90%	6%	4%	21%	41%	38%

[1] Target age distribution fractions inferred from age of residences (HAZUS demographics file) and compared to age of residences used in this study
[2] Target height distribution fractions based on CAPSS data (ATC 2005)
[3] Target height distribtion fractions inferred from CAPSS data (ATC 2005) considering reduced fractions of high-rise buildings in counties that have relatively less tall building square footage than San Francisco)

The 1994 Northridge earthquake showed the vulnerability of multistory apartment buildings with a “tuck-under” garage area, another soft-story configuration. These types of apartment buildings are common to many urban and high-density suburban areas. For example, in Santa Clara County, a 2002 survey of multifamily wood residences found that about 11% of all units were in multistory apartments that had a soft-story due to a tuck-under garage configuration (Vukazich et al. 2006). While the buildings in San Francisco identified by the CAPSS study as having soft-story configurations are primarily of pre-1950 vintage, the apartment houses surveyed in Santa Clara are primarily of post-1950 vintage. Few, if any, of these buildings have been strengthened.

This study assumes that 25% of all wood residences (i.e., model building types W1 and W2) built before 1950 and located in San Francisco or Alameda counties are susceptible to soft-story collapse. Such collapse of a soft story does not necessarily imply the total collapse of all levels of the structure. Although data (such as that of the CAPSS survey) is not available, older areas of Alameda County (e.g., Oakland) are considered similar to San Francisco. The 25% fraction is based on the assumption that about half of all buildings identified as having a soft story are actual collapse hazards. For all other

Table 7. Comparison of estimated URM building square footage, CSSC (2005), and this study

	Number of URM Buildings (CSSC 2005)			Estimated Square Footage	
County	Total	Mitigated	Rate	CSSC[2]	This Study
Alameda	2,597	1,031	39.7%	46,746,000	46,987,658
Contra Costa	431	100	23.2%	7,758,000	6,036,680
Lake	49	10	20.4%	882,000	130,078
Marin	124	52	41.9%	2,232,000	4,243,723
Mendocino	67	2	3.0%	1,206,000	458,026
Merced[1]	NA	NA	NA	NA	779,241
Monterey	209	75	35.9%	3,762,000	4,160,652
Napa	122	36	29.5%	2,196,000	1,368,159
Sacramento[1]	NA	NA	NA	NA	8,943,267
San Benito	28	2	7.1%	504,000	203,706
San Francisco	1,976	1,419	71.8%	35,568,000	60,577,535
San Joaquin	0	0		0	4,059,295
San Mateo	166	123	74.1%	2,988,000	11,165,383
Santa Clara	388	253	65.2%	6,984,000	12,408,111
Santa Cruz	112	21	18.8%	2,016,000	2,719,800
Solano	174	17	9.8%	3,132,000	1,998,840
Sonoma	578	203	35.1%	10,404,000	3,408,494
Stanislaus[1]	NA	NA	NA	NA	2,352,677
Yolo	0	0		0	1,340,970
Total	7,021	3,344	47.6%	126,378,000	156,066,8443[3]

[1] URM data are not available for Merced, Sacramento, San Joaquin, Stanislaus, and Yolo counties (e.g., Seismic Zone 3 counties)
[2] Square footage based on average 18,000 sq. ft./building (Rutherford & Chekene 1990)
[3] Total square footage, excluding Merced, Sacramento, San Joaquin, Stanislaus, and Yolo counties

counties, 10% of all wood residences built before 1950 are assumed susceptible to soft-story collapse. This study assumes that 10% of all larger multifamily residences (i.e., model building type W2) built after 1950 are susceptible to soft-story collapse (e.g., due to "tuck-under" garage configuration). Single-family and smaller multifamily residences (i.e., model building type W1) built after 1950 are assumed not susceptible to soft-story collapse.

In 1986, California enacted law that required local governments in Seismic Zone 4 to inventory URM buildings, to establish loss reduction programs, and to report progress. This law and related local ordinances have generated both a very good understanding of the number of URM buildings, and a significant mitigation of the risk. Table 7 summarizes URM building data for counties of the study region obtained from the report Status of the Unreinforced Masonry Building Law (CSSC 2005). These data include the number of URM buildings, total and strengthened, and estimates of the corresponding square footage. For comparison, Table 7 includes the square footage of URM buildings of the study region. As of 2004, about half of URM buildings have been strengthened, although in San Francisco this rate is more than 70%. Strengthening criteria among different California local jurisdictions can vary significantly, but this level of detail is beyond the present study's scope.

Overall, study region URM building square footage compares well with estimates of "actual" square footage. URM buildings account for roughly 2.2% of all study region buildings. Mapping schemes do not permit matching the "actual" URM square footage of each county. For Alameda and San Francisco counties (i.e., counties with large URM populations), mapping schemes are adjusted to achieve conservative estimates of URM building square footage. The square footage of URM buildings used in this study is close to the "actual" value for Alameda County, but substantially overestimates URM square footage for San Francisco County. This study assumes approximately 9% of all San Francisco building square footage is URM; actual URM square footage is about 5% of the total. Overestimation of URM building square footage has little effect on economic losses, but significantly affects casualties, in particular, deaths. Accordingly, estimated casualties for San Francisco County (as reported in this paper) include adjustment to reflect "actual" URM building square footage of 5% of the total.

In contrast to URM buildings, little data are available on the number (and the square footage) of nonductile concrete frame buildings and how many (and the square footage) of these buildings have been strengthened. Informal queries of structural engineers in San Francisco produced a very rough estimate that all concrete frames built before 1975, with or without infill walls, are to some degree vulnerable (i.e., due to limited ductility). This study assumes that 40% (pre-1950) and 20% (1950–1974) of these buildings are collapse hazards, and that about 20% of these buildings have been strengthened.

The seismic design levels of model building types are assigned by building vintage, based on the above information and other assumptions, as documented in Table 8. In general, model building types other than URM, soft-story wood, and nonductile concrete frame buildings are assigned a seismic design level consistent with HAZUS default assignments. That is, the seismic design level is assumed to be High-Seismic Code if built after 1974, Moderate-Seismic Code if built between 1950 and 1974, and Low-Seismic Code if built before 1950. Use of default assignments does not imply that URM, soft-story wood, and nonductile concrete are the only seismically vulnerable building types. There are certainly other seismically vulnerable building types, e.g., older precast-concrete tilt-up buildings that performed poorly in the 1994 Northridge earthquake, but default inventory (and damage and loss functions) are considered adequate for this study.

BUILDING EXPOSURE

Economic loss is calculated through a complex process in HAZUS, but ultimately as a fraction of building exposure. Therefore, the accuracy of estimated losses is directly related to the accuracy of building exposure. HAZUS develops building exposure from estimates of square footage (from census data for residential occupancies and from Dun & Bradstreet data for other occupancies) and Means cost data. As an alternative source of building exposure data, Risk Management Solutions (RMS), in Newark, California,

Table 8. Rules used in this study to assign the seismic design level to model building type

Model Building Type[1,2]		Building Vintage (Age Group)			
		Pre-1950			
		San Francisco and Alameda	Other Counties	1950–1974 All Counties	Post–1974 All Counties
General Rule (for Model Building Types other than those below)		Low-Seismic Code (LC)		Moderate-Seis. Code (MC)	High-Seismic Code (HC)
W1 (Wood under 5,000 sq. ft.)	w/o Retrofit w/Retrofit (LS)	MC - 40% LC - 25% PC - 25% MC - 10%	MC - 40% LC - 40% PC - 10% MC - 10%	HC - 50% MC - 50%	HC
W2 (Wood over 5,000 sq. ft.)	w/o Retrofit	MC - 50% LC - 25% PC - 25%	MC - 50% LC - 40% PC - 10%	HC - 50% MC - 40% PC - 10%	HC - 90% PC - 10%
URM (Unreinforced Masonry)	w/o Retrofit w/Retrofit (LS) w/Retrofit (CP)	PC - 25% MC - 5% LC - 70%		PC - 25% MC - 5% LC - 70%	NA
C1/C3 (Concrete frame w & w/o infill)	w/o Retrofit w/Retrofit (LS)	LC - 40% PC - 40% MC - 20%		LC - 60% PC - 20% MC - 20%	HC

[1] Pre-Code (PC) Seismic Design Level is used in this for study to designate the fraction of vulnerable building types considered to be especially high collapse hazard buildings
[2] Retrofitted model building types distinguish crudely between Life Safety (LS) and Collapse Prevention (CP) performance, where CP performance is considered typical of URM mitigation

provided estimated replacement costs of residential and nonresidential buildings for each county of the study region. These data were aggregated from databases that RMS develops for the insurance industry (RMS 2005).

Table 9 summarizes and compares building exposure from default HAZUS databases and RMS "insurance industry" databases. Residential building exposure is almost the same. On average, HAZUS default residential building exposure is about 10% less than corresponding RMS exposure values. However, nonresidential building exposure is quite different. On average, HAZUS nonresidential building exposure is only about one-half of RMS exposure values. Most likely, the main source of the difference is an underestimation of nonresidential building square footage by HAZUS default databases. RMS insured exposure estimates are considered more reliable and an appropriate source of building value for this study. Accordingly, building exposures used in this study are based on HAZUS default values increased by 1.1 for all residential building occupancies and by 2.0 for all nonresidential building occupancies, as summarized in Table 9. The factors are applied uniformly to structural and nonstructural systems of buildings. As

Table 9. Comparison of HAZUS default building exposures, RMS building exposures, and building exposures used in this study (dollars in millions)

County	Residential Building Exposure			Nonresidential Bldg. Exposure			Total Building Exposure used in this Study[1]
	HAZUS Default	RMS	Ratio	HAZUS Default	RMS	Ratio	
Alameda	$100,936	$112,203	1.11	$22,335	$45,735	2.05	$155,700
Contra Costa	$74,902	$74,759	1.00	$10,207	$19,687	1.93	$102,807
Lake	$3,520	$3,232	0.92	$462	$980	2.12	$4,796
Marin	$24,338	$25,961	1.07	$4,639	$8,217	1.77	$36,050
Mendocino	$5,056	$5,308	1.05	$862	$1,867	2.17	$7,285
Merced	$9,500	$9,572	1.01	$1,226	$2,700	2.20	$12,901
Monterey	$22,740	$23,196	1.02	$4,380	$7,324	1.67	$33,773
Napa	$9,126	$10,166	1.11	$2,270	$3,641	1.60	$14,579
Sacramento	$77,172	$79,433	1.03	$12,836	$25,066	1.95	$110,562
San Benito	$3,113	$2,763	0.89	$356	$796	2.24	$4,136
San Francisco	$56,633	$72,001	1.27	$18,941	$40,334	2.13	$100,179
San Joaquin	$30,207	$31,747	1.05	$4,764	$9,709	2.04	$42,756
San Mateo	$57,814	$64,316	1.11	$10,353	$21,410	2.07	$84,301
Santa Clara	$123,200	$153,773	1.25	$23,896	$54,865	2.30	$183,312
Santa Cruz	$19,408	$19,582	1.01	$3,517	$6,002	1.71	$28,383
Solano	$25,519	$23,606	0.93	$3,375	$5,793	1.72	$34,820
Sonoma	$35,203	$31,243	0.89	$6,067	$9,426	1.55	$50,858
Stanislaus	$23,513	$25,237	1.07	$3,982	$7,685	1.93	$33,828
Yolo	$9,573	$9,864	1.03	$1,974	$4,069	2.06	$14,479
All 19 Counties	$711,473	$777,960	1.09	$136,441	$275,305	2.02	$1,055,503

[1] Improved building exposures used in this study are based on HAZUS default exposures factored by 1.1 for residential buildings and by 2.0 for nonresidential buildings.

shown in Table 9, total building exposure for San Francisco is approximately $100 billion, very similar to total building exposure used in the CAPSS study (ATC 2005).

Nonresidential building square footage is increased by 1.8, i.e., roughly the ratio of 2.0/1.1, to reflect likely underestimation of commercial and other nonresidential building square footage by HAZUS default databases. Based on improved exposure and square footage data, average building replacement costs range from $94.23 per square foot (Lake County) to $151.94 (Marin County), with an average replacement cost of $136.21 for the entire study region. Average building replacement cost is $149.15 in San Francisco County. The reader should keep in mind that these are building construction or repair costs, not the much higher real estate values that include land and location factors.

TIME-OF-DAY POPULATIONS

Census data provide reliable estimates of the total population of the study region but are not directly applicable for estimation of casualties at different times of day. Rather,

Table 10. Comparison of HAZUS default populations and those used in this study

Time of Day	Indoor (IN) COM	Indoor (IN) RES	Indoor (IN) other	Outdoor (OUT)	Commuting (COMM)	Total - IN, OUT and COMM	Fraction of Total Population
	Populations by Time of Day based on HAZUS Default Demographics Data						
2 a.m.	61,589	9,735,241	116,503	9,923	51,261	9,974,517	1.0
2 p.m.	3,545,864	1,668,706	2,389,042	1,229,063	461,351	9,294,025	0.9
5 p.m.	2,515,082	3,445,197	425,708	2,352,999	6,835,400	15,574,387	1.5
	Populations by Time of Day used in this Study						
2 a.m.	61,589	9,735,241	116,503	9,923	51,261	9,974,517	1.0
3 a.m.	3,673,004	1,668,706	2,389,042	1,312,109	922,702	9,965,562	1.0
5 a.m.	1,306,727	2,411,638	425,708	1,627,157	4,511,351	10,282,581	1.0

HAZUS assigns appropriate fractions of the total population to buildings by occupancy, considering both indoor and outdoor occupants, and to the commuting population by time of day. These fractions are necessarily very different at night (e.g., 2 a.m.), during the day (e.g., 2 p.m.), or during peak commute (e.g., 5 p.m.), but for any given time should still add up to the total population of the study region for that time. A check for reasonableness of the default "time-of-day" populations was performed, as summarized in Table 10. The default nighttime population is essentially the same as the total population of the study region, as expected; the default daytime population is slightly less than the study region population (i.e., 90%); and the default commute population is much greater than study region population (i.e., 150%), which would affect significant overestimation of casualties at 5 p.m. Several adjustments are made, including adjustment of the default number of commuters inferred from the census data to a number comparable to published studies (MTC 2003, Table 7). As shown in Table 10, this study reduces the commuting population and adjusts other time-of-day populations, such that the sum of indoor, outdoor, and commuting populations is approximately equal to the total population of the study region at 2 a.m., 2 p.m., and 5 p.m., respectively.

BUILDING DAMAGE AND LOSS ESTIMATION METHODS IMPROVEMENT

A number of significant improvements are made to HAZUS default methods to estimate building damage, including (1) improvement of building response functions to better reflect effects of shaking duration, (2) development of new damage and loss functions for retrofitted model building types, (3) improvement of damage functions to better distinguish between model building types by seismic design level (and susceptibility to collapse), and (4) improvement of certain social and economic loss functions, including increase in economic loss rates to account for post-earthquake "surge" in repair and replacement costs. The first three topics are based largely on parameters found in the Advanced Engineering Building Module (AEBM) of HAZUS (NIBS 2002), while the changes to economic loss rates are based on recommendations of RMS, consistent with insurance industry practice. The following sections provide an overview of these improvements to the methods.

STRUCTURAL RESPONSE DURATION

HAZUS methods estimate peak building response using a simple "pushover" approach, for which peak inelastic demand (e.g., building deflection) is based, in part, on shaking duration as inferred from earthquake magnitude (e.g., long duration for large magnitude events). In the context of damage and loss estimation methods of HAZUS, duration applies to the amount of time that the structure is responding dynamically at or near the point of peak inelastic response. Long duration is appropriate for sites relatively far from fault rupture for which the structure could see many cycles of response at or near peak response. Conversely, for sites relatively close to fault rupture, for which ground motions can be quite intense, but typically last only for a few seconds of the earthquake, short duration bests describes the time the structure is responding at or near peak response. Ideally, the duration parameter would be dependent on both earthquake magnitude and distance from the fault, e.g., short duration for sites close to large-magnitude fault rupture (e.g., less than 15 km), long duration for sites relatively far from large-magnitude fault rupture (e.g., greater than 40 km), and moderate duration for sites in between, but current HAZUS technology permits only a single duration parameter, regardless of distance.

This study assumes short-moderate shaking duration as a compromise between earthquake magnitude and distance from the source. This compromise recognizes that most of the San Francisco peninsula is within 15 km of the San Andreas Fault and that most of the buildings of the study region are within 40 km of the fault. "Degradation" factors account for the effects of shaking duration on peak inelastic building response, and for this study are based on interpolations of values corresponding to short and moderate shaking duration given in Table 5.2 of the AEBM (NIBS 2002). The assumption of short-moderate shaking duration improves estimates of peak inelastic building response (and hence damage and loss) for most of the highly populated Bay Area counties, but it underestimates peak inelastic building response at sites in distant areas, such as Sacramento County. Such distant areas contribute little to the total damage and loss of the study region, and thus the approximation used in this particular study is justifiable.

NEW MODEL BUILDING TYPES—RETROFITTED STRUCTURES

This study incorporates new model building types representing seismically vulnerable (i.e., older wood structures with a soft story, URM buildings, and nonductile reinforced concrete buildings) that have been strengthened (i.e., so-called retrofitted structures). Properties of each retrofitted model building type are based on those of the existing model building type that best represents performance of the retrofitted structure. For example, URM buildings retrofitted to what seismic codes and guidelines often term life safety performance are deemed best represented by Moderate-Seismic Code reinforced-masonry buildings, whereas URM buildings retrofitted to Collapse Prevention performance, a lower performance level, are deemed best represented by Low-Seismic Code reinforced-masonry buildings.

In general, default damage parameters of the existing model building type are used directly, except for two important modifications. For this study, damage state variability is reduced to reflect a better understanding (less uncertainty) in the seismic performance of the retrofitted model building type. Second, this study decreases the default collapse rate (i.e., the percentage of building area within the Complete damage state this is expected to collapse) by one-half to reflect the reduced likelihood of building collapse of a retrofitted structure (e.g., by strengthening a weak or soft story, etc.).

DAMAGE FUNCTIONS

HAZUS building damage functions, which are formulated as fragility curves, describe the probability of reaching or exceeding discrete states of damage for the structure and for nonstructural systems. The damage states are None, Slight, Moderate, Extensive, and Complete. Descriptions of these damage states may be found in the HAZUS technical manual (NIBS 1997) and the HAZUS Advanced Engineering Building Module technical and user's manual (NIBS 2002). Each damage function is a lognormal probability function described by a median value and a lognormal standard deviation (beta) factor. This study modifies default building damage functions: (1) to reflect higher damage potential of soft-story wood structures and (2) to distinguish performance of model building types based on their seismic design level and retrofit condition. Additionally, this study increases the default collapse rate (i.e., rate of collapse given Complete structural damage state) by a factor of 5 for older soft-story wood buildings, and by a factor of 2 for nonductile concrete and URM buildings, to reflect the susceptibility of these vulnerable structures to collapse.

Default median values of damage functions are used in all cases, except for soft-story wood buildings (W1 and W2 model building types, Pre-Code seismic design level). Default median values are documented in Table 6.3 of the HAZUS Advanced Engineering Building Module technical and user's manual (NIBS 2002), and selected median values used in this study are shown in Table 11. For W1 and W2 buildings with a soft story, most of which in this study region are single-family houses and multifamily residential buildings, respectively, this study reduces the default median value of Extensive structural damage from an average interstory drift ratio of 0.025 to 0.016, and reduces the default median value of Complete structural damage from an average interstory drift ratio 0.06 to 0.03. This change is significant considering that wood buildings are by far the most common model building type and that this study assumes a significant fraction of these buildings (e.g., 25% of all older residences) have a soft story and are particularly susceptible to collapse.

In lieu of default values, this study develops lognormal standard deviation (beta) values for all building damage functions. These values of beta are based on Tables 6.5–6.7 of the HAZUS AEBM (NIBS 2002) and on assumptions regarding various sources of damage function variability, as described in Table 12. In brief, the variability of structural damage functions of a given retrofitted model building type is assumed to be slightly less than that of the corresponding existing model building type, due to improved knowledge of structure performance (i.e., better understanding of building capacity and damage states). Similarly, the variability of the structural damage functions of a given model building type and design vintage, i.e., seismic design level, is assumed to be slightly less than that of the same model building type of older design vintage, due to less uncertainty in post-yield building response (i.e., degradation). As shown in Table 12,

Table 11. Selected values of median parameters of structural damage functions used in this study for low-rise buildings (after Table 6.3 of the HAZUS AEBM, NIBS 2002)

Model Building Type		Seismic Design Level	Average interstory drift ratio of structural damage state			
Label	Description		Slight	Moderate	Extensive	Complete
W1/W2	Wood Frame Structures	HC	0.004	0.012	0.04	0.1
		MC/LC	0.004	0.012	0.031	0.075
W1/W2	Wood Frame w/Soft Story	PC	0.003	0.008	0.016	0.03
W1R	Retrofitted W1 w/Soft Story	Retrofit (LS)	0.004	0.012	0.031	0.075
		HC	0.005	0.01	0.03	0.08
C1L	Low-rise Concrete Frame	MC	0.005	0.009	0.023	0.06
	Structures	LC	0.005	0.008	0.02	0.05
		PC	0.004	0.006	0.016	0.04
C1LR	Retrofitted C1L Structures	Retrofit (LS)	0.005	0.009	0.023	0.06
C3L	Low-rise Concrete Frame	LC	0.003	0.006	0.015	0.035
	Structures with Masonry Infill	PC	0.002	0.005	0.012	0.028
C3LR	Retrofitted C3L Structures	Retrofit (LS)	0.004	0.007	0.019	0.053
URML	Low-rise Unreinforced Masonry	LC	0.003	0.006	0.015	0.035
	Wall Structures	PC	0.002	0.005	0.012	0.028
URMLR	Retrofitted URML Structures	Retrofit (CP)	0.004	0.006	0.016	0.044
		Retrofit (LS)	0.004	0.007	0.019	0.053

Table 12. Assumptions and values of lognormal standard deviation parameters of building damage functions used in this study[1]

Fragility Parameter	Existing Model Building Types			Retrofitted Model Building Types		
Damage-State Variability	Moderate (β_{ds}=0.4)			Small (β_{ds}=0.2)		
Capacity-Curve Variability	Moderate (β_C=0.4)			Small (β_C=0.2)		
Post-Yield Degradation	Minor	Moderate	Major	Minor	Moderate	Major
Damage States - Building Height	Seismic Design Level			Seismic Design Level		
	HC	MC/LC	PC	HC	MC/LC	PC
All Structural - Low-Rise	0.8	0.9	0.95	0.7	0.75	0.85
All Structural - Mid-Rise	0.75	0.8	0.85	0.65	0.7	0.75
All Structural - High-Rise	0.7	0.75	0.8	0.6	0.65	0.7
All Nonstructural - NSD	Same as structural			Same as structural		
All Nonstructural - NSA	0.65	0.65	0.65	0.65	0.65	0.65

[1] Parameters derived from Tables 6.5, 6.6 and 6.7 of the AEBM (NIBS 2002)

differences in structural betas are relatively small but provide a consistent trend between model building types of different design vintage (seismic design level) and retrofit condition.

LOSS FUNCTIONS

This study uses the default loss functions of HAZUS for all types of losses, except displaced household rates and direct economic loss rates. If there is Extensive structural damage to the residence, default values of displaced household weight factors (Table 14.1, HAZUS 1997) are increased such that 50% (rather than 10%) of single-family units are assumed uninhabitable and 100% (rather than 90%) of multifamily units are assumed uninhabitable. Displaced household rates are increased for consistency with the Association of Bay Area Governments (ABAG) nine-county estimate of approximately 160,000 displaced households due to San Andreas Fault rupture (ABAG 2003, Table 1). If there is Complete structural damage, all residences are assumed uninhabitable (i.e., no change to the default assumption)

In the case of direct economic losses, this study uniformly increases all loss rates by 30% to account for anticipated "amplification" in repair and replacement costs following a major earthquake. Loss amplification is expected because of temporary increases in the costs of materials and labor due to high demand for construction and related services. The 30% factor is based on information provided by Risk Management Solutions, consistent with methods used to estimate insured earthquake losses.

VALIDATION USING LOMA PRIETA EARTHQUAKE DATA

This study validates study region inventory and methods by comparing damage and loss estimates based on 1989 Loma Prieta earthquake ground motions with observed values of damage and loss. Observed values of damage and loss are taken from several sources including Practical Lessons from the Loma Prieta Earthquake (Fratessa 1994, Tierney 1994), Competing Against Time (California Governor's Board of Inquiry 1990), and the Loma Prieta Earthquake Reconnaissance Report (EERI 1990). Building damage and losses are often not known accurately, and published sources of damage and loss data do not always agree.

With respect to dollar loss, estimates range from $5.6 billion, an early estimate from the Office of Emergency Services (Governor's Board of Inquiry 1990), to more than $7 billion (EERI 1990), to $10 billion (Fratessa 1994). These estimates of economic loss increase with time, perhaps due to better information. Certainly, the more recent estimates of loss include costs to repair highway system damage, which was significant for the Loma Prieta earthquake. The estimated number of "damaged" buildings is more than 27,000 (Fratessa 1994). Unfortunately, the type and degree of damage to these buildings is not known. Societal losses include 62 deaths (42 of which were due to collapse of the Cypress Street Viaduct) and 3,757 injuries (EERI 1990). Table 11.2 of the Loma Prieta Earthquake Reconnaissance Report (EERI 1990) provides a breakdown of fatalities taken from a paper in the Journal of the American Medical Association showing not more than 16 building-related deaths. Approximately 1,100 persons were seen in hospitals on the night of the earthquake, 73% of which were treated and released (Tierney

1994), indicating that about 300 injuries were serious enough to require hospitalization. Serious injuries include casualties resulting from the Cypress Street Viaduct collapse and other nonbuilding causes, so perhaps only 200 of the 300 serious injuries are building (collapse) related. About 12,000–13,000 people were displaced from their homes, of which about 2,500 were provided shelter nightly at the peak period (Tierney 1994). These numbers are roughly consistent with estimates of 5,100 housing units in San Francisco and 3,400 housing units in Alameda County that either were damaged or destroyed (EERI 1990).

So, the following question is raised: Can the HAZUS-based methods and 19-county study region inventory data replicate the damage and losses, described above, within some reasonable margin of error, when evaluated using ground motions of the 1989 Loma Prieta earthquake (Pitarka et al. 1997)? Margins of error for loss estimation are necessarily broad due to uncertainties in study region inventory and methods, uncertainties in actual losses (e.g., number and type of damaged buildings), and most of all, the inherent variability in consequences from one event to the another (i.e., each earthquake produces a different pattern of damage and loss). In general, it is considered acceptable to overestimate or underestimate losses by not more than a factor of 2, particularly for deaths and serious injuries that are highly dependent on extreme structural damage to a relatively small number of buildings. This assumes a relatively large scale of casualties. For example, where the actual number of fatalities was only one or two, an estimated figure of five to ten or more would not be considered unacceptably inaccurate. In contrast to casualties, economic losses are more stable, since they are the accumulation of all states of structural and nonstructural damage to a relatively large number of buildings. Estimates of economic losses are often considered acceptable if they overestimate or underestimate actual loss by not more than 50%. For reference, previous comparisons of estimated and observed losses for the 1994 Northridge earthquake found HAZUS-based estimates to match observed losses quite well (Kircher 2006). In that case, estimates of direct economic losses due to building damage were within about 20% of reported losses.

Comparisons of damage and loss for the 1989 Loma Prieta earthquake using a study region with 2006 population and inventory data require adjustment of observed damage and social losses (circa 1989) to account for the additional number of people now living in the study region (and a corresponding increase in building square footage). Similarly, comparison of economic losses requires adjustment to reflect both the increased building square footage and the additional cost per square foot to replace or repair damaged buildings. Figure 5 shows that the population of the region has increased about 25% since 1989 and that building exposure has increased by about a factor of 2. In simple terms, a total economic loss of $7–10 billion in 1989 is roughly equivalent to about $14–20 billion of loss in terms of 2006 exposure.

The study region is evaluated for 1989 Loma Prieta ground motions, and selected results are reported in Table 13 with corresponding values of “actual” damage and losses that occurred in 1989 (as best they can be estimated), factored to represent 2006 exposure and population. Estimated building-related economic losses are about $19 billion, including business interruption, roughly 25% greater than the actual loss estimate of $15

Table 13. Comparison of estimates of damage and loss with "actual" values of damage and loss for the 1989 Loma Prieta earthquake

Damage or Loss Parameter	Estimated Damage or Loss	Actual Damage or Loss 2006[1]	Actual Damage or Loss 1989
Number of Damaged Buildings			
Moderate Structural Damage	100,212	34,000	27,0002[2]
Extensive or Complete Structural Damage	11,215		
Social Losses			
Temporary Public Shelter (peak number of people)	6,636	3,100	2,500[3]
Serious Injuries (5 p.m.)—Severity Levels 2 & 3	347	250	200[4]
Immediate Deaths (5 p.m.)—Severity Level 4	60	20	16[5]
Direct Economic Losses ($ in billions)			
Residential Buildings	$11.2		
Commercial Buildings	$4.4		
All Buildings w/o Business Interruption	$17.4	$15	$7.5[6]
All Buildings w/Business Interruption	$19.1		

[1] 2006 building damage and social losses based on 1.25 × 1989 values; 2006 direct economic losses based on 2 × 1989 loss to account of increases in population and building exposure
[2] Total number of damaged structures (Fratessa 1994)
[3] People in temporary shelter (Tierney 1994)
[4] Estimated 200 building-related serious injuries based on approximate 300 total serious injuries (Tierney 1994)
[5] Estimated 16 building-related deaths of total 63 deaths (Table 11.2, EERI 1990)
[6] Estimated $7.5 billion building-related loss based on $10 billion total loss (Fratessa 1994)

billion. Estimated serious injuries, about 300 people, compare well with actual building-related serious injuries, estimated to be about 250 people. Estimated immediate deaths, 49, are about 2.5 times actual building-related deaths. Estimated number of buildings with moderate damage, about 100,000, and the estimated number of buildings with severe (Extensive or Complete) damage, about 11,000, are more or less consistent with the actual number of damaged buildings, 34,000. The figure for actual damaged buildings certainly includes all severely damaged structures but not necessarily all moderately damaged buildings.

Trends in comparisons of estimated and actual losses, shown in Table 13 for the 1989 Loma Prieta earthquake, are consistent with those of the 1994 Northridge earthquake (Kircher 2006). Estimates of direct economic losses tend to be close to, or only modestly greater than, actual losses. Estimates of social losses, including displaced households, quantified in terms of the number of persons in need of temporary shelter, and casualties, tend to be consistently greater than actual losses. In particular, deaths are significantly overestimated. Deaths have been quite modest in recent U.S. earthquakes, and loss estimation methods have inherent limitations with respect to estimating relatively small losses (i.e., tens of deaths in a total population of several million). The methods are more accurate when estimating larger losses. Thus, while estimates of 1906 earthquake losses made by this study are likely high, the degree of overestimation of these losses, if any, is expected to be less than that of the Loma Prieta comparisons.

BUILDING DAMAGE AND LOSS—1906 EARTHQUAKE GROUND MOTIONS

This study estimates building damage and related losses for two sets of earthquake scenario ground motions, 1906 MMI ground motions (Boatwright et al. 2006, this issue) and magnitude M7.9 ground motions, as previously described in the Earthquake Hazard section of this paper. In both cases, damage and loss results include the effects of ground failure other than earthquake-induced landslides and surface faulting, as well as ground motions. Ground failure increases damage and loss marginally, e.g., about a 10% increase in economic and social losses). Damage and loss results do not include the effects of fire following earthquake or other, secondary, sources of potential damage and loss such as hazardous materials releases.

Although fire following is not expected to increase damage and loss by more than about 5%–10%, there is always the possibility of a significant conflagration, particularly in those areas of relatively dense urban construction and vulnerable structures. Weather conditions are of particular importance to the spread of fire, as was the case in the 20 October 1991 East Bay Hills fire, which killed 25 people, damaged or destroyed about 3,500 living units, and caused more than $1.5 billion in fire loss. In that fire, unusually hot temperatures and hot dry wind spread a single ignition of fire out-of-control, even though firefighters were already on the scene (Parker 1992). In contrast, the 294 cases of fire following the 17 January 1994 Kobe earthquake occurred during more fortunate weather conditions. Winter weather and light winds helped limit fire losses to about 5% of total economic loss, although fire still destroyed more than 7,500 buildings in the Kobe earthquake (UNCRD 1995).

BUILDING DAMAGE

Table 14 summarizes the number of residential buildings estimated to have either Extensive or Complete structural damage by county. This table distinguishes between single-family dwellings (SFDs) and other residential buildings, which include, primarily, multifamily dwellings (MWDs). The table provides estimates for both 1906 MMI ground motions and M7.9 ground motions. As described earlier these are the Boatwright et al. mapped values and those calculated within HAZUS in parallel with current seismic code methods, respectively. Similarly, Table 15 summarizes the number of nonresidential buildings estimated to have either Extensive or Complete structural damage by county. The table distinguishes between commercial buildings and other nonresidential buildings, which include industrial, government, religious, and education occupancies. Extensive and Complete structural damage corresponds roughly to damage that would likely be assigned either Yellow Tag (limited entry) or Red Tag (unsafe) ratings by post-earthquake safety evaluations following the guidelines of ATC-20 (ATC 1989).

Tables 14 and 15 show estimates of residential and nonresidential buildings with Ex-

Table 14. Estimates of Extensive or Complete structural damage to single-family dwellings and other residential buildings due to 1906 MMI and M7.9 ground motions, by county

	Single-Family Dwellings					Other Residential Buildings				
	Total	No. of Damaged Bldgs.				Total	No. of Damaged Bldgs.			
County	Number	06 MMI	%	M7.9	%	Number	06 MMI	%	M7.9	%
Alameda	367,738	13,497	3.7%	12,237	3.3%	31,824	3,564	11%	3,902	12%
Contra Costa	298,498	1,959	0.7%	949	0.3%	16,352	355	2.2%	367	2.2%
Lake	19,102	21	0.1%	2	0.0%	9,891	12	0.1%	1	0.0%
Marin	84,696	1,521	1.8%	3,874	4.6%	5,701	237	4.1%	791	14%
Mendocino	25,934	465	1.8%	257	1.0%	5,406	197	3.6%	136	2.5%
Merced	49,261	22	0.0%	4	0.0%	6,626	3	0.0%	3	0.1%
Monterey	96,996	376	0.4%	853	0.9%	9,904	119	1.2%	384	3.9%
Napa	38,556	458	1.2%	29	0.1%	5,200	150	2.9%	25	0.5%
Sacramento	340,964	1	0.0%	2	0.0%	28,767	2	0.0%	31	0.1%
San Benito	14,943	168	1.1%	494	3.3%	1,095	28	2.5%	153	14%
San Francisco	125,176	14,864	12%	23,810	19%	36,796	7,074	19%	10,862	30%
San Joaquin	142,587	8	0.0%	8	0.0%	13,510	3	0.0%	12	0.1%
San Mateo	202,877	14,325	7.1%	23,228	11%	10,925	1,522	14%	3,236	30%
Santa Clara	444,273	11,328	2.5%	20,299	4.6%	37,093	2,578	7.0%	4,786	13%
Santa Cruz	78,198	1,646	2.1%	3,016	3.9%	9,932	500	5.0%	1,313	13%
Solano	110,733	366	0.3%	225	0.2%	7,922	72	0.9%	66	0.8%
Sonoma	150,870	4,826	3.2%	1,423	0.9%	14,751	1,209	8.2%	312	2.1%
Stanislaus	116,518	17	0.0%	6	0.0%	11,685	4	0.0%	8	0.1%
Yolo	39,644	1	0.0%	0	0.0%	5,128	1	0.0%	3	0.1%
All 19 Counties	2,747,564	65,869	2.4%	90,717	3.3%	268,508	17,630	6.6%	26,388	9.8%

tensive or Complete structural damage totaling 92,014 (1906 MMI) and 129,659 (M7.9). For reference, more than 140,000 buildings were severely damaged or collapsed during the 1995 Kobe earthquake (AIJ 1995). These numbers are in contrast to the 1994 Northridge earthquake for which post-earthquake safety inspections identified only about 15,000 buildings sufficiently damaged to warrant either a Yellow or Red Tag (Table 4-2, EQE 1995).

While the total number of buildings with Extensive or Complete structural damage is similar for 1906 MMI and M7.9 ground motions for the entire study region, individual census tract results are often very different. As shown in Tables 14 and 15, the number of damaged buildings can be quite different for the two ground motion scenarios, even when aggregated at the county level. For example, the M7.9 ground motions cause almost twice as many single-family dwellings (SFDs) to have Extensive or Complete structural damage as the 1906 MMI ground motions in San Francisco, San Mateo, and Santa Clara counties. However, in Alameda, Contra Costa, and, in particular, Sonoma, counties, the trend is reversed, and the 1906 MMI ground motions cause more SFD

Table 15. Estimates of Extensive or Complete structural damage to commercial and other nonresidential buildings due to 1906 MMI and M7.9 ground motions, by county

County	Commercial Buildings					Other Nonresidential Buildings				
	Total Number	No. of Damaged Bldgs.				Total Number	No. of Damaged Bldgs.			
		06 MMI	%	M7.9	%		06 MMI	%	M7.9	%
Alameda	10,667	1,197	11%	1,307	12%	3,276	383	12%	491	15%
Contra Costa	5,726	143	2.3%	97	1.7%	705	24	3.4%	18	2.5%
Lake	194	4	2.0%	1	0.4%	69	2	2.5%	0	0.6%
Marin	2,324	137	5.9%	444	19%	474	36	7.6%	107	23%
Mendocino	453	35	7.6%	27	5.9%	47	2	5.1%	1	2.8%
Merced	649	2	0.3%	1	0.1%	142	0	0.2%	0	0.1%
Monterey	2,389	60	2.5%	122	5.1%	549	20	3.6%	43	7.8%
Napa	991	64	6.5%	9	0.9%	306	16	5.2%	3	0.9%
Sacramento	7,252	0	0.0%	5	0.1%	1,808	0	0.0%	4	0.2%
San Benito	198	11	5.7%	35	18%	43	3	5.9%	8	20%
San Francisco	9,527	2,482	26%	3,560	37%	1,432	382	27%	518	36%
San Joaquin	2,522	2	0.1%	5	0.2%	596	1	0.1%	1	0.1%
San Mateo	5,037	1,051	21%	2,054	41%	976	255	26%	454	46%
Santa Clara	10,854	1,170	11%	2,059	19%	3,062	345	11%	543	18%
Santa Cruz	1,657	128	7.7%	328	20%	353	25	7.2%	69	20%
Solano	1,810	30	1.7%	25	1.4%	358	7	1.9%	3	0.9%
Sonoma	2,988	408	14%	169	5.7%	626	86	14%	38	6.1%
Stanislaus	1,980	2	0.1%	2	0.1%	505	1	0.2%	1	0.2%
Yolo	1,023	0	0.0%	1	0.1%	254	0	0.0%	0	0.1%
All 19 Counties	68,241	6,927	10%	10,251	15%	15,581	1,588	10%	2,303	15%

damage. Tables 14 and 15 also show the fraction of all buildings of a given type that have Extensive or Complete structural damage. These fractions can be quite significant for counties relatively close to the fault. For example, 21% (1906 MMI) and 41% (M7.9) of all commercial buildings in San Mateo and 26% (1906 MMI) and 37% (M7.9) of all commercial buildings in San Francisco are estimated to have Extensive or Complete structural damage. This level of damage would likely cause the building to be closed, or have its use be restricted, until earthquake repairs can be made.

DIRECT ECONOMIC LOSSES

Table 16 summarizes estimates of direct economic losses for buildings due to 1906 MMI ground motions, and Table 17 provides the same information for M7.9 ground motions. Direct economic losses include capital stock losses and income losses. Capital stock losses include repair and replacement costs of the structural system, the nonstructural system and building contents. Income losses include business interruption, temporary space rental and moving costs, and other losses related to loss of building function (due to structural system damage).

Table 16. Estimates of direct economic losses for buildings due to 1906 MMI ground motions, by county (dollars in millions)

	Capital Stock Losses						
County	Structural	Nonstruct.	Contents	Total	Ratio	Income Loss	Total Loss
Alameda	$2,701	$9,650	$2,401	$14,752	7.9%	$1,419	$16,170
Contra Costa	$578	$2,577	$604	$3,759	3.1%	$272	$4,031
Lake	$15	$65	$17	$98	1.7%	$8	$105
Marin	$388	$1,581	$364	$2,333	5.5%	$198	$2,531
Mendocino	$96	$408	$97	$601	6.9%	$61	$661
Merced	$14	$65	$15	$94	0.6%	$6	$100
Monterey	$198	$775	$194	$1,167	2.9%	$109	$1,276
Napa	$143	$593	$164	$900	5.0%	$90	$990
Sacramento	$8	$19	$3	$30	0.0%	$3	$33
San Benito	$39	$169	$37	$244	5.0%	$19	$263
San Francisco	$3,888	$13,673	$3,060	$20,622	17.5%	$2,582	$23,204
San Joaquin	$22	$81	$18	$121	0.2%	$10	$130
San Mateo	$2,440	$9,474	$2,072	$13,987	14.1%	$1,059	$15,045
Santa Clara	$2,893	$11,729	$2,953	$17,575	8.0%	$1,509	$19,084
Santa Cruz	$398	$1,691	$382	$2,471	7.4%	$190	$2,661
Solano	$124	$572	$144	$840	2.0%	$56	$897
Sonoma	$927	$4,033	$1,012	$5,972	9.8%	$468	$6,440
Stanislaus	$27	$105	$25	$156	0.4%	$12	$168
Yolo	$5	$18	$4	$27	0.2%	$2	$30
All 19 Counties	$14,904	$57,278	$13,566	$85,748	5.2%	$8,071	$93,819

Estimates of total direct economic loss are $93.8 billion (1906 MMI) and $122.4 (M7.9). Again, for reference, building-related losses in the 1995 Kobe earthquake were 7.5 trillion yen, or about $80 billion (UNCRD 1995). Building-related economic losses in the 1994 Northridge earthquake were about $20 billion (Comerio et al. 1996). Of course, these losses are a decade old and should be factored by approximately 1.5 for comparison with the current (2006) estimates of this study.

Tables 16 and 17 provide average loss ratios for each county. The average loss ratio is calculated as the value of estimated capital stock losses divided by total building exposure. Figures 8 and 9 are maps of the study region showing the average loss ratio by census tract for 1906 MMI and M7.9 ground motions, respectively. Loss ratio varies greatly from areas of the strongest ground shaking (e.g., census tracts close to fault rupture) to areas of weakest ground shaking (e.g., census tracts farthest from fault rupture). Average loss ratios are about 25% for San Francisco and San Mateo counties, 12% for San Mateo and Santa Clara counties, 7% for Alameda County, and only 0.1% for Sacramento County (but still $89 million).

Tables 16 and 17 also reveal the relative contributions of structural and nonstructural system damage to direct economic loss. Costs of repair and replacement of damaged

Table 17. Estimation of direct economic losses for buildings due to M7.9 ground motions, by county (dollars in millions)

	Capital Stock Losses						
County	Structural	Nonstruct.	Contents	Total	Ratio	Income Loss	Total Loss
Alameda	$2,704	$8,742	$2,119	$13,565	7.4%	$1,450	$15,015
Contra Costa	$347	$1,355	$308	$2,011	1.7%	$184	$2,195
Lake	$5	$16	$4	$25	0.4%	$2	$27
Marin	$843	$3,305	$774	$4,923	11.5%	$473	$5,396
Mendocino	$61	$249	$62	$371	4.2%	$45	$416
Merced	$8	$27	$6	$40	0.3%	$4	$44
Monterey	$321	$1,208	$302	$1,832	4.5%	$171	$2,002
Napa	$33	$130	$35	$198	1.1%	$21	$219
Sacramento	$30	$50	$8	$89	0.1%	$19	$108
San Benito	$85	$372	$84	$541	11.0%	$42	$583
San Francisco	$5,662	$20,285	$4,215	$30,162	25.9%	$3,605	$33,767
San Joaquin	$24	$78	$18	$119	0,2%	$14	$133
San Mateo	$4,182	$16,535	$3,726	$24,443	24.6%	$1,914	$26,357
Santa Clara	$4,437	$17,438	$4,203	$26,078	11.9%	$2,349	$28,427
Santa Cruz	$691	$2,784	$652	$4,127	12.2%	$355	$4,483
Solano	$66	$247	$60	$374	0.9%	$37	$410
Sonoma	$418	$1,651	$411	$2,480	4.1%	$230	$2,710
Stanislaus	$19	$66	$15	$100	0.3%	$10	$111
Yolo	$6	$16	$3	$25	0.1%	$3	$28
All 19 Counties	$19,942	$74,557	$17,007	$111,505	6.4%	$10,926	$122,431

nonstructural systems and contents dominate capital stock losses. Seismic strengthening of the structural system greatly improves life safety and building functionality, and decreases income-related losses (by decreasing downtime); however, only incremental improvement of capital-related losses is possible without also improving seismic performance of nonstructural systems and contents.

DISPLACED HOUSEHOLDS AND TEMPORARY SHELTER

Table 18 gives estimates of the number of displaced households and related number of people seeking public shelter. Displaced households are a function of the number of residences with either Extensive or Complete structural damage. People from displaced households will seek alternative shelter. Some fraction will stay with friends or relatives, some fraction will rent housing, and some fraction of displaced people will seek public shelter.

Estimates of the number of displaced households are 167,499 (1906 MMI) and 245,649 (M7.9), respectively. The corresponding estimates of the number of people seeking public shelter are 40,413 (1906 MMI) and 57,989 (M7.9), respectively. For reference, more than 300,000 people were left homeless by the 1995 Kobe earthquake

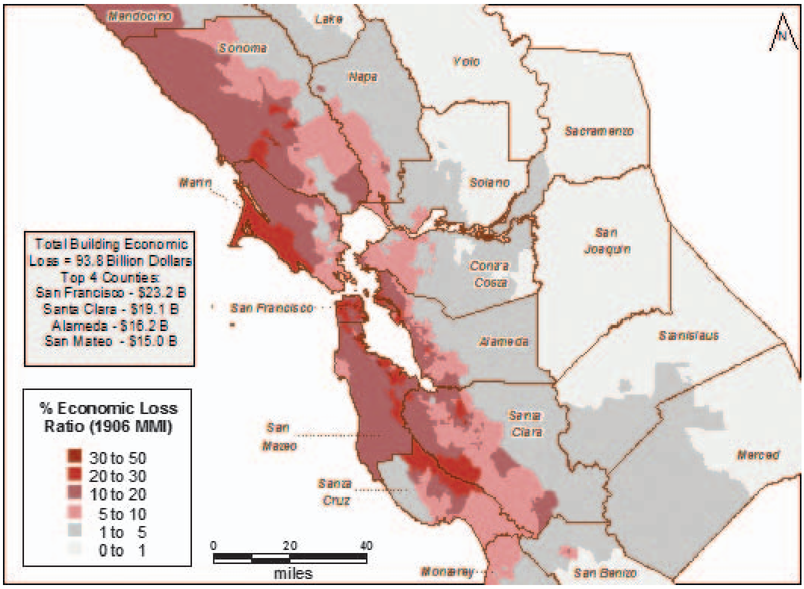

Figure 8. Map of study region showing direct economic loss ratio by census tract for all buildings based on 1906 MMI ground motions. In color: see plates following p. S68.

(EERI 1995a), and approximately 20,000 people camped outside in park facilities the first night after the 1994 Northridge earthquake (EQE 1997). The American Red Cross registered 11,088 households (28,500 people) and reported providing shelter for a maximum of 17,500 people at any one time for the Northridge earthquake.

While validation shows the methods used in this study to estimate the number of people seeking temporary shelter to be conservative (by a factor of more than 2 for the 1989 Loma Prieta earthquake), estimates of 40,000–60,000 people in need of public shelter may still be low. These estimates assume that most (i.e., 80%–90%) of the people from displaced households can find alternative housing on their own. This may not be an appropriate assumption considering that 400,000–600,000 people are estimated to be displaced (assuming 2.5 people per household).

CASUALTIES

Table 19 summarizes estimates of the number of daytime (2 p.m.) and nighttime (2 a.m.) casualties for 1906 MMI ground motions, and Table 20 provides the same information for M7.9 ground motions. Casualties include serious injuries (i.e., injuries requiring hospitalization), persons trapped in collapsed buildings and in need of immediate rescue to avoid death, and instantaneous deaths. For reference, more than 5,000 people died, primarily from building collapse, and more than 30,000 people were injured in the Kobe earthquake, which occurred very early in the morning when most residents were at home (UNCRD 1995). In contrast, 60 people died in the 1994 Northridge earth-

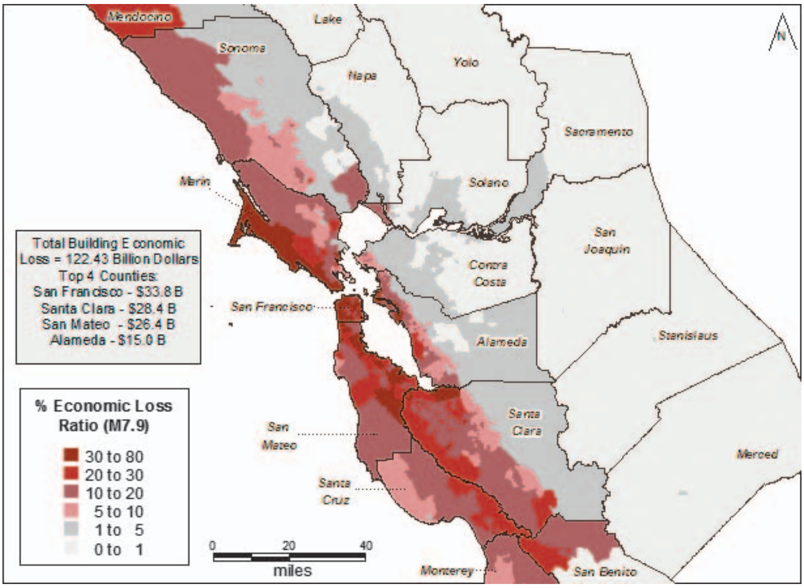

Figure 9. Map of study region showing direct economic loss ratios by census tract for all buildings based on magnitude M7.9 ground motions.

quake; 26 of these deaths were building related (EQE 1995, Table 5-9). There were 1,044 serious injuries in this earthquake requiring hospitalization (EERI 1995b, Table 7-1).

Table 19 shows an estimated 831 deaths and 3,942 serious injuries at night (2 a.m.) for the study region evaluated using 1906 MMI ground motions. The reader should keep in mind that HAZUS calculates specific loss figures without rounding, and thus a value such as "831" should not be taken as implying the ability of any loss estimation method to accurately predict such precise outcomes. In San Francisco, estimated nighttime casualties include 287 deaths and another 149 people trapped and requiring immediate rescue to avoid death. These estimated casualties are consistent with those that likely occurred in 1906 due to building collapse, considering changes in population and building stock since that date. Table 19 shows an estimated 1,558 deaths and 6,187 serious injuries during the day (2 p.m.) for the study region evaluated using 1906 MMI ground motions. Daytime casualties are typically higher than nighttime casualties. At night, most people are at home and, on average, residences are less susceptible to collapse than commercial buildings.

Table 20 shows an estimated 1,846 deaths and 7,959 serious injuries at night for the study region evaluated using M7.9 ground motions, more than a factor of 2 greater than casualties estimated using 1906 MMI ground motions. Although this is less than one-half of the deaths and serious injuries of the 1995 Kobe earthquake, these estimates are still consistent with Kobe casualties, considering the increased vulnerability of Japanese

Table 18. Estimates of the number of displaced households and people seeking temporary public shelter due to 1906 MMI and M7.9 ground motions, by county

County	Households					Number of People Seeking Public Shelter	
	Total number	1906 MMI		M7.9			
		Displaced	%	Displaced	%	1906 MMI	M7.9
Alameda	523,366	36,786	7.0%	38,955	7.4%	9,678	10,393
Contra Costa	344,129	4,523	1.3%	4,032	1,2%	1,125	1,067
Lake	23,974	59	0%	18	0%	16	5
Marin	100,650	2,402	2.4%	6,991	6.9%	517	1,497
Mendocino	33,266	732	2.2%	471	1.4%	199	129
Merced	63,815	45	0.1%	57	0.1%	13	18
Monterey	121,236	1,230	1.0%	2,553	2.1%	325	690
Napa	45,402	1,051	2.3%	245	0.5%	262	62
Sacramento	453,602	38	0.0%	499	0.1%	11	142
San Benito	15,885	224	1%	623	4%	58	157
San Francisco	329,700	60,254	18.3%	87,995	26.7%	14,817	21,192
San Joaquin	181,629	73	0.0%	179	0.1%	21	53
San Mateo	254,103	21,348	8.4%	41,356	16.3%	4,535	8,822
Santa Clara	565,863	28,639	5.1%	52,911	9.4%	6,403	11,597
Santa Cruz	91,139	2,434	2.7%	5,216	5.7%	593	1,303
Solano	130,403	757	0.6%	502	0.4%	200	132
Sonoma	172,403	6,791	3.9%	2,855	1.7%	1,610	678
Stanislaus	145,146	87	0.1%	130	0.1%	24	35
Yolo	59,375	28	0.0%	60	0.1%	8	17
All 19 Counties	3,655,086	167,499	4.6%	245,649	6.7%	40,413	57,989

residences to collapse. Table 20 shows an estimated 3,411 deaths and 12,562 serious injuries during the day for the study region evaluated using M7.9 ground motions.

Comparison of daytime (2 p.m.) and nighttime (2 a.m.) casualties for San Francisco and San Mateo counties highlights differences in life safety risk due to differences in building performance. While estimates of daytime casualties are similar for the two counties, San Francisco County has significantly more risk at night due to a greater number of vulnerable residences. It is also of interest to note that there are approximately 1.5 million people living in these two counties, so that the combined number of estimated daytime fatalities, 1,836 deaths, represents roughly a casualty rate of one death per 1,000 people for M7.9 ground motions. As described earlier, M7.9 ground motions are the same as those of the design basis earthquake for these two counties.

Tables 21 and 22 distribute estimates of nighttime and daytime fatalities, respectively, between model building types. In both tables, fatalities are based on M7.9 ground motions. The tables show the corresponding fraction of all fatalities for each model building type (MBT). Additionally, the tables show MBT square footage and the corre-

Table 19. Estimates of casualties due to 1906 MMI ground motions, by county

	No. of Casualties—2 a.m.				No. of Casualties—2 p.m.			
County	Total Number	Serious Injuries	Requires Rescue	Immediate Deaths	Total Number	Serious Injuries	Requires Rescue	Immediate Deaths
Alameda	4,394	759	93	179	5,560	988	143	276
Contra Costa	739	101	10	20	890	127	15	28
Lake	17	2	0	0	27	4	0	1
Marin	425	73	9	17	543	87	11	22
Mendocino	196	43	7	12	203	37	5	10
Merced	22	1	0	0	25	3	0	0
Monterey	360	60	8	15	377	58	7	14
Napa	173	23	2	4	250	39	5	10
Sacramento	8	0	0	0	9	1	0	0
San Benito	61	7	1	1	93	16	2	4
San Francisco	7,213	1,420	149	287	10,313	2,037	211	404
San Joaquin	27	1	0	0	44	3	0	0
San Mateo	3,273	531	55	105	5,698	1,069	161	312
Santa Clara	4,197	623	66	128	6,914	1,205	171	332
Santa Cruz	494	81	10	18	674	117	17	33
Solano	154	15	1	2	183	24	2	5
Sonoma	1,230	198	22	42	2,023	370	55	107
Stanislaus	33	2	0	0	40	4	0	0
Yolo	7	0	0	0	5	0	0	0
All 19 Counties	23,022	3,942	433	831	33,869	6,187	806	1,558

sponding fraction of total building square footage for each MBT. Finally, a "relative risk" factor is calculated as the ratio of the fraction of deaths divided by the fraction of total square footage for each MBT. Values greater than 1.0 imply above-average life safety risk, compared to other model building types.

Nighttime deaths are dominated by and distributed somewhat equally between wood, concrete (including precast concrete), and masonry (including URM) buildings. Table 21 shows that 490 of the 535 estimated fatalities in wood buildings are due to collapse of "soft-story" configurations. Likewise, estimated fatalities in URM buildings (before seismic retrofit) and nonductile concrete frames show these building types to be dominant contributors to life safety risk. The combined square footage of soft-story wood, nonductile concrete, and URM buildings (before seismic retrofit) represents less than 3.5% of the total square footage of all buildings, yet these buildings account for more than 50% of life safety risk at night.

Table 22 shows a different pattern of daytime deaths, but tells the same story. Wood buildings, primarily used for residences, are not a significant contributor to life safety risk during the day. Still, soft-story wood, nonductile concrete, and URM buildings ac-

Table 20. Estimates of casualties due to M7.9 ground motions, by county

	No. of Casualties—2 a.m.				No. of Casualties—2 p.m.			
County	Total Number	Serious Injuries	Requires Rescue	Immediate Deaths	Total Number	Serious Injuries	Requires Rescue	Immediate Deaths
Alameda	5,032	1,005	140	269	6,880	1,300	196	378
Contra Costa	660	124	17	32	635	96	11	21
Lake	4	0	0	0	6	1	0	0
Marin	1,340	266	36	69	2,077	404	62	121
Mendocino	220	71	13	24	190	41	7	13
Merced	12	1	0	0	11	1	0	0
Monterey	830	163	23	44	986	182	27	52
Napa	34	3	0	0	46	5	0	1
Sacramento	31	2	0	0	35	3	0	0
San Benito	191	31	4	7	364	74	12	23
San Francisco	13,383	2,873	301	574	18,799	3,977	430	823
San Joaquin	31	2	0	0	52	4	0	0
San Mateo	8,165	1,546	192	370	15,540	3,218	521	1,013
Santa Clara	8,634	1,503	187	361	14,111	2,699	413	802
Santa Cruz	1,237	240	32	62	1,968	391	62	120
Solano	80	8	1	1	105	14	2	3
Sonoma	590	118	17	31	864	149	20	39
Stanislaus	23	1	0	0	27	2	0	0
Yolo	7	0	0	0	6	0	0	0
All 19 Counties	40,506	7,959	962	1,846	62,703	12,562	1,764	3,411

count for more than 40% of the life safety risk during daytime. In terms of the relative risk factor, URM and nonductile buildings (without seismic retrofit) are at least 20 times more "risky" than other buildings, on average.

While the probable performance of a wide variety of buildings is considered by the fragilities used in HAZUS, the seismic characteristics and occupancies of individual, specific buildings are not modeled. The anomalous collapse of one or two high-occupancy buildings could thus cause casualties greater than the expected value presented here.

CONCLUSION

This paper provides interim results of an ongoing study of the potential consequences of a repeat of the 1906 San Francisco earthquake for a 19-county region of the greater San Francisco Bay Area and adjacent areas of Northern California. Results include estimates of building damage and related losses: direct economic impacts, temporary shelter demands, and casualties. The 19-county study region has a population of more than ten million people, and buildings worth more than $1 trillion without contents, or about $1.5 trillion with contents.

Table 21. Distribution of estimated nighttime (2 a.m.) deaths due to M7.9 ground motions by model building type

Model Building Type (MBT)			Relative MBT Use		Deaths		
Label	Description	Seismic Design Level	Area (SF $\times 10^3$)	Percent of Total	Number	Percent of All	Relative Risk Factor
W1	Wood Frame (<5,000 SF)	All non-PC	4,376,668	56%	39	2.1%	0.0
W1	W1 w/Soft Story	PC	147,605	1.9%	330	17.9%	9.4
W1R	Retrofitted W1 w/Soft Story	Retrofit	99,702	1.3%	2	0.11%	0.1
W2	Wood Frame (>5,000 SF)	All non-PC	576,702	7.4%	4	0.22%	0.0
W2	W2 w/Soft Story	PC	34,498	0.45%	160	8.7%	19.5
	All Wood Buildings	All	5,235,174	68%	535	29.0%	0.4
C1/C3	Nonductile Concrete Frame	PC	43,480	0.56%	208	11.3%	20.1
C1/C3R	Retrofitted Nonductile C1/C3	Retrofit	22,576	0.29%	9	0.49%	1.7
	All Concrete Buildings	All	875,221	11.3%	607	32.9%	2.9
URM	Unreinforced Masonry	PC	40,139	0.52%	256	13.9%	26.8
URMR	Retrofitted URM	Retrofit	131,879	1.7%	33	1.8%	1.0
	All Masonry Buildings	All	697,316	9.0%	410	22.2%	2.5
	All Steel Buildings	All	778,835	10.1%	293	15.9%	1.6
MH	All Mobile Homes	All	162,610	2.1%	1	0.05%	0.0
	All Buildings	All	7,749,156	100%	1,846	100%	1.0

This study calculates damage and losses using the HAZUS earthquake loss estimation technology, incorporating significant improvements to both default inventories and various default damage and loss methods. Special efforts are made to improve models of the most seismically vulnerable building types, including soft-story wood, nonductile concrete, and unreinforced masonry (URM) buildings, and to develop new "retrofitted" model building types. Finally, this study validates improved inventory and methods by comparing damage and loss estimated for 1989 Loma Prieta earthquake ground motions with actual damage and losses for this event. Validation results show improved inventory and methods provide reasonably accurate and modestly conservative estimates of actual damage and loss.

Using improved and validated inventory and methods, this study estimates that a repeat of the "Big One" will instantaneously kill more than 800 people at night or more than 1,500 people during the day; require immediate rescue of people trapped in collapsed buildings of about one-half of these numbers (to avoid additional fatalities); and seriously injure about 4,000 people at night or more than 6,000 people during the day. More than 160,000 households (about 400,000 people) will be displaced from their

Table 22. Distribution of estimated daytime (2 p.m.) deaths due to M7.9 ground motions by model building type

Model Building Type (MBT)			Relative MBT Use		Deaths		
Label	Description	Seismic Design Level	Area (SF $\times 10^3$)	Percent of Total	Number	Percent of All	Relative Risk Factor
W1	Wood Frame (<5,000 SF)	All non-PC	4,376,668	56%	9	0.3%	0.0
W1	W1 w/Soft Story	PC	147,605	1.9%	80	2.3%	1.2
W1R	Retrofitted W1 w/Soft Story	Retrofit	99,702	1.3%	0	0.00%	0.0
W2	Wood Frame (>5,000 SF)	All non-PC	576,702	7.4%	40	1.2%	0.2
W2	W2 w/Soft Story	PC	34,498	0.45%	24	0.70%	1.6
	All Wood Buildings	All	5,235,174	68%	153	4.5%	0.1
C1/C3	Nonductile Concrete Frame	PC	43,480	0.56%	456	13.4%	23.8
C1/C3R	Retrofitted Nonductile C1/C3	Retrofit	22,576	0.29%	23	0.67%	2.3
	All Concrete Buildings	All	875,221	11.3%	1,364	40.0%	3.5
URM	Unreinforced Masonry	PC	40,139	0.52%	637	18.7%	36.1
URMR	Retrofitted URM	Retrofit	131,879	1.7%	117	3.4%	2.0
	All Masonry Buildings	All	697,316	9.0%	1,044	30.6%	3.4
	All Steel Buildings	All	778,835	10.1%	849	24.9%	2.5
MH	All Mobile Homes	All	162,610	2.1%	1	0.03%	0.0
	All Buildings	All	7,749,156	100%	3,411	100%	1.0

homes due to Extensive or Complete structural damage. The earthquake will temporarily, or permanently, close almost 7,000 commercial buildings, or about 10% of all commercial buildings in the study region, due to Extensive or Complete structural damage. In the hardest hit counties, San Francisco and San Mateo counties, upwards of 25% of all commercial buildings will be temporarily, or permanently, closed. Estimated cost of repair or replacement of damaged buildings and their contents is in excess of $85 billion and total direct economic loss (including also business interruption losses) is more than $93 billion.

The above damage and loss estimates are based on the "1906 MMI" ground motions developed by Boatwright et al. (2006), which provide the best available estimate of the ground shaking that occurred in 1906. Every earthquake, even on the same fault, generates a different set of ground motions, and a similar magnitude earthquake on this fault in the future would be unlikely to generate an identical ground motion pattern. As a "second opinion," this study evaluates damage and loss for ground motions of a magnitude M7.9 earthquake assumed to occur on the segments of the fault near San Francisco, motions calculated from methods paralleling that of modern seismic provisions in building codes. The M7.9 ground motions are essentially the same as those of the design basis earthquake for sites relatively close to fault rupture, including most of San Francisco and San Mateo counties.

This study estimates substantially larger damage and loss using the M7.9 ground motions. Direct economic losses increase by about 30% to more than $120 billion. The number of commercial buildings with Extensive or Complete structural damage increases by about 50% to more than 10,000 buildings, or about 15% of all commercial building in the study region, and includes about 40% of all commercial buildings in San Francisco and San Mateo counties. Similarly, almost 250,000 households (about 600,000 people) will be displaced from their homes due to Extensive or Complete structural damage. However, the most significant increase is in the number of casualties. Deaths and serious injuries increase by more than a factor of 2. The M7.9 ground motions instantaneously kill more than 1,800 people at night or more than 3,400 people during the day, and seriously injury about 8,000 people at night or more than 12,500 people during the day.

The primary source of risk to life safety comes from the most seismically vulnerable building types. Collapse of soft-story wood, nonductile concrete, and URM buildings (before seismic retrofit) accounts for 50% of all deaths at night (2 a.m.) and more than 40% of all deaths during the day (2 a.m.), even though these building types represent less than 3.5% of all buildings in the study region (by square footage).

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