CAPSS Soft-Story Loss Study

Scenario Losses to Large Soft-story Woodframe Buildings in San Francisco for ATC 52-2, Community Action Plan for Seismic Safety (CAPSS)

Prepared for
Applied Technology Council
Redwood City, CA

By
Keith Porter
SPA Risk LLC
Denver CO, USA

10 April 2009

SPA Project 10007-02-08-05

Revision history

Ver.	Date	Comments
1.0	12 Jan 2009	Initial release
1.1	25 Jan 2009	Add lower end of results range using upper end of fragility range
1.2	10 Apr 2009	Reflect fragility revisions; reflect wording changes for clarity

EXECUTIVE SUMMARY

San Francisco has 2,800 woodframe, soft-story buildings with at least 3 stories and 5 dwellings each. “Soft-story” means the lowest story is much weaker or more flexible than those above. Here, that means one ground-story façade is at least 80% open (i.e., the wall has window and door openings covering at least 80% of the gross area of the ground-story façade), or two are at least 50% open. These buildings, which perform poorly in earthquakes, house 58,000 people—8% of the population—in 29,000 dwelling units. To inform public policy, a study for San Francisco’s Community Action Plan for Seismic Safety (CAPSS) quantifies the risk. We estimate the impacts on these buildings from 4 large, hypothetical, realistic earthquakes.

In one scenario (a M7.2 earthquake on the San Andreas Fault), 80% of these buildings are posted unsafe to occupy, and 30% collapse – that is, in just this one class over 2,000 buildings are posted unsafe (rendering 46,000 persons homeless) and over 800 buildings (housing 17,000 persons) collapse. These results seem realistic: average shaking citywide in this scenario is 4 times stronger than in the Marina District in the 1989 Loma Prieta Earthquake, where approximately 1 in 4 corner soft-story apartment buildings were posted as unsafe to enter or occupy (red-tagged) or collapsed.

Retrofitting ground stories with cantilever steel columns and wood sheathing reduces red tags to fewer than 10%. It reduces collapses to fewer than 1 in 100. Retrofitting of these buildings would cost $260 million, equivalent to $10,000 to $20,000 per dwelling unit, depending on building details. The methodology is validated against experience in 1989.

TABLE OF CONTENTS

EXECUTIVE SUMMARY 3

OBJECTIVES AND SCOPE OF WORK 7

AVAILABLE METHODOLOGIES 9

DETAILS OF THE SELECTED METHODOLOGY 11

APPLICATION TO SAN FRANCISCO SOFT-STORY DWELLINGS 12

RESULTS 21

VALIDATION 23

SUMMARY AND CONCLUSIONS 24

REFERENCES 27

INDEX OF FIGURES

Figure 1. CAPSS index buildings 13

Figure 2. Collapses of large midblock woodframe buildings 15

Figure 3. Shaking intensity in 4 scenario earthquakes... 19

INDEX OF TABLES

Table 1. Area and replacement cost by index building and site class.............................. 14

Table 2. Summary of retrofits costs per building.. 16

Table 3. Retrofits cost per housing unit (using number of units per index building)....... 17

Table 4. Total estimated retrofits cost for all 2,800 buildings... 17

Table 5. Modeled damage to housing among *all* 2,800 buildings in the study 22

Table 6. Damage estimates as interpreted by Project Engineering Panel......................... 22

Table 7. Hindcasting damage to corner buildings in the Marina District in 1989........... 23

OBJECTIVES AND SCOPE OF WORK

Soft-story conditions make woodframe buildings significantly more vulnerable. Buildings like these collapse at lower excitation than other woodframe buildings of comparable size. To quantify the number of such buildings in San Francisco, volunteer structural engineers working under the direction of the San Francisco Department of Building Inspection (DBI) performed a sidewalk survey of at least 4,400 residential woodframe buildings in the city to ascertain a number of potentially seismically important parameters: height, number of housing units, evidence of retrofit, corner vs. midblock location, sloped versus level site, 1st story use, and openness of each ground-level façade. To this database was added information from the county tax assessor and from a Dun & Bradstreet database: square footage, year built, number of businesses, and number of employees.

The present work considers only those buildings that have 3 or more stories, 5 or more housing units, and soft-story conditions meeting either of 2 criteria: at least 80% open on one street-level façade or at least 50% open on two. This subset of buildings contains 29,000 housing units (7% of the total in San Francisco) and is home to 58,000 residents—8% of the city's population—along with 2,100 businesses and 6,900 employees.

It is desired to quantify the risk that these buildings pose in large San Francisco earthquakes. At the direction of Mayor Gavin Newsom, a study of these buildings was performed for the City of San Francisco's Community Action Plan for Seismic Safety (CAPSS). Its objective was to estimate the damage and potential repair costs in each of several scenario earthquakes, and to quantify costs and benefits that might derive from practical seismic rehabilitation to these buildings. SPA Risk LLC undertook several tasks in this regard for the Applied Technology Council:

(1) To identify common building components of buildings in this era of construction, and to develop fragility functions for them, i.e., relationships between component forces or deformation and the probability of various levels of damage to those components.

(2) To develop seismic vulnerability relationships for these buildings, i.e., relating overall repair cost as a fraction of replacement cost new to spectral acceleration response.

(3) To select or design a loss-estimation methodology, perform the loss calculations, and present the methodology and results in meetings and in a written report.

Tasks 1 and 2 are addressed in other reports. Meetings related to task 3 occurred in September 2008 through February 2009. The present document is our task-3 report.

AVAILABLE METHODOLOGIES

Several methodologies exist to estimate earthquake risk. Commercial loss-estimation firms such as RMS, EQECAT, and AIR offer proprietary loss-estimation models, based in part on empirical seismic vulnerability functions developed from earthquake experience of various insurance companies. In general however these seismic vulnerability functions lack resolution of various categories of soft-story woodframe construction with or without various seismic retrofit options, and they are generally unavailable for open review.

Early among open models (i.e., models whose derivation and parameter values are available for review), the ATC-13 effort led by the Applied Technology Council (1985) developed probabilistic relationships between shaking intensity, measured in terms of modified Mercalli intensity (MMI), and the probability of each of 38 general building classes entering each of 7 discrete damage states (defined in terms of damage factor, meaning the repair cost as a fraction of replacement cost). The ATC-13 damage-probability matrices (DPMs) were derived from a modified Delphi process, in which multiple experts rendered judgments about seismic vulnerability, self-judged their level of expertise, and attempted to reconcile significant differences among themselves. Their judgments were combined to create weighted average DPMs and relationships between MMI and the conditional probability distribution of damage factor. The ATC-13 methodology does not distinguish between varieties of woodframe buildings, however, and cannot resolve the effects of soft-story construction or seismic retrofit.

The HAZUS-MH methodology (NIBS and FEMA 2003a) was developed during the 1990s with the support of the US Federal Emergency Management Agency (FEMA) and reflects performance-based earthquake engineering principles. Instead of relying on expert opinion to relate shaking intensity directly to damage and loss, the HAZUS-MH methodology applies engineering principles: it idealizes a building as a single-degree-of-freedom nonlinear damped harmonic oscillator, and applies the capacity spectrum method (CSM) of structural analysis to estimate the building's structural response in a particular earthquake. It applies relationships between structural response and damage developed from laboratory tests and earthquake experience to estimate the probabilistic damage state of the building's various components, and applies estimates of repair cost given each level of damage to estimate repair cost. HAZUS-MH differentiates among 8 classes of woodframe construction based on size (2 categories) and code era (4 categories). It does not address soft-story construction or the benefits to be derived from various seismic retrofit options.

The HAZUS-MH Advanced Engineering Building Module (AEBM; NIBS and FEMA 2003b) is software developed to model the seismic performance of individual buildings by allowing the user to input the values of the various parameters of structural performance, damage, and loss. These are the same parameters as are used in the main HAZUS-MH methodology. NIBS and FEMA (2003b) provide some guidance on how to develop these parameters. The AEBM software was has been found to have a programming flaw that causes it not to follow the HAZUS-MH methodology accurately. The frequency with which the flaw occurs has not been definitively established, nor has the severity of the error when it does.

An adaptation of the HAZUS-MH methodology has been developed that honors all HAZUS-MH principles but avoids the iteration sometimes required in the CSM, and performs the calculations outside of HAZUS-MH or the AEBM, thus avoiding the programming flaw. The methodology, detailed in Porter (2009c, d) and summarized in Porter (2009b), can be performed in a spreadsheet, database, or other programming environment. The methodology has been peer reviewed by 6 engineers and independently validated by 3 people, and produces table relating probabilistic damage state and mean damage factor to shaking intensity in terms of $S_a(0.3, 5\%)$ and $S_a(1.0, 5\%)$, conditioned on magnitude, distance range, site soil classification, occupancy category, and seismic domain (plate boundary or continental interior). Again, mean damage factor is the expected (average) repair cost as a fraction of replacement cost new. In light of the limitations of the foregoing models, and the capability of this one to produce transparent and validated results, this last is used here.

DETAILS OF THE SELECTED METHODOLOGY

Damage is estimated using Equation (1), and economic loss according to Equation (2). In Equation (1), $E[N_d]$ refers to the expected value of the number of subject buildings in the study area that would be in damage state d after a given earthquake scenario. The damage states are red-tagging, collapse, and the structural and nonstructural drift-sensitive damage states of HAZUS-MH. See NIBS and FEMA (2003) or Kircher et al. (1997) for detail on the latter damage states. In the equation, n is the number of buildings under consideration and $p_i[D = d|S = s]$ refers to the probability that the i^{th} building is in damage state d, given that it is subjected to shaking intensity s. In Equation (2), $E[L]$ refers to the expected value of repair cost L in a given earthquake scenario, R is the estimated replacement cost per square foot, A_i is the square footage of the i^{th} building, $y_i(s_i)$ is the mean damage factor to the i^{th} building (damage factor means repair cost as a fraction of building replacement cost new) given that it is subjected to shaking of intensity s_i. Shaking intensity is measured either in terms of $S_a(0.3$ sec, 5%) or $S_a(1.0$ sec, 5%), depending on whether a capacity-spectrum-method analysis indicates the performance point lies on the constant-acceleration or constant-velocity portion of an idealized acceleration response spectrum. See Porter (2009c) for more detail on that issue. In most cases relevant here, the performance point lies on the constant-velocity portion of the response spectrum.

$$E\left[N_d\right] = \sum_{i=1}^{n} p_i\left[D = d \middle| S = s\right] \tag{1}$$

$$E\left[L\right] = \sum_{i=1}^{n} R \cdot A_i \cdot y_i\left(s_i\right) \tag{2}$$

APPLICATION TO SAN FRANCISCO SOFT-STORY DWELLINGS

Area of subject buildings A_i, and the design of index buildings. The locations and square footage of each subject building is taken from the DBI database described above. Analysis of the San Francisco Department of Building Inspection database indicates that there are an estimated 29,000 housing units in 2,800 large woodframe buildings with soft-story conditions. "Large" here means 3 or more stories and 5 or more housing units, and "soft story" means the building meets either or both of two criteria: one ground-story façade is at least 80% open, or two are each at least 50% open. They house approximately 58,000 people, representing 8% of the population and 7% of its stock of housing units.

Cobeen (2008) designed 4 prototypical index buildings to represent the range of housing addressed here (Figure 1). The designs and 3 retrofits each were selected in consultation with DBI and consulting structural engineers. Each building in the exposed building stock was associated with the damageability information described in a companion document, Porter (2008a), as follows.

- Index building 1 (IB1): This is a 3+ story corner building with garage openings on one side of the building only. Therefore, corner woodframe buildings in the DBI database were associated with IB1 when they met the CAPSS "Significant Ground Floor Openings" criterion 1 (80% or more open on any one side), but did not meet criterion 2 (50% or more open on any two sides).
- Index building 2 (IB2): This is a 3+ story corner building with ground-story openings for garages on two sides of the building. Corner woodframe buildings in the DBI database were associated with IB2 when they met criterion 2 (at least 50% open on any two sides).
- Index building 3 (IB3) is a midblock structure built before 1950, which most likely has straight sheathing on the exterior wall and wood lath and plaster interior wall finish. Accordingly, midblock soft-story buildings with 3+ stories and 5+ housing units, built before 1950 were associated with IB3.
- Index building 4 (IB4) is a midblock post-1950 building. The most important feature of IB4 is plywood sheathing on exterior walls and gypsum-board interior

wall finish. IB4 is therefore likely to be stiffer, stronger, and more damage resistant than IB3. Therefore, midblock soft-story buildings with 3+ stories and 5+ housing units built after 1950 were associated with IB4.

(1) (2)

(3) (4)

Figure 1. CAPSS index buildings. Four older, soft-story, woodframe, multifamily dwellings representing a realistic range of performance of buildings of this class in San Francisco: (1) corner, 3 story, no interior walls at garage level, one street facade ≥ 80% open at ground floor; (2) corner, 4 story, both street facades ≥ 50% open at ground floor; (3) mid-block, 4 story, pre-WWII, neighbors on both sides; (4) mid-block, 3 story, post-1950, neighbors on both sides. Square footage is 3,600, 5,800, 2,300, and 1,800 sf, respectively.

By associating buildings in the DBI database with index buildings 1-4 on this basis, it is found that the total building area is fairly evenly distributed among the 4 index buildings: 19% index building 1 (IB1), 25% IB2, 35% IB3, and 21% IB4. Most of the area is built at a location whose NEHRP site soil classification is D.

Table 1. Area and replacement cost by index building and site class

Subset	Replacement cost, $B	% of units	% of area & value
IB1	$2.8	20%	19%
IB2	$3.5	26%	25%
IB3	$4.9	33%	35%
IB4	$3.0	21%	21%
Site class B	$1.6	10%	10%
Site class C	$1.2	8%	8%
Site class D	$10.5	73%	74%
Site class E	$1.1	8%	8%

Adjacency. Do midblock buildings, with buildings on either side to support them, actually collapse in earthquakes? Can they be modeled as Cobeen (2008) has done in the CAPSS study as if they were freestanding, i.e., ignoring pounding? The issue is important enough to dwell on it briefly. These buildings do seem to collapse. Most of the woodframe building collapses that appear in photographs in the 1906 San Francisco Earthquake in Gilbert et al. (1907), Pierce (1906), Klett and Lundgren (2006), and Tobriner (2006) are midblock; see Figure 2 for examples. However, it is unclear from most of the available photos how close the collapsed midblock buildings were to their neighbors. The DBI database has no field for adjacency: the field surveyors did not record gap widths.

However, based on the limited data available from the Marina District in 1989, where only 1 of the 7 collapsed buildings was midblock, it seems that midblock soft-story buildings are less likely to collapse than corner soft-story buildings, all else being equal. Ultimately a very simple approach was used here to deal with pounding and adjacency. The *structural* models (Cobeen 2008) do not treat pounding or adjacency, and the *loss* model makes midblock buildings less likely to collapse than corner buildings and at least as likely as the average pre-code 1- or 2-story woodframe building. It does so by setting the vulnerability term P_c (fraction of area collapsed in buildings with complete structural damage) for as-is index buildings 3 and 4 to the HAZUS-MH default value of 3%, in contrast to the 10% figure used for corner buildings; see Porter (2009a).

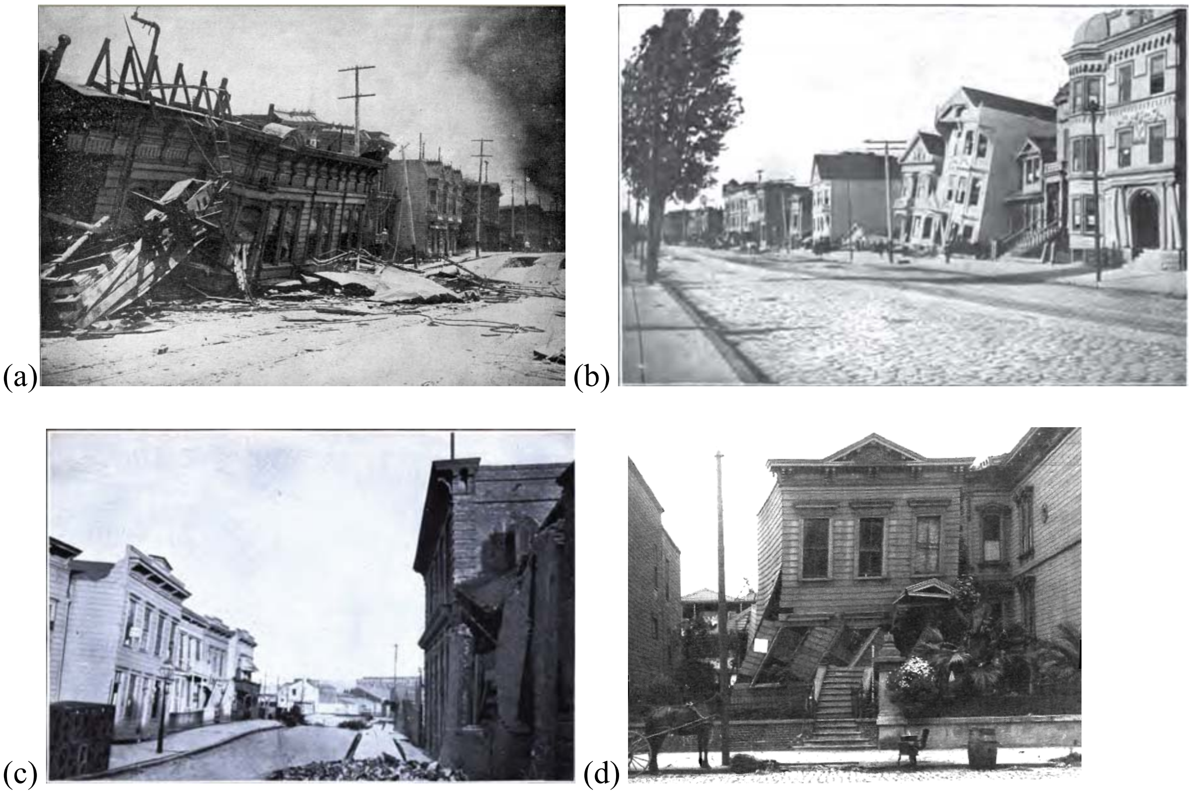

Figure 2. Collapses of large midblock woodframe building in the 1906 San Francisco earthquake: (a) Valencia St. Hotel (Pierce 1906), (b) Howard St (Gilbert et al. 1907), (c) Dore St. between Bryant and Brannan (Gilbert et al. 1907), (d) unknown location, where collapse is associated with “cripple-wall and shear failure” (Tobriner 2006)

Seismic retrofits. As described in Cobeen (2008), 3 seismic retrofits were designed for each index building. The retrofits are designed to meet various performance objectives defined in SPUR (2008). Retrofit 1 is intended to meet SPUR performance category D, safe but not repairable, meaning that “Buildings may experience extensive structural damage and may be on the verge of collapse. They … are expected to receive a red tag after the expected earthquake.” The “expected” earthquake is one that produces shaking with 10% exceedance probability in 50 years, and is approximated here by a M7.2 earthquake on the Peninsula segment of the San Andreas Fault. Retrofit 1 generally comprises the addition of a steel frame at openings and some wood sheathing at existing walls. Retrofit 2 is intended to make the building meet SPUR performance category C, safe and usable after repair, meaning that the building “may experience significant structural damage that will require repairs prior to resuming unrestricted occupancy and therefore are expected to receive a yellow tag after the expected earthquake." Retrofit 2 generally comprises the steel frame and more structural sheathing. Retrofit 3 is intended to make the building approximately satisfy SPUR performance category B, safe and occupiable during repair, meaning that "Buildings will experience damage and disruption to their utility services, but no significant damage to the structural system. They may be occupied with out restriction are expected to receive a green tag after expected earthquake."

Kidd (2008) prepared detailed cost estimates of Cobeen's retrofit designs, and found that the seismic retrofits would cost between $50,000 and $130,000 per building, as summarized in Table 2, or $6,000 to $30,000 per housing unit (apartment or condominium) per Table 3. The costs account for local construction costs, permit fees, removal and replacement of finishes and other materials at the ground floor during construction, and other contingencies. The costs do not include engineering design fees or business relocation or interruption expenses, and are appropriate for San Francisco construction in 2008. The cost estimates are detailed in Kidd (2008) and summarized in Table 2. It is noteworthy that retrofit 3, intended for better performance than retrofit 2, generally costs less. The total cost of retrofit is roughly $200 to 300 million, as shown in Table 4.

The index buildings have on average somewhat fewer dwellings per building than the average real building stock, and there are other differences between the index buildings and real building stock, so the real cost of retrofit per dwelling unit might differ somewhat from these figures, but a figure of $10,000 to $20,000 per dwelling unit agrees with the experience of several engineers consulted for this project.

Table 2. Summary of retrofits costs per building

		Cost per building, $000			
Retrofit	SPUR (2008) performance objective	IB1	IB2	IB3	IB4
1. Steel frames, shearwalls	D, safe not repairable	$ 79	$ 71	$ 59	$ 49
2. Same, more shearwalls	C, safe, usable after repair	120	130	110	59
3. Cantilever columns + shearwalls	C or B, safe and usable during repair	110	110	96	58

Table 3. Retrofits cost per housing unit (using number of units per index building)

Retrofit	SPUR (2008) performance objective	Cost per unit, $000			
		IB1	IB2	IB3	IB4
1. Steel frames, shearwalls	D, safe but not repairable	$ 20	$ 6	$ 10	$ 12
2. Same, more shearwalls	C, safe and usable after repair	30	11	18	15
3. Cantilever columns + shearwalls	C or B, safe and usable during repair	28	9	16	15

Table 4. Total estimated retrofits cost for all 2,800 buildings

Retrofit	SPUR (2008) performance objective	Total retrofit cost, $ million
1. Steel frames, shearwalls	D, safe but not repairable	$180
2. Same, more shearwalls	C, safe and usable after repair	$300
3. Cantilever columns + shearwalls	C or B, safe and usable during repair	$260

Shaking intensity s. Treadwell and Rollo estimated the shaking intensities across San Francisco from each of four scenario earthquakes: a M7.9 earthquake on the San Andreas Fault, representing a repeat of the 1906 earthquake; a M7.2 event rupturing the Peninsula segment of the San Andreas Fault; a M6.5 event on a smaller portion of the San Andreas fault, and a M6.9 event on the Hayward Fault (see Golesorkhi and Gouchon 2002). The study predated the Next Generation Attenuation (NGA) relationships; see Power et al. (2008) for an overview of NGA. The authors used then-current leading attenuation relationships, in particular an equally weighted average of the Abrahamson and Silva (1997), Campbell (1997), and Sadigh et al. (1997) relationships. They accounted for site soil amplification using the median relationship for rock to reflect NEHRP site class B, the median relationship for soil to reflect site class D, and the average of the two to reflect site class C. To estimate shaking on site class E, the authors used the equally weighted average of the 3 relationships' median spectral acceleration response on rock, and applied the 1997 NEHRP site amplification factors for E. The resulting maps of shaking intensity in terms of peak ground acceleration are shown in Figure 3. Maps measuring shaking in terms of 5%-damped, 0.3-sec and 1.0-sec spectral acceleration response were also generated, but are not shown here.

Treadwell and Rollo's estimates suggest average shaking on the order of S_a(1.0 sec, 5%) = 0.30g in the M6.9 Hayward Fault event, 0.35g in the M6.5 San Andreas Fault event, 0.50g in the M7.2 San Andreas Fault event, and 0.67g in the M7.9 San Andreas Fault event. "Average shaking" here means an equally weighted average of the S_a(1.0 sec, 5%) values estimated at the sites of each of the 2,800 large, soft-story woodframe buildings studied here. For reference, the USGS ShakeMap for the 1989 Loma Prieta earthquake estimates that sites in the San Francisco Marina District on soft soil (NEHRP categories D or E) experienced roughly S_a(1.0 sec, 5%) = 0.17g, i.e., 1/4 to 1/2 the average citywide shaking of any of these events.

For reference, of the 111 corner, soft-story woodframe buildings of 3 or more stories and 5 or more dwelling units in the Marina District shown in the DBI database, approximately 33 were red-tagged (i.e., 30%), including 6 collapses (5%), per Seekins et al.'s (1990) map. Harris and Egan (1992) studied 74 soft-story apartment buildings in the Marina District and report that 11 of the 74 (15%) experienced major damage or collapsed. Here, major damage refers to ATC-13 (1985) damage state 6, equivalent to the HAZUS-MH (NIBS and FEMA 2003) complete damage state[1]. Collapse here means that at least the 1st story gravity system failed to the point that the 2nd floor dropped to the ground, touching the 1st floor. Thus, the CAPSS scenarios produce 2-4x the 1989 shaking in the Marina District, which caused 30% of corner buildings to be red-tagged, 5% of them to collapse, and 15% to suffer total economic loss (repairs costing ≥ 60% of replacement cost).

---

[1] This equivalence is only approximate, since ATC-13 damage states deal with the damage to the building as a whole, whereas in HAZUS-MH one assigns a damage state to each of 3 general components separately.

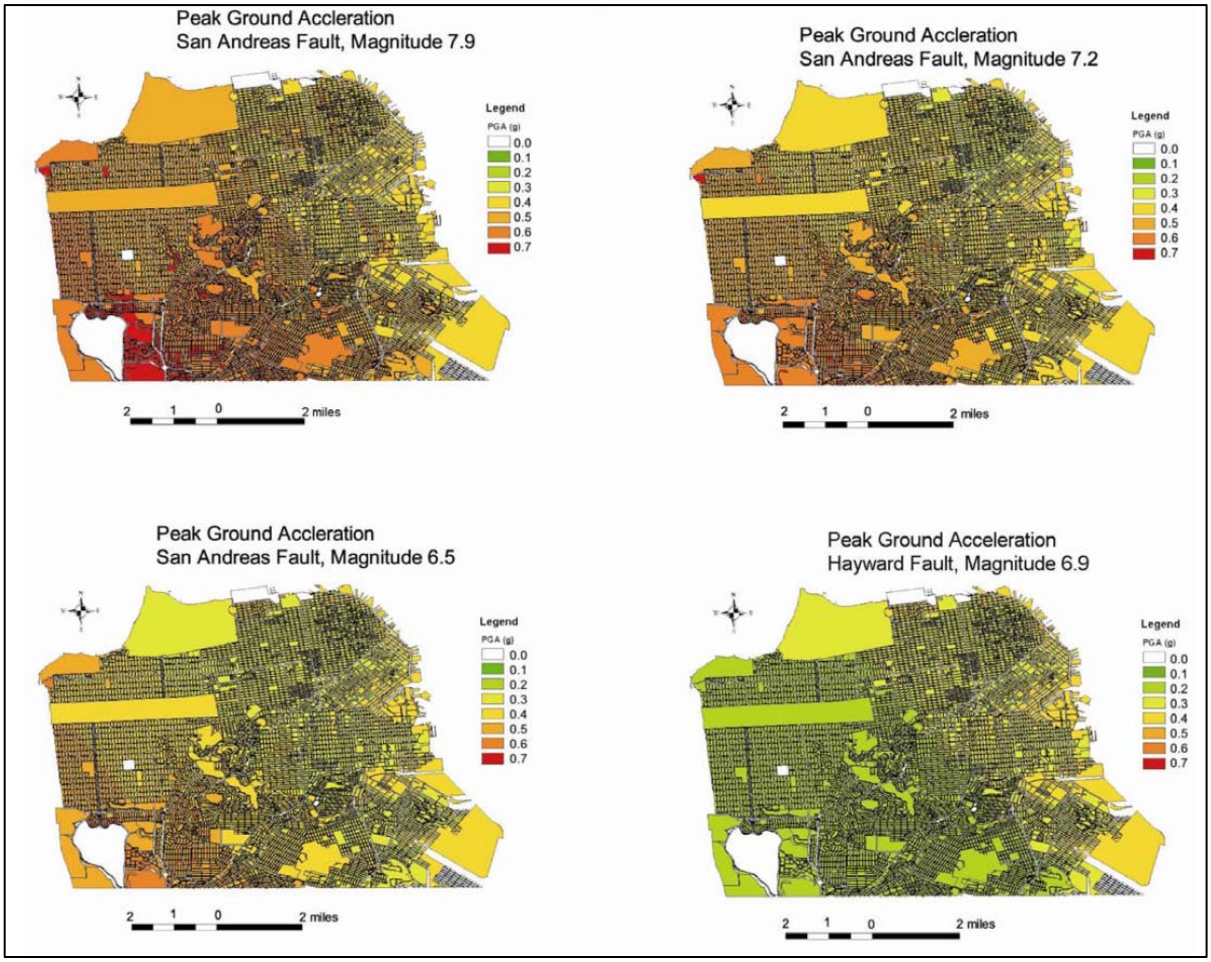

Figure 3. Shaking intensity in 4 scenario earthquakes (Golesorkhi and Gouchon 2002).

Replacement cost R. Five local specialists were asked to give their estimates of the per-square-foot cost to build new multi-family wood frame apartment buildings in San Francisco in 2008, with either garage or commercial space at the ground floor. These specialists included a local architect who recently has constructed this type of building, an employee of a local development company that has recently constructed this type of building, a local insurance agent, an insurance analyst who works with software that calculates building replacement costs, and a risk modeling company that provides services to the insurance industry. These estimates ranged from $190 per square foot to $350 per square foot. The two lowest values came from insurance-company models that one specialist acknowledged as likely to be lower than actual building costs. The two highest estimates, both $350 per square foot, stated that they thought this was a minimum cost and that actual construction costs can be higher. Estimates from local professionals working in San Francisco might reasonably be considered more credible than estimates from computer models, so the two estimates from computer models were discarded. The average value of the remaining three estimates, $330 per square foot, is used here to estimate post-earthquake rebuilding and repair costs (calculated as a percentage of rebuilding costs). This value does not take into account that construction costs may be higher than normal after an earthquake due to labor and materials shortages and other phenomena often collectively referred to as demand surge.

At $330 per square foot replacement cost, these soft-story buildings have a total value of $8.1 billion. Residential content value is commonly estimated by insurers to represent roughly 40% of total replacement cost, so the total replacement cost of these multifamily dwellings is estimated to be approximately $14 billion.

Seismic vulnerability functions. Seismic vulnerability functions $y(s)$ and fragility functions $p[D=d|S=s]$ were developed for each of the 4 index buildings under as-is and each of 3 retrofitted conditions. See Porter (2009b) for the results. In general, the retrofits reduce damage by up to half, though at high levels of shaking the benefit of retrofit is reduced. Note that the HAZUS-MH methodology does not estimate the number of buildings in the collapsed damage state, but rather estimates the fraction of total square footage that is collapsed. In the case of soft-story woodframe buildings, this would generally be the bottom floor, so one can estimate the total square footage of subject buildings where at least part of the building is collapsed by multiplying the fraction collapsed by the average number of stories, which here is roughly 4.

The HAZUS-MH structural damage states and SPUR performance levels can be approximately equated with safety tag colors as defined in ATC-20 (Applied Technology Council 1996). ATC-20 is the de facto international standard in rapid post-earthquake safety evaluation procedures. Here, the HAZUS-MH complete structural damage state and SPUR performance level D are equated with a red tag in ATC-20, unsafe to enter or occupy. HAZUS-MH’s extensive structural damage and SPUR performance level C are equated with a yellow tag, indicating that limited use is allowed. Lower HAZUS-MH structural damage states and SPUR performance levels A and B are equated with green (inspected) tag.

RESULTS

Equations (1) and (2) were evaluated for each of 4 earthquake scenarios and 4 retrofit conditions: all buildings as-is, and all buildings with retrofit 1, 2, and 3, respectively. Estimated losses are as follows. Under as-is conditions, the scenario earthquakes are estimated to cause 50-90% of soft-story multifamily dwellings to be red-tagged or collapse; see Table 5. The Project Engineering Panel felt that these figures represent an upper bound, and interpreted them to produce a range of outcomes they considered to be reasonable; these results are shown in Table 6. Ultimately the PEP decided that the economic loss estimates were not central to the objectives of the study, so these figures are not reported here.

Here, SPUR performance level E (colored violet in the table) means that at least a portion of the building is likely to collapse during the hypothetical earthquake, most likely the ground story. SPUR performance level D (colored red in the table to indicate red-tagging) means that after the hypothetical earthquake, the ground story of the building would be leaning at least 2 inches, which would tend to cause building safety inspectors to post the building as unsafe to enter or occupy under the ATC-20 post-earthquake inspection procedures (Applied Technology Council 1996). Under current City of San Francisco policy, these buildings would have to be repaired unless they actually collapse. SPUR performance level C (colored yellow, indicating a yellow tag) means that restricted use of the buildings would be allowed, such as temporary occupancy to remove personal property. SPUR performance levels A and B (color coded green to indicate a green tag) means that the buildings would be labeled “Inspected” and it would therefore be lawful to occupy these buildings even if some repairs were required.

Table 5. Modeled damage to housing among *all* 2,800 buildings in the study

Scenario	Retrofit	SPUR performance level among 2,800 buildings (%)				
		A	B	C	D	E
M 6.9 Hayward Fault	As-is	15	18	19	30	18
	1	50	22	18	8	2
	2	68	16	10	6	0.3
	3	72	16	9	3	0.2
M6.5 San Andreas Fault	As-is	9	13	17	39	22
	1	38	23	23	13	4
	2	56	20	15	9	1
	3	59	20	15	6	0.3
M7.2 San Andreas Fault	As-is	2	5	9	54	31
	1	17	19	28	28	8
	2	35	22	24	18	1
	3	44	23	21	12	0.7
M7.9 San Andreas Fault	As-is	0	1	2	62	35
	1	4	8	21	52	14
	2	10	14	26	47	3
	3	13	15	26	44	3

Table 6. Damage interpretation by Project Engineering Panel

Scenario	Retrofit	SPUR performance level among 2,800 buildings (%)			
		A-B	C	D	E
M6.9 Hayward Fault	As-is	33 – 49	19 – 27	18 – 30	6 – 18
	1	72 – 75	18 – 20	4 – 8	1 – 2
	2	84 – 86	10 – 11	3 – 6	0.2 – 0.3
	3	88 – 89	9 – 10	2 – 3	0.1 – 0.2
M6.5 San Andreas Fault	As-is	22 – 42	17 – 27	23 – 39	8 – 23
	1	61 – 66	23 – 26	6 – 13	2 – 4
	2	76 – 79	15 – 17	4 – 9	0.3 – 0.5
	3	79 – 81	15 – 16	3 – 6	0.2 – 0.3
M7.2 San Andreas Fault	As-is	6 – 35	9 – 23	32 – 54	11 – 31
	1	36 – 48	28 – 34	14 – 28	4 – 8
	2	57 – 64	24 – 27	9 – 18	0.5 – 1
	3	67 – 71	21 – 23	6 – 12	0.3 – 0.7
M7.9 San Andreas Fault	As-is	1 – 33	2 – 18	37 – 62	12 – 35
	1	13 – 35	21 – 32	26 – 52	7 – 14
	2	23 – 40	27 – 35	24 – 47	1 – 3
	3	28 – 44	26 - 33	22 - 44	1 – 3

VALIDATION

Treadwell and Rollo estimated 2-4x greater shaking intensities in the 4 scenarios examined here, compared with the USGS's ShakeMap estimates of intensities in the San Francisco Marina District in the 1989 Loma Prieta earthquake. It seems reasonable therefore that the scenarios examined here would cause greater damage on average to soft-story buildings than occurred in the Marina District in Loma Prieta. The same methodology presented above was applied to corner apartment buildings in the San Francisco Marina District in the 1989 Loma Prieta earthquake. The official USGS estimate of shaking in this areas was $S_a(1.0 \text{ sec}, 5\%) \approx 0.17g$. According to the present study, index buildings 1 and 2 would have on average 39% probability of being in the "complete" structural damage state, including those buildings with some fraction of their floor area collapsed.

A comparison on an aggregated basis is shown in Table 7. The table shows damage experienced by corner apartment buildings on all soil profiles in the Marina District in the 1989 Loma Prieta earthquake, versus a hindcast considering only corner (index buildings 1 and 2). The 1989 "observed" figures are calculated from Harris and Egan's (1992) estimates of the damage state to 74 corner apartment buildings in the San Francisco Marina District after the 1989 Loma Prieta earthquake. Agreement is reasonable, with the figures generally agreeing within ±50%. The present study does not reflect ground failure, but the "observed" figures do not change substantially by excluding buildings in the region that had ground failure in the 1989 earthquake.

Table 7. Hindcasting damage to corner buildings in the Marina District in 1989.

HAZUS-MH structural damage state	Approximate ATC-13 state	1989 estimate	1989 observed
None	None	5%	3%
Slight or moderate	Slight, light, moderate	56%	74%
Extensive or complete	Heavy, major, destroyed	39%	24%

SUMMARY AND CONCLUSIONS

Analytical framework. A study was undertaken to estimate the effects of several large, hypothetical but realistic earthquakes on some of the most seismically vulnerable buildings in San Francisco: woodframe buildings of 3 or more stories with 5 or more housing units and soft-story conditions on the 1st floor. The study used the HAZUS-MH analytical framework developed by Kircher, Holmes, and many others to estimate the risk, but implemented outside of HAZUS-MH to avoid a programming flaw in the HAZUS-MH software and to make the methodology more transparent. Several enhancements over the basic HAZUS-MH methodology were made, such as adding new fragility information about particular components of San Francisco housing like straight sheathing and brick veneer. While this approach offers less fidelity than PEER-style dynamic nonlinear MDOF analyses, the HAZUS-MH methodology is much simpler, more practical for present purposes, and has been shown in several instances to produce realistic aggregate results.

Large soft-story woodframe residential buildings in San Francisco. Index buildings were selected that approximately represent the range of existing soft-story woodframe buildings in San Francisco. This selection was made in consultation with several DBI and experienced consulting structural engineers. The study employed a house-by-house DBI database of important features, and related the index buildings to the buildings in the DBI database through key observable parameters: corner vs. midblock, and pre-1950 vs. post-1950 construction. The buildings in the DBI database are approximately equally distributed among the 4 index buildings.

Soil and hazard information. The study's soil and shaking hazard model is site-specific, coming from Treadwell and Rollo's study for the original CAPSS project (Golesorkhi and Gouchon 2002). This is in contrast to HAZUS-MH's basic census-tract-level analysis and reliance on two basic woodframe types, neither of which seems to apply in this case. Roughly 3/4ths of the subject buildings are estimated to stand on soil of NEHRP site class D.

Structural and component fragility models. Structural analysis of those buildings was performed by Kelly Cobeen, a Bay Area SE with extensive experience in assessing the performance of woodframe buildings, having led extensive efforts for the CUREE-Caltech Woodframe Project and various FEMA projects to improve understanding of woodframe behavior. Another study included the creation of building-component fragility functions from experimental and earthquake performance of the index buildings' dominant components: straight sheathing, lath and plaster walls, stucco exterior finish, and masonry veneer (Porter 2009b). That assessment was reviewed by Sig Freeman, another highly regarded Bay Area structural engineer. The benefit of adjacency (where buildings abut each other within inches or less, and thus may support each other in earthquakes) is addressed approximately, by making midblock buildings 1/3rd as likely to collapse as corner buildings, given that they experience complete structural damage.

Seismic retrofits. Cobeen (2008) designed three seismic retrofits for each index building, intended to meet enhanced performance objectives defined by SPUR (2008), ranging from safe but not repairable (performance category D, using methods labeled “retrofit 1”) to safe and usable during repair (performance category B, using methods labeled “retrofit 3”). Kidd (2008) estimated their costs, which are generally in the range of $10,000 to $20,000 per dwelling unit.

Loss calculations. The study employs a loss-calculation procedure (“cracking an open safe”; Porter 2009c,d) that honors all HAZUS-MH methodologies while avoiding the iteration and a programming error recently discovered in AEBM. This alternative procedure has been peer-reviewed by at least 6 engineers and its results independently validated by 3. In addition to the stepwise validation or quality assurance at each stage, the overall procedure was validated by hindcasting with reasonable accuracy the damage to corner apartment buildings in the San Francisco Marina District in the 1989 Loma Prieta Earthquake. The results therefore seem valid for the present limited purposes of assessing community-wide retrofit policy alternatives. Losses were calculated for the entire stock of 2,800 buildings under as-is conditions and again under each retrofit level, i.e., assuming all the buildings were upgraded to retrofit 1, then 2, then 3. Losses were calculated for each of 4 earthquake scenarios, focusing on a M7.2 earthquake on the Peninsula segment of the San Andreas Fault.

Results. This large but highly realistic M7.2 earthquake is estimated to be capable of causing half of the 2,800 large soft-story woodframe dwellings in San Francisco to be red-tagged, and 30% more to collapse. Most of the collapses are estimated to occur in corner buildings. There is a tendency to higher damage on softer soil, but 3/4ths of the subject buildings are on NEHRP site class D to begin with. Seismic retrofit involving new steel cantilever columns and shearwalls at the ground-floor level could reduce collapses to fewer than 1 in 100 buildings, at a cost on the order of $260 million.

REFERENCES

Abrahamson, N.A. and W.J. Silva, 1997. Empirical response spectral attenuation relations for shallow crustal earthquakes. *Seismological Research Letters.* 68 (1), 94-127. Jan.-Feb. 1997

(ATC) Applied Technology Council, 1985. *ATC-13, Earthquake Damage Evaluation Data for California.* Redwood City, CA, 492 pp.

(ATC) Applied Technology Council, 1996. *ATC-20: Procedures for Postearthquake Safety Evaluation of Buildings*. Redwood City, CA, 144 pp.

Campbell, K.W., 1997. Empirical near-source attenuation relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity, and pseudo-absolute acceleration response spectra. *Seismological Research Letters*, **68** (1), 154-179.

Cobeen, K., 2008. *Design and Structural Response Characteristics of Some Large, Soft-story Woodframe Buildings*. Wiss, Janney, and Elstner, Inc., Emeryville, CA.

Gilbert, C.G., R.L. Humphrey, J.S. Sewell, and F Soule, 1907. *The San Francisco Earthquake and Fire of April 18, 1906*. Bulletin 324, U.S. Geological Survey, Washington, DC, 300 pp.

Golesorkhi R., and J. Gouchon, 2002. *CAPSS Seismic Hazard (Earthquake Scenario).* Treadwell and Rollo, San Francisco, CA, 7 pp.

Harris, S.K., and J.A. Egan, 1992. Effects of ground conditions on the damage to four-story apartment buildings. O'Rourke, T.D., ed., *The Loma Prieta, California, Earthquake of October 17, 1989 − Marina District*. Professional Paper 1551-F, US Geological Survey, Washington DC, 181-194.

Kidd, J. 2008. *CAPSS Study, Comparative Estimate Summaries*. Young and Associates, Palo Alto CA.

Kircher, C.A., A.A. Nassar, O. Kustu, and W.T. Holmes, 1997. Development of building damage functions for earthquake loss estimation. *Earthquake Spectra*, 13 (4) 663-682

Klett, M., and M. Lundgren, 2006. After the Ruins 1906 and 2006 *Rephotographing the San Francisco Earthquake and Fire*. University of California Press, Berkeley CA, 134 pp.

(NIBS and FEMA) National Institute of Building Sciences and Federal Emergency Management Agency, 2003a. *Multi-hazard Loss Estimation Methodology, Earthquake Model, HAZUS*$^{®MH}$ *Technical Manual,* Federal Emergency Management Agency, Washington, DC, 690 pp

(NIBS and FEMA) National Institute of Building Sciences and Federal Emergency Management Agency, 2003b. *HAZUS-MH MR1 Advanced Engineering Building Module Technical and User's Manual,* Federal Emergency Management Agency, Washington, DC, 119 pp.

Pierce, C.C., and Co., 1906. *The Picture Story of the San Francisco Earthquake, Wednesday, April 18, 1906*. George Rice & Sons, Inc., Los Angeles, CA, 32 pp.

Porter, K.A., 2009a. *Component fragility functions for older woodframe construction*. SPA Risk LLC, Denver CO.

Porter, K.A., 2009b. *Seismic Vulnerability Functions for Some Large, Soft-Story Woodframe Buildings*. SPA Risk LLC, Denver CO.

Porter, K.A., 2009c (expected). Cracking an open safe: HAZUS vulnerability functions in terms of structure-independent spectral acceleration. Expected for publication in *Earthquake Spectra* May 2009.

Porter, K.A., 2009d (expected). Cracking an open safe: more HAZUS vulnerability functions in terms of structure-independent spectral acceleration. Expected for publication in *Earthquake Spectra* August 2009.

Power, M., B. Chiou, N. Abrahamson, Y. Bozorgnia, T. Shantz, and C. Roblee, 2008. An overview of the NGA project. *Earthquake Spectra* 24 (1): 3-21

Sadigh, K., C.Y. Chang, J.A. Egan, F. Makdisi, and R.R. Youngs, 1997. Attenuation relationships for shallow crustal earthquakes based on California strong motion data. *Seismological Research Letters*, **68** (1), 180-189.

Scawthorn, C.R., K.A. Porter, and F.T. Blackburn, 1992. Loma Prieta, California Earthquake of October 17, 1989, strong ground motion and ground failure, Marina District: performance of emergency-response services after the earthquake. *Loma Prieta, California Earthquake of October 17, 1989: Marina District, USGS Professional Paper 1551-F.* O'Rourke, Thomas D, ed., US Government Printing Office, Washington DC, F195-F215.

Seekins, L.C., F. Lew, and L. Kornfield, 1990. Areal distribution of damage to surface structures. *Effects of the Lorna Prieta earthquake on the Marina District, San* Francisco, California. U.S. Geological Survey Open-File Report 90-253, C1-C5.

(SPUR) San Francisco Planning and Urban Research Association, 2008. *The Resilient City: Defining What San Francisco Needs from It's Seismic Mitigation Policies (January 16, 2008 Draft)*. San Francisco, CA.

Tobriner, S., 2006. *Bracing for Disaster, Earthquake Resistant Architecture and Engineering in San Francisco 1838-1933*. California and Heyday Books, Berkeley, CA, 330 pp.