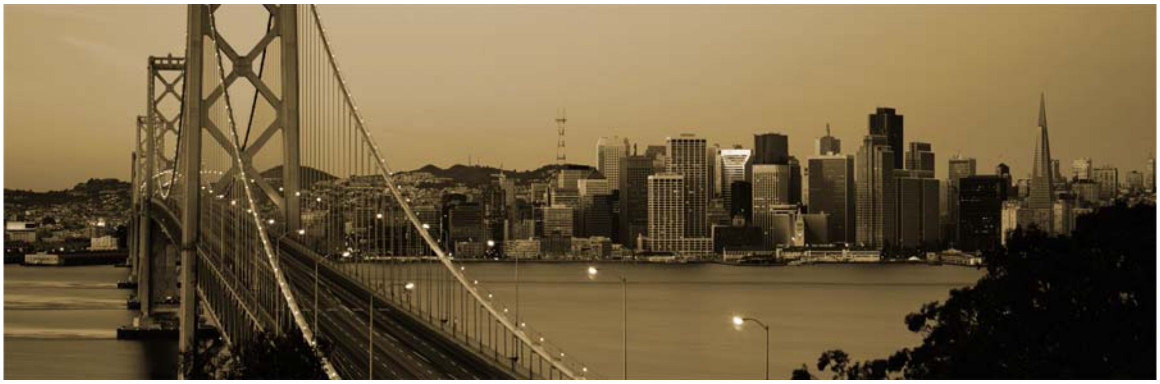
When the *Big One* Strikes Again – Estimated Losses due to a Repeat of the 1906 San Francisco Earthquake



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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 on-going 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, 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 over 10 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 hundred years causes the range of estimated fatalities, approximately 800 to 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 to $120 billion; 7,000 to 10,000 commercial buildings in the region are estimated to be

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closed due to serious damage; and about 160,000 to 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.

INTRODUCTION

The great earthquake of April 18, 1906, caused widespread damage to San Francisco and other Bay Area locales, ranging from as far north as Mendocino County to as far south as Monterey County. The literature for many years has reported approximately 700 to 800 deaths (see for example Freeman, 1932, p. 8) although some recent studies (Hansen et al., 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 over 500 downtown blocks.

In 1906, about 390,000 people lived in San Francisco, and less than 1 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 ten fold. In 1906, few buildings were over 10 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 damages 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 on-going ’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 these damages. 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 damages to the region's infrastructure caused by earthquake ground motions and ground failure, and induced (or secondary) damages 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 on-going 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., URM, non-ductile 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., URM 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 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, 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 "non-ductile" 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 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 United States 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 United States Geological Survey (USGS) described in "Using Modified Mercalli Intensities to Estimate Acceleration Response Spectra for the 1906 San Francisco Earthquake," (Boatwright et al., 2006). 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 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 1-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 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 1-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 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 help calibrate the original HAZUS technology. Figure 3 is a map of 1-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 nine 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 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 10 million people. There are an estimated 3 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 1/3 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 ten-fold increase in population. Likewise, buildings have been constructed essentially in parallel with this growth. Table 2 summarizes population and Building Cost Index, BCI (ENR, 2005) data from 1990 to 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 three.

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). Relatively 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 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 '06. 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 one-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 one-half of the San Francisco.

Over the period from 1906 to present, seismic provisions of building codes (Seismic Codes) have evolved, and construction methods have improved, most notably in the 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 near San Jose City, 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.

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/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 6 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 multi-family 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 review 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 commercial 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, unreinforced masonry (URM) buildings, non-ductile concrete frame buildings, and soft-story wood single-family and multi-family 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 multi-family 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 1^{st}-floor and the foundation) and open 1^{st}-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).

The 1994 Northridge earthquake showed the vulnerability of multi-story 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 multi-family wood residences found that about 11% of all units were in multi-story 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 (e.g., Oakland) are considered similar to San Francisco. The 25% fraction is based on the assumption that about one-half of all buildings identified as having a soft story are actual collapse hazards. For all other counties, 10 % of all wood residences built before 1950 are assumed susceptible to soft-story collapse. This study assumes that 10% of all larger multi-family 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 multi-family 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 has generated both a very good understanding of the number of URM buildings, as well 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 one-half of URM buildings have been strengthened, although in San Francisco this rate is over 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 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 non-ductile 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 non-ductile 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 non-ductile concrete are the only seismically vulnerable building types. There are certainly other seismically vulnerable building types, e.g., older, pre-cast 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), Newark, California, provided estimated replacement costs of residential and non-residential 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, non-residential building exposure is quite different. On average, HAZUS non-residential building exposure is only about one-half of RMS exposure values. Most likely, the main source of the difference is an underestimation of non-residential 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 non-residential building occupancies, as summarized in Table 9. The factors are applied uniformly to structural and nonstructural systems of buildings. As 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).

Non-residential 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 non-residential 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 very 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, 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 AM), during the day (e.g., 2 PM) or during peak commute (e.g., 5 PM), 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 over estimation of casualties at 5 PM. Several adjustments are made including adjustment of the default number of commuters inferred from the census data to a number comparable to published studies (Table7, MTC, 2003). 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 AM, 2 PM, and 5 PM, 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), (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, unreinforced masonry buildings and non-ductile 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 AEBM Users and Technical 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 5 for older, soft-story wood buildings, and by a factor of 2 for non-ductile 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 AEBM 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 multi-family residential buildings respectively, this study reduces the default median value of Extensive structural damage from an average inter-story drift ratio of 0.025 to 0.016, and reduces the default median value of Complete structural damage from an average inter-story 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 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, 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 that 100% (rather than 90%) of multi-family units are assumed uninhabitable. Displaced household rates are increased for consistency with the Association of Bay Area Governments (ABAG) 9-county estimate of approximately 160,000 displaced households due to San Andreas Fault rupture (Table 1, ABAG, 2003). 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 Earthquake* (Fratessa, 1994, Tierney, 1994), *Competing Against Time* (California Governor's Board of Inquiry, 1990) and "Loma Prieta Earthquake Reconnaissance Report," *Earthquake Spectra* (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 over $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 over 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 *Earthquake Spectra* (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 non-building causes, so perhaps only 200 of the 300 serious injuries are building (collapse) related. About 12,000 to 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 billion to $10 billion in 1989 is roughly equivalent to about $14 billion to $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 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. Social losses, and in particular deaths, have been quite modest in recent United States 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) 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 October 20, 1991 Oakland-Berkeley 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 fire fighters were already on the scene (Parker, 1992). In contrast, the 294 cases of fire following the January 17, 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 (SFD's) and other residential buildings, which include, primarily, multi-family dwellings (MWD's). 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 non-residential buildings estimated to have either Extensive or Complete structural damage by county. The table distinguishes between commercial buildings and other non-residential 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 non-residential buildings with Extensive 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 (SFD's) 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 County, the trend is reversed, and the 1906 MMI ground motions cause more SFD 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 its use 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).

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 dollars).

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 nonstructural systems and contents dominate capital stock losses. Seismic strengthening of the structural system greatly improves life safety, 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 (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 to 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 to 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 pm) and nighttime (2 am) 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 earthquake; 26 of these deaths were building related (Table 5-9, EQE, 1995). There were 1,044 serious injuries in this earthquake requiring hospitalization (Table 7-1, EERI, 1995b).

Table 19 shows an estimated 831 deaths and 3,942 serious injuries at night (2 am) 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 pm) 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 two greater than casualties estimated using 1906 MMI ground motions. Although less than one-half of the deaths and serious injures of the 1995 Kobe earthquake, these estimates are still consistent with Kobe casualties considering the increased vulnerability of Japanese 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 pm) and nighttime (2 am) 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 corresponding 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 pre-cast 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 non-ductile concrete frames show these building types to be dominant contributors to life-safety risk. The combined square footage of soft-story wood, non-ductile 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, non-ductile concrete and URM buildings account for more than 40% of the life-safety risk during daytime. In terms of the relative risk factor, URM and non-ductile 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 on-going 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 10 million people and buildings worth more than $1 trillion without contents, or about $1.5 trillion with contents.

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, non-ductile concrete and unreinforced masonry 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 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) that 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 two. The M7.9 ground motions instantaneously kill over 1,800 people at night or over 3,400 people during the day, and seriously injury about 8,000 people at night or over 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, non-ductile concrete and unreinforced masonry buildings (before seismic retrofit) accounts for 50% of the all deaths at night (2 am) and more than 40% of all deaths during the day (2 am), even though these building types represent less than 3.5% of all buildings in the study region (by square footage).

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