SESM 16-03

An Earthquake Urban Search and Rescue Model Illustrated with a Hypothetical M_w 7.0 Earthquake on the Hayward Fault

By

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Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
	Area	
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)

International System of Units to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)

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Abstract

We seem to have relatively little quantitative knowledge about the potential for earthquake-induced building collapses to trap people and little quantitative treatment of the potential for electrical failure to trap building occupants. To estimate demand for urban search and rescue (USAR) related to building collapse in a future California earthquake, I compiled a database of photographic evidence of 73 building collapses in California earthquakes between 1965 and 2014. The database includes all images in the University of California Berkeley National Information Service for Earthquake Engineering (NISEE) e-Library whose descriptions use any of the words “collapse,” “fail,” “fell,” or “parapet,” along with data taken from other sources on 14 additional buildings. I interpreted each image to estimate the fraction of building area that collapsed in each case. I also interpreted each image to estimate the fraction of occupants in the collapsed area who would realistically be trapped by the collapse and require extrication by others. The proportions vary by structural material, but on average, collapse involves 23 percent of building area and traps 66 percent of the occupants in the collapsed area. Using this new knowledge and other information about the number of collapsed buildings, one can estimate the number of people requiring extrication by USAR personnel. In the case of a particular hypothetical M_w 7.0 earthquake on the Hayward Fault in the San Francisco Bay Area, it seems realistic

that 2,500 people would be trapped in 5,000 collapsed buildings. (Not every building collapse traps people.) If all buildings were designed to be 50 percent stronger than currently required under the International Building Code, both figures could be reduced by approximately a factor of 4. Using statistics about how many elevators there are in the United States, how many have emergency power, and what fraction of them are occupied and traveling between floors, I estimated that loss of power in the mainshock of a M_w 7.0 Hayward Fault earthquake could trap 22,000 people in 4,500 stalled elevators, placing further demands on USAR personnel. If newer elevators were provided with emergency power, the number trapped in elevators could be reduced to 14,000 people in 3,000 elevators. Work is needed to determine how best to equip older elevators with emergency escape equipment.

Introduction

What do we mean when we say a building collapses in an earthquake? When it collapses, what does the damage look like? The answer matters for at least two reasons. (1) Engineers would like to create 2nd generation, performance-based earthquake engineering (PBEE-2) models of the effects of collapse on safety. See, for example, an early effort by Yeo and Cornell (2002). So and Pomonis (2012) recently proposed a process for estimating fatalities in collapsed buildings during earthquake ground shaking using her engineering judgment of fatality rate by building type, informed by fatality data from various recent earthquakes. (2) Collapse affects the demand for urban search and rescue (USAR). Elevators stalled without power may also trap substantial numbers of people who must be rescued by USAR personnel (for example, Schiff, 2008). The present study seeks to advance mathematical modeling of USAR and to illustrate the new model by applying it to a hypothetical Mw 7.0 earthquake on the Hayward Fault in the San Francisco Bay Area.

Objective

This report describes the use of USAR modeling and addresses the following questions:

1. When engineers use the word "collapse" to describe the seismic performance of a building, what fraction of the occupiable floor area deforms severely enough to threaten life safety in that area? I offer an empirical answer by examining a database of photographs of building collapses.
2. What fraction of occupants in the collapsed areas require extrication, and by whom? I answer this question by interpreting the image database in light of Federal Emergency Management Agency (FEMA) Urban Search and Rescue guidelines (for example, PerformTech, Inc., 2011).
3. How many elevators are in the affected metropolitan area, how many of them are carrying how many passengers between floors at the time of the earthquake, and what fraction of those elevators have emergency power to bring the elevator to a floor and open the doors?

To keep the level of effort commensurate with the value of the information, let us consider only one extensive, though not exhaustive, data source: the Earthquake Engineering Online Archive provided by the National Information Service for Earthquake Engineering (NISEE), University of California, Berkeley. NISEE refers to the archive as the NISEE e-Library (http://nisee.berkeley.edu/elibrary/). NISEE describes the e-Library as "a database of significant, publicly-funded research and development literature, photographs, data and software in earthquake, structural, and geotechnical engineering." Let us exclude manufactured housing, fences, equipment, and bridges from the objective. Let us also acknowledge that the NISEE e-Library is not exhaustive. It is treated here as a sample, not as documentation of the population of collapsed buildings, with the expectation that it is a diverse and perhaps representative sample.

One could conceivably address the building collapse questions with structural analysis, either instead of or in addition to the empirical approach of examining photographic evidence. But it seems doubtful that structural analysis would reliably reveal the extent of collapse, because structural analysis is not yet capable of reliably predicting the onset of collapse, its dynamics, and the eventual shape of a collapsed building. The authors of FEMA P–695 (Applied Technology Council 2009), for example, identified collapse in a large number of sample structural models as the condition that lateral dynamic instability appeared in incremental dynamic analysis, meaning that collapse occurs when structural analysis of a mathematical representation of the building fails to converge. Failure of a mathematical model to converge following the loss of vertical load carrying capacity provides little information about how much of or how far a floor or roof diaphragm falls. The authors of FEMA P-695 further cite examples of possible nonsimulated collapse modes, meaning collapse modes that a structural analysis might not reveal. These include "shear failure and subsequent axial failure in reinforced concrete columns, fracture in the connections or hinge regions of steel moment frame components, or failure of tie-downs in light-frame wood shear walls. Component failures such as these may be difficult to simulate directly." Another reason to favor an empirical study over an analytical study is that empirical models are more credible than analytical ones, at least among the loss-estimation community, where an empirical model is always preferred to an analytical one. Analytical models often serve to validate an empirical one or to provide insight where empirical data are lacking. None of this is to say that an analytical study will never have anything to offer to the question of affected area, but rather an empirical study seems more likely to provide defensible results in the near term for much less effort.

Literature Review

Literature About People Trapped by Building Collapse

It is believed that building collapse dominates earthquake casualty risk and contributes substantially to USAR demands. The 2009 National Earthquake Hazards Reduction Program (NEHRP) provisions (Building Seismic Safety Council, 2009) assert that "Most earthquake injuries and deaths are caused by structural collapse." The National Fire Protection Association (2014) offers descriptive patterns of earthquake-induced building collapses in earthquakes and explains the causes and nature of voids where occupants can escape injury in collapsed buildings (fig. 1).

The authors of National Institute of Building Sciences and Federal Emergency Management Agency (NIBS and FEMA) (2012) offer estimates of the fraction of occupants in collapsed area who are killed. Their estimates draw on the judgment-based ATC-13 (Applied Technology Council 1985), which they "revised based on comparison with a limited amount of historical data," and validated against "several recent events, including the Northridge, Loma Prieta and Nisqually earthquakes..." They estimate that 10 percent of occupants in collapsed areas of buildings are killed and 65 percent are injured to some degree. The two leading public models of earthquake risk, Hazus-MH and ATC-13 (Applied Technology Council, 1985), do not address search and rescue demands.

Collapse fragility functions, which estimate the probability that a building will collapse under various levels of excitation, are available or can be derived (see for example Applied Technology Council, 2009 or NIBS and FEMA 2012). But I could find no prior work that quantifies the fraction of the building area that collapses when a building experiences some collapse.

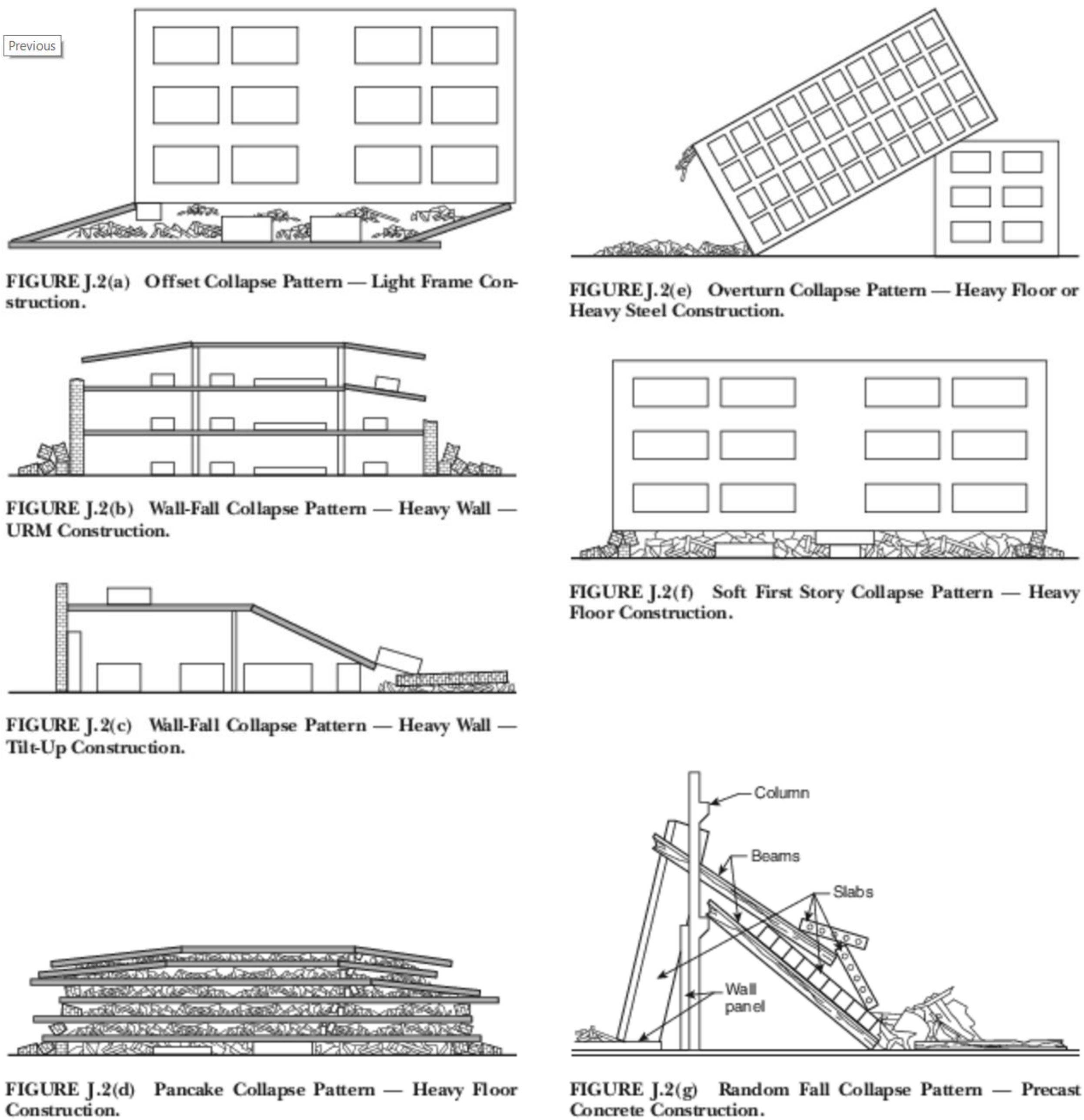


Figure 1. Illustrations of building collapse patterns in earthquakes (National Fire Protection Association, 2014).

When buildings in California collapse, they rarely pancake. That is, they rarely collapse such that the floor or roof over every square foot of occupiable floor area drops because of the loss of vertical load carrying capacity of the portion of the gravity system that supports it. One could conceivably use structural analysis to model the collapse behavior of sample buildings, but the state of the practice seems to enable structural engineers only to estimate the excitation associated with the onset of collapse, as the authors of FEMA P–695 (Applied Technology Council, 2009) did quite extensively. Another approach, explored here, is to review postearthquake observations of building collapse. The present work focuses on California buildings.

The International Building Code (International Code Council, 2009) does not use the word "collapse" at all. The authors of ASCE 7-10 (American Society of Civil Engineers, 2010) use the word "collapse" in defining the probabilistic (MCE_R) ground motion and in describing the anticipated maximum probability of failure for earthquake loading. It does not define collapse per se, but it does define progressive collapse as "the spread of an initial local failure from element to element, resulting eventually in the collapse of an entire structure or a disproportionately large part of it." It also defines the term "limited local collapse" with an example: "the containment of damage to adjacent bays and stories following the destruction of one or two neighboring columns in a multibay structure."

The 2009 NEHRP provisions (Building Seismic Safety Council, 2009) mention structural collapse, collapse of small structural systems (such as a hospital canopy), and collapse of nonstructural components (such as light fixtures, ductwork, and piping systems), but they do not define the word. FEMA P–695 (Applied Technology Council, 2009) defines collapse as "including both partial and global instability of the seismic-force-resisting system," excluding "local failure of components not governed by global seismic performance factors, such as localized out-of-plane failure of wall anchorage and potential life-threatening failure of nonstructural systems." It does not include in its consideration of collapse damage to or failure of "components that are not designated as part of the seismic-force-resisting system" because those components "are not controlled by seismic-force-resisting system design requirements," and they are therefore not within the scope of the project. The authors of

FEMA P–695 include among the possible definitions of collapse the occurrence of a sidesway mechanism, and more generally the "state of lateral dynamic instability."

In more recent work, the present author and colleagues developing the third edition of FEMA P–154 and FEMA P–155 (Applied Technology Council, 2015a,b) propose the following definition. We generally define building collapse as the condition in which

> any part of the gravity system experiences dynamic instability leading to the loss of load-bearing capacity. The dynamic instability leads to severe structural deformation of a potentially life-threatening nature, especially falling of all or portions of a structure... [P]artial building collapse means that the dynamic instability occurs only in a portion of the building... In the case of mobile homes and wood frame buildings, building collapse also includes the condition that the mobile home falls off one or more of its supports, or the cripple walls of a wood frame building experience a sidesway mechanism and lose their vertical load-carrying capacity... Building collapse does not include wood frame buildings sliding relative to their foundations if there is no vertical drop in any part of the floor or roof. Nor is the falling of a parapet from a URM building or brick veneer or chimney from any FEMA Building Type considered to constitute building collapse.

The United States Federal Emergency Management Agency (FEMA) National Urban Search and Rescue Response System (2009) estimates that, of people injured in buildings in earthquakes, 50 percent are injured but not trapped, and can be aided by emergent, untrained volunteers—civilians—who happen to be nearby at the time of the earthquake (fig. 2). Another 30 percent are injured and trapped but not by structural components, for example, by overturning of furniture, and are extracted by trained local community emergency response teams (CERTs). CERTs are trained to perform search and rescue in buildings that have damage to decorative work and to interior contents but are not collapsed or fallen from their foundations; that would presumably include chimney and parapet damage (PerformTech, Inc., 2011). A further 15 percent of people injured are rescued from the collapse of light structures, such as wood frame construction and manufactured housing, by emergency services rescue forces—generally firefighters—without the need for heavy excavation equipment. The remaining 5 percent must be extracted by trained urban search and rescue forces aided by equipment to penetrate heavy structures—masonry, concrete, and structural steel.

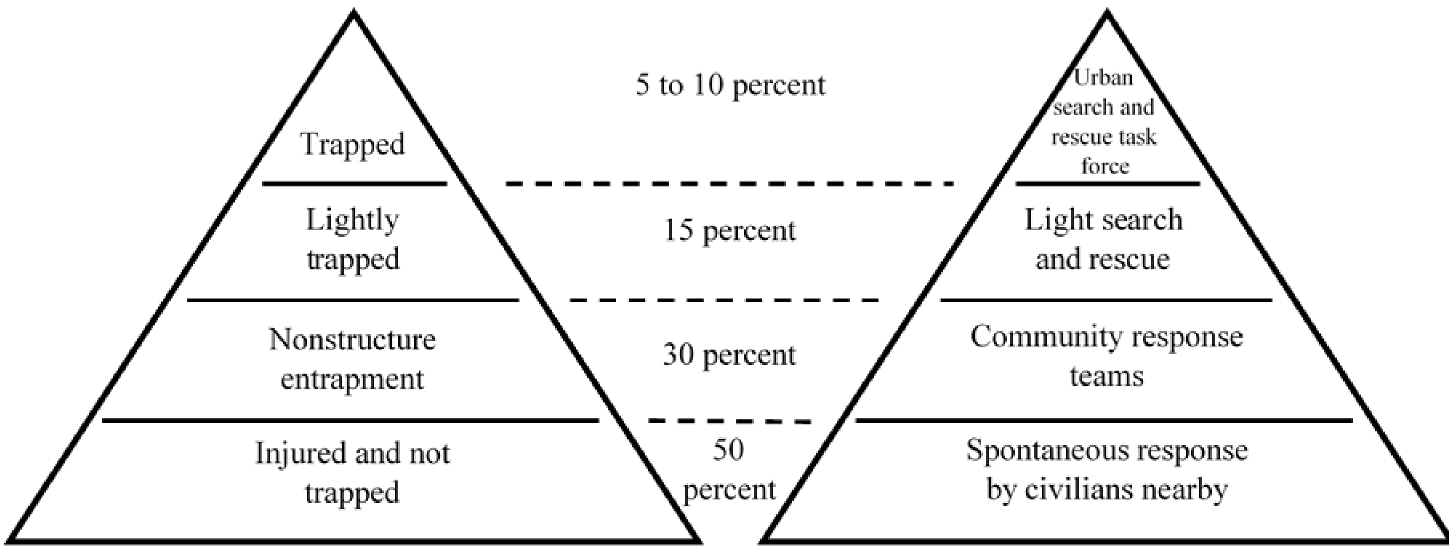


Figure 2. Pyramid charts showing the distribution of assistance in a large earthquake (after National Urban Search and Rescue Response System, 2009).

There do not appear to be any published statistics on the frequency of each collapse pattern or what faction of occupants require extrication by search and rescue personnel, although there is limited anecdotal evidence about individual buildings, such as Krimgold's (1988) statistics from the 12-story Juarez Hospital that collapsed in the 1985 Mexico City earthquake.

Literature About People Trapped in Elevators

What about people trapped in elevators? The vast majority of San Francisco Bay Area (herein Bay Area) buildings do not have uninterruptible power supplies or emergency generators to power elevators in the absence of commercial power. According to National Elevator Industry, Inc. (2014), there are 900,000 elevator units in the United States, or approximately one elevator per 344 people. Each elevator makes an average rise of 4 to 5 floors, or 40 feet, and each carries an average of 5 people per trip. Each passenger averages 4 trips per day, 250 days per year. According to the Emporis Corporation (2007) database of high-rise buildings, there are approximately 600 high-rise buildings with approximately 3,700 elevators in the San Francisco Bay Area.

Sample calculations in Strakosch and Caporale (2010) suggest that an elevator is in motion with the doors closed approximately 30 percent of the time that it is in use with passengers inside. Some elevators have battery power to operate briefly to move the cab to a floor and open doors.

According to Bay Area elevator consultant von Klan (written commun., 2015), elevators installed in high-rise buildings in the last 40 years or so have been required to have emergency power for elevators, and he estimates that perhaps 60 percent of high-rise buildings in the Bay Area date from this requirement. He also estimates that less than 5 percent of elevators in mid- and low-rise buildings have emergency power. Even if there is emergency power available, seismic safety devices installed in newer elevators may stop the elevator between floors until an elevator technician inspects the elevator.

Methodology

Methodology for Estimating the Number of People Trapped by Collapse

The illustrations in figure 2 do not appear to be exhaustive. If a portion of a parapet falls, it does not constitute building collapse, but engineers do speak of parapets collapsing. Let us include in collapse (1) the falling of a floor or roof such that the clear height is reduced to less than 2 meters (m) and (2) the falling of parapets, chimneys, and other elements, but we exclude the falling of other contents and movable furnishings, such as cubicles. For purposes of estimating the probability of being injured or trapped by collapse, let us define collapse as follows:

Collapse constitutes the condition where, in a portion of the building or in the entire building, the gravity load-carrying system (for example, its beams, columns, floors, and shear walls) loses the ability to carry its own weight and the weight of whatever else it supports. That failure leads to severe building deformation of a potentially life-threatening nature, especially if all or portions of a building fall. The nonstructural portions of a building are included in our definition of collapse, along with the structural portions, such as parapets, chimneys, and porches. So some nonstructural collapses are included (parapets, chimneys, and porches), but some structural failures are not (permanent lateral displacement of the building relative to the foundation where no vertical drop occurs).

Let us estimate fatality rate and USAR needs in future earthquakes as follows. Let us estimate fatality rate as the product of the collapse probability conditioned on ground motion, the fraction of the building floor area that actually collapses when there is at least some collapse, and the fraction of occupants in that collapsed area that are killed, as in equation 1.

$$F(h) = P(h) \times A \times R \qquad (1)$$

In the equation, $F(h)$ represents the fatality rate in a building (fraction of occupants killed) that is shaken with severity h. $P(h)$ denotes collapse probability given shaking h. A denotes affected area, that is, the fraction of the building area that collapses, given that at least some collapse occurs. R denotes the fatality rate in the collapsed area.

Let us model search and rescue needs by an analogous equation: let $S(h)$ and E denote, respectively, the fraction of building occupants requiring extrication and the fraction of occupants in the collapsed area who need extrication, as in equation 2.

$$S(h) = P(h) \cdot A \cdot E \tag{2}$$

Implicit in equation 2 is the assumption that people are uniformly distributed throughout the building: an occupant is as likely to be in one place as another. This assumption might be conservative: buildings with soft-story conditions are likely to collapse onto the soft story, which tends to be less densely occupied garage space rather than more densely occupied living space. To account for that fact requires a model of the number of buildings that collapse onto soft garage levels. Let us assume for the remainder of this work that one lacks a damage model that detailed.

If one already has an estimate of the number of collapsed buildings (let us denote this number by N_b), then the estimated number of people, N_c, who are trapped in collapsed buildings and require extrication by USAR personnel can be estimated as

$$N_c(t) = N_b \cdot O(t) \cdot A \cdot E \tag{3}$$

where $O(t)$ denotes the average number of occupants per building at time t, and A and E again denote the fraction of the building area that collapses and the average fraction of occupants in the collapsed area who need extrication by USAR personnel. One might want to condition each term in equations 1, 2, and 3 on building type, era of construction, or other parameters. The analyst must estimate the quantity $O(t)$, for example, using estimates of average building area per occupant from Hazus-MH (National Institute of Building Sciences and Federal Emergency Management Agency, 2012) or ATC-13 (Applied Technology Council, 1985).

To estimate A, I examined every photograph of a building in the NISEE e-Library images database from every California earthquake in the last 50 years in which the photo description uses the word “collapse,” “fail,” “fell,” or “parapet.” I supplemented these images with photos of buildings where I knew collapse had occurred. I also added data on tilt-up roof collapses in the 1971 San Fernando earthquake extracted from a 1973 National Oceanic and Atmospheric Administration (NOAA) report that showed building plan area and area of roof collapse.

I estimated E, the fraction of occupants in collapsed area requiring extrication, as the fraction of the collapsed area in which heavy debris or structural elements fell to the floor or ground. For example, in the case of bricks littering a sidewalk from collapsed parapets or chimneys, it seems reasonable to assume that anyone in that debris field would be injured or killed and would require extrication by others. In the case of collapsed porch roofs resting entirely on the ground or porch, anyone beneath the porch would require extrication. In the case of houses off their foundations but where the roof or upper floors do not fall, I assume that residents can generally escape through a window or a door that is not blocked. It seems realistic that there will be cases of injured or physically disabled people who cannot escape through a window unaided, but I assigned $E = 0$ based on the assumption of the more likely case, that the occupant is not physically disabled or seriously injured.

Social scientists speak of such an approach to sampling as a convenience sample, a nonprobability sampling technique where subjects are selected because of their convenient accessibility and proximity to the researcher. The main problem with convenience sampling is the potential for sampling bias, in which one does not know that the sample is representative of the entire population. If a database existed of all collapsed buildings in a particular earthquake or particular geographic region, one could perform a randomized sample or an exhaustive survey and avoid worries about sampling bias, but such a database does not exist, so for present purposes let us fall back on this convenience sample and advocate for a better database in the future.

In the present convenience sample, the first California earthquake in the 50-year period studied here is the 1968 Borrego Mountain earthquake; the last is the 2014 South Napa earthquake. In each case, I estimated the fraction of the building affected area by the collapse. In many cases, particularly ones where only a small portion of a large building was affected, the photograph shows the affected area but not the overall size of the building, and the building no longer exists. In many cases, I found additional evidence of the building location and other photographs that show more of the building, and in several cases, I estimated building area from the area of building shown in Google Earth Pro, which includes parcel outlines and recent and historic satellite imagery and has a tool for measuring area.

Table 1 summarizes the results. Its columns list the earthquake associated with the collapse, NISEE's image identifier number, NISEE's photo description, the building type (using FEMA's building typology), the estimated fraction of the building's occupiable floor area that was affected by the collapse (A), the fraction of occupants in the affected area that would require extrication by others (E), and the technical qualifications of the people most likely to perform the extrication (T). The quantities *A* and *E* are bounded by 0 and 1. Options for *T* are labeled by the order in which USAR personnel would arrive: 1 = emergent civilian volunteers (neighbors); 2 = CERT; 3 = firefighters; and 4 = FEMA USAR Task Force.

Details of each estimate of *A* are provided in the appendixes. I binned the fraction of affected area on a quarter order-of-magnitude basis, that is, approximately 10^{-2}, $10^{-1.75}$, $10^{-1.5}$, ... 10^{0}, which is to say 1 percent, 2 percent, 3 percent, 6 percent, 10 percent, 18 percent, 32 percent, 56 percent, and 100 percent. From these data, one can create histograms of the data as a whole and subdivide by the structural material (wood, unreinforced masonry, or concrete).

I estimated *T*, the technical qualifications of the USAR personnel, as 1 (untrained emergent civilian volunteer) if the extrication could be done by a single person without tools, as in picking up bricks. I assigned *T* = 2 (CERT) if the extrication requires two or more people but no heavy equipment and would not violate the CERT training guidelines (PerformTech, Inc., 2011). I assigned *T* = 3 if the extrication requires equipment but not heavy lifting or cutting of reinforced concrete, for example, in the case of a collapsed wood frame building where a roof or an upper floor falls onto the floor or furnishings below. For example, firefighters extracted Sherra Cox from a collapsed building in the San Francisco Marina District after the 1989 Loma Prieta earthquake (Scawthorn and others, 1992). I assigned *T* = 4 if the extrication requires heavy lifting or cutting of reinforced concrete. I made no assignment (*T* = blank) if *E* = 0, that is, no extrication is required.

Table 1. Summary of parameters used in the urban search and rescue (USAR) model.

[*ID*, image identifier from Earthquake Engineering Online Archive; *Type*, model building type according to Federal Emergency Management Agency (2015a); *A*, affected area; *E*, fraction of occupants trapped; *T*, technical qualifications of USAR personnel; %, percent; in., inch; St., Street, Rd., Road; Ave., Avenue]

Earthquake	ID	Damage description	Type	A	E	T
Santa Rosa 1969	S3715	Two-story wood frame building off foundations. Foundations were rotted and poorly braced. Gas lines ruptured when house fell. 718 Beaver St., Santa Rosa, California.	W1	0%	0	

Earthquake	ID	Damage description	Type	A	E	T
	S3726	Miramar Building. Collapsed portion of a wall fell on a car. 203 Old Courthouse Square, Santa Rosa, California.	URM	1%	1.0	
San Fernando 1971	S4473	Damage to porches (probable cripple wall failure?); chimney fell away from house. In the vicinity of Knox and Orange Grove Streets, in the fault zone.	W1	8%	0.5	
	S4533	Chimney fell towards otherwise undamaged wood frame house.	W1	0%	0	
	S4581	Furniture store. Unreinforced masonry parapet collapsed, dumping bricks into the street and on to the sidewalk. Large plate-glass windows are gone, presumably shattered by the earthquake.	URM	19%	1.0	
	S4597-S4602	Apartments over retail space. Note that the failure of the nonreinforced bearing walls did not result in collapse. Unit masonry construction, built prior to 1933. Downtown San Fernando commercial area.	URM	3%	1.0	
	S4489	Partial collapse on older wood frame house, probable cripple wall failure of house. Between Glen Oaks and Hubbard Streets.	W1	0%	0	
	S4491, S4492	Pink structure at the rear was a residence over a garage. The first story collapsed; note remains of automobile under the building.	W1	50%	1.0	
	S4624	Roof to the wall failed first. Ground cracks in the vicinity. Rear wall bulged out, and rear roof fell. See S4625-4633. Light industrial buildings. Bradley Tract. 12884 Bradley Ave.	TU	11%	0.1	
	Benfe and Coffman (1973, p. 123)	12840 Bradley Ave.	TU	44%	0.1	
	Ditto	12874 Bradley Ave.	TU	12%	0.1	
	Ditto	12950 Bradley Ave.	TU	10%	0.1	
	Ditto	12881 Bradley Ave.	TU	10%	0.1	
	Ditto	12975 Bradley Ave.	TU	23%	0.1	
	Ditto	13001 Bradley Ave.	TU	8%	0.1	
	Ditto	13069 Bradley Ave.	TU	16%	0.1	
	Ditto	15200 Bledsoe St.	TU	19%	0.1	
	Ditto	15151 Bledsoe St.	TU	8%	0.1	
	Ditto	12860 San Fernando Rd.	TU	16%	0.1	
	Ditto	12806 San Fernando Rd.	TU	18%	0.1	
	Ditto	12744 San Fernando Rd.	TU	26%	0.1	
	Ditto	12814 Bradley Ave.	TU	15%	0.1	
	GoddenJ53	Collapse of a split-level wooden home. Large numbers of these split-level homes suffered significant damage because of a lack of adequate ties between the two levels. The upper level ripped away and crushed the lower garage walls, which did not have adequate lateral bracing.	W1	33%	1.0	
	S4195	Collapsed Semi-Ambulant Building at Veterans Authority Hospital, built in 1925, masonry construction.	URM	50%	1.0	
	S4529	Damage to older house caused by cripple wall collapse.	W1	0%	0	
	S4065	Collapsed tower at southeast corner. Olive View Hospital. Rear [east] elevation of Medical Treatment Building.	C2	3.3%	1.0	
	S4070	Ambulance garage collapsed. Olive View Hospital. Southern elevation of Medical Treatment Building. See also S4139-44.	C1	100%	0.5	
	S4115, S4117	Soft-story collapse, most evident at upper right of photo. Originally a one- and two-story building, irregular in plan, the first story collapsed in the earthquake.	C1	67%	1.0	
	S4519	Collapsed wood frame house under construction on Tucker Street near Pacoima Dam.	W1	67%	0.5	
	S4501	Two-story section over garage of this wood frame house on Almetz Street has collapsed in the first story. In a new housing tract in Sylmar at base of hills and between Olive View and Veterans Administration Hospitals.	W1	33%	1.0	
	R0070	Old masonry building in upper center of photo has completely collapsed. Constructed in 1925-1926, with major additions in 1938 and 1949, the entire complex was demolished after the 1971 earthquake and the entire 97 acres were dedicated in 1977 as Veterans Memorial Park.	URM	100%	1.0	4

Earthquake	ID	Damage description	Type	A	E	T
Imperial Valley 1979	S5584	Cripple wall collapse—wood frame house on G Street in Brawley, California.	W1	0%	0	
	S5585	Cripple wall collapse—wood frame house on G Street in Brawley, California.	W1	0%	0	
Westmorland 1981	N/A	Collapsed two-story building on W Main Street in Westmorland, California	URM	100%	1.0	3
Coalinga 1983	GoddenJ52	Chimney collapse of a modern house, 1983 Coalinga earthquake. Most of the chimneys were thrown down because of the lack of proper connections (straps) to the buildings. Additional discussion of this image is available in Godden Set J: V. V. Bertero Introduction to Earthquake Engineering.	W1	9%	1.0	1
	GoddenJ19	This two-story wood frame dwelling underwent a lateral displacement of more than half a meter as illustrated by the slant in the porch columns and also fell more than half a meter from its foundation, owing to lack of adequate anchorage and support during the 1983 Coalinga earthquake.	W1	0%	0	
	GoddenJ23	Collapse of a wooden porch (owing to lack of proper anchorage to the wooden frame of the house and of a proper later-resistant supporting system) was due to vibratory response during the 1983 Coalinga earthquake. Additional discussion of this image is available in Godden Set J: V. V. Bertero Introduction to Earthquake Engineering.	W1	15%	1.0	3
	GoddenJ29	The second-story, 8-in. unreinforced solid brick masonry walls of this commercial building in Coalinga collapsed because of inadequate tying at the floor, roof, and transverse walls. Additional discussion of this image is available in Godden Set J: V. V. Bertero Introduction to Earthquake Engineering.	URM	30%	0.60	1
	R0323	Porch running the full width of the church simply pulled away from the rest of the building. Built in 1946, the stabilized adobe building was heavily damaged but did not collapse. On the corner of Jefferson St.	URM	7%	1.0	3
Morgan Hill 1984	S5840	Most severely damaged dwelling. Sheathing between first floor and foundation was fibreboard with little strength. Morgan Hill, California Anderson Lake area.	W1	0%	0	
	S5839	Dwelling on the left moved, owing to landsliding from the earthquake. Morgan Hill, California, Anderson Lake area.	W1	20%	1.0	3
Whittier Narrows 1987	S6014	Damage to roof from chimney collapsing. Whittier, California.	W1	0%	0	
	S6023	Chimney collapsed away from the house. Whittier, California.	W1	3%	1.0	1
	S6020	Chimney fell through porch roof. See S6021 and s6040. Whittier, California.	W1	2%	1.0	2
	S6022	One chimney collapsed, but not the other. Whittier, California.	W1	3%	1.0	1
Loma Prieta 1989	LP0042	Wall collapse in unreinforced masonry (URM) building. Santa Cruz, California.	URM	1%	1.0	1
	LP0070	Older building with failed parapets on Main Street. 307 Main Street, Watsonville, California.	URM	18%	1.0	1
	LP0072	Older building with failed parapets on Main Street. 311 Main Street, Watsonville, California.	URM	9.4%	1.0	1
	LP0462, LP0460	Collapse of unreinforced brick wall. 6th and Bluxome Streets, South of Market District, San Francisco, California.	URM	5.3%	1.0	1
	LP0375	Collapse of two four-story apartment buildings (soft ground floors). Marina District, San Francisco, California.	W1A	25%	1.0	3
	LP0375, S6120	Ditto; there were two buildings in the image.	W1A	25%	1.0	3
	LP0499	Collapsed apartment building at 2090 Beach Street, after the fire was much advanced. Note the firefighter directing water onto exposed side of building. Marina District, San Francisco, California.	W1A	75%	1.0	3
	S6144	Soft-story collapse of apartment building in the Marina District, San Francisco, California.	W1A	33%	1.0	3
	LP0459	Collapse of unreinforced masonry wall from third floor of building. 235 Front St. at Davis St., Embarcadero/Financial District, San Francisco.	URM	2.9%	1.0	1
	LP0041	Interior structural failures at Ford's Department Store. Santa Cruz, California.	URM	33%	1.0	3
	LP0081-LP0085	Front view of damaged St. Patrick's church. Watsonville, California.	URM	4.5%	1.0	1

Earthquake	ID	Damage description	Type	A	E	T
	LP0087	Damaged bike store with failed parapet. Watsonville, California.	URM	25%	1.0	1
	LP0090	Pink frame house with failed foundation. Watsonville, California.	W1	0%	0	
Northridge 1994	NR327, NR353, NR357, NR358	Collapsed apartment building, three-story wood frame. Northridge, California. According to Todd et al. (1994, p. 23), four buildings experienced collapse. This is the first.	W1A	33%	1.0	3
	Ditto	Ditto, the second building.	W1A	33%	1.0	3
	Ditto	Ditto, the third building.	W1A	17%	1.0	3
	Ditto	Ditto, the fourth building.	W1A	4%	1.0	3
	NR408-409	1004 West Channel Road at Pacific Coast Highway (near Pacific Palisades). Damage to two-story masonry building. Heavy shear cracking on side walls. Out of plane failure of the second story. State Beach Cafe, Santa Monica, California.	URM	13%	1.0	1
	NR412-414	Four-story masonry building, 827 Fourth Street, Santa Monica, California. Damage to the fourth and third floor of the building. The masonry facade fell out of plane and took with it the fourth-floor terrace. This building had been scheduled for a retrofit to begin on Monday, January 17, 1994. Three-layers-thick unreinforced masonry. Damage in the top story and balcony. Little damage on the sides and below the third story. See also NR412–414.	URM	2.1%	1.0	1
	20101224	This residential chimney of unreinforced blocks collapsed during the 1994 Northridge earthquake.	W1	2.7%	1.0	1
	NR559	Parking structure on Zelzah Ave., California State University, Northridge, campus. This is a three-story precast concrete parking structure. Overall view showing collapse at east end of the structure.	C1	35%	1.0	4
	NR579	Collapse of parking garage floors. See NR459–461 for damage to Broadway department store. Fashion Center, Northridge, California.	PC1	35%	1.0	4
	NR221	Northridge Fashion Island Center. Interior reinforced concrete columns remain standing following collapse of second- and third-floor concrete waffle slabs. Intact portion of waffle slab roof shows typical slab construction.	C1	78%	1.0	4
	NR303	View of partial roof collapse. South elevation, east of front entry. View from east. Taken at 3 p.m. California State University, Northridge.	C1? C2?	1%	1.0	4
	NR542, NR543	Complete collapse of parking structure. Los Angeles, California.	C1	100%	1.0	4
	NR328	Soft-story collapse of apartment building, at Hazeltine Ave. and Milbank St. Sherman Oaks, California.	W1A	33%	1.0	3
	NR160, NR162	Overall view of Kaiser Permanente office building looking toward the northeast. The brick facades at either end of the structure have separated from the concrete frame, and the second floor of the structure has completely collapsed. The bays at the north and south ends of the building are also partially collapsed from the second to the fifth floor. Granada Hills, California.	C1	30%	1.0	4
San Simeon 2003	NM0001-NM0012	House of Bread, was located in the Mastagni/Acorn Building, which collapsed. By the time these pictures were taken, emergency personnel had removed the front wall of the building and a great deal of debris. Built in 1892, the clock tower of this unreinforced masonry building had become a symbol of the town of Paso Robles. The second story of the building collapsed during the earthquake, killing two employees of Ann's Dress Shop. The roof of the building collapsed directly westward onto Park Street and landed on a row of parked cars. Debris from the north wall went through the roof of an adjacent shop at 1220 Park Street. Paso Robles, California.	URM	78%	1.0	3
South Napa 2012	P9050177, P9080152	Don Perico's Restaurant in Napa. At the time of the earthquake, the restaurant was located at 1025 1st St., Napa, California, in the west end of the building at lat 38.299029 N., long 122.285868 W. That address seems to occupy approximately 60 ft × 60 ft. The collapsed wall appears to fill 25 ft by 12 ft, suggesting a collapsed portion of 8.3%.	W2	8.3%	1.0	1

The database of photos of collapse that I compiled from NISEE and the other sources contains 73 California buildings that experienced at least some collapse in earthquakes between 1965 and 2014, inclusive. The database contains wood, concrete, and unreinforced masonry buildings. Areas affected range from zero (for example, cripple wall collapse that did not cause height reduction of an occupiable area) to 100 percent (for example, complete collapse of a parking structure). Among the sample of collapsed California buildings of the last 50 years, the average had 24 percent of its occupiable floor affected area. That is, on average 23 percent of occupants or passersby—people walking within a few feet of the building—could have been trapped or injured by a portion of building falling on them. On average, I estimate that 66 percent of occupants in the collapsed area would need extrication by USAR personnel, even if only by emergent civilian volunteers. Statistics by structural material are shown in table 2.

Table 2. Average affected area (*A*) and average fraction of occupants in collapsed areas requiring extrication (*E*) in the urban search and rescue (USAR) model.

%, percent

Material	Count	Average *A*	Average *E*
All	73	23%	0.66
Tilt-up concrete	14	17%	0.10
Other concrete	9	50%	0.94
Unreinforced masonry	18	28%	0.98
Wood	32	17%	0.66
All except unreinforced masonry	54	22%	0.56
All except chimneys	66	25%	0.65

In California, the 1934 Field Act outlawed the use of unreinforced masonry (URM) in most buildings. Consequently, URM buildings have become rarer in California than elsewhere in the western United States, and many have been retrofitted, so including the data of their past performance could conceivably bias estimates of future performance. Nonetheless, removing unreinforced masonry buildings and chimneys from the data does not substantially change the average affected area. The weighted average considering only tilt-up, other reinforced concrete, and wood is 22 percent. If one removes the cases where the collapse was limited to or caused by chimney collapse (that is, also removing the case where a chimney penetrated a roof), the average increases to 25 percent.

Table 3 shows the estimated distribution of minimum USAR technical qualifications. It suggests that most search and rescue would have to be done by firefighters, rather than by untrained emergent civilian volunteers. This estimate is not necessarily inconsistent with figure 1, whose bottom two strata are people who are not trapped by collapse and are not represented in the collapse photos examined here.

Table 3. Distribution of minimum technical qualifications for urban search and rescue (USAR) personnel.

[CERT, community emergency response team; URM, unreinforced masonry; %, percent]

Technical qualifications	All	URM	Not URM	Tilt-up	Other concrete	Wood	Chimney	Not chimney
1 Civilian	27%	67%	11%	0%	0%	23%	80%	22%
2 CERT	2%	0%	2%	0%	0%	5%	20%	0%
3 Firefighter	59%	28%	71%	100%	22%	73%	0%	64%
4 USAR Task Force	13%	6%	16%	0%	78%	0%	0%	14%

Considering all buildings, the distribution of affected area resembles an exponential distribution (though it does not pass a Lilliefors goodness-of-fit test at the 5 percent significance level). An exponential distribution would mean that a building is approximately equally likely to collapse on 1 percent (10^{-2}) of its occupiable area, 2 percent ($10^{-1.75}$), 3 percent ($10^{-1.5}$), and so on, through 100 percent (10^{0}). Among the wood buildings, the affected area tends to be lower; among the 9 concrete buildings, the affected area tends to be higher, but nearly the full range is exhibited among each of the three materials, as illustrated in figure 1.

Suppose one wanted to perform Monte Carlo simulation of USAR needs using a simple parametric model, for example, a mathematic idealization of the data presented here. To inform such simulations, I evaluated a few common parametric cumulative distribution functions for affected area:

uniform, exponential, lognormal, power-law, and the distribution shown in equation 4. The equation reflects a model in which there is a constant probability f that the affected area is zero and a probability $(1 - f)$ that the affected area is greater than zero. If the affected area is nonzero, it is exponentially distributed.

$$P\left[X \leq x\right] = 1 - \left(1 - f\right)\exp\left(-Lx\right);\ X \geq 0 \tag{4}$$

where f and L are constants. The affected area data and equation 4 are plotted together in figure 4 for comparison. Let us refer to equation 4 as a frequency-and-exponential-severity model. Of all the forms examined, only the one shown in equation 4 passed the Lilliefors (1967) goodness-of-fit test at the 5 percent significance level. The Lilliefors test is intended to check whether a sample is drawn from a normally distributed population with parameters of the distribution estimated from the sample. The test is not intended for this frequency-and-exponential-severity model. I am aware of no comparable test for this frequency-and-exponential-severity model, so let the passing of the Lilliefors test merely indicate reasonableness in a qualitative manner. A parametric expression similar to a power law is also shown in figure 4. It does not fit quite as well as the frequency-and-exponential distribution, but it is simpler.

Given a building that is modeled as having collapsed, one could simulate affected area by inverting equation 4 at the value of a sample of a random variable uniformly distributed between 0 and 1; that is, if we draw a sample $u \sim \mathrm{U}(0,1)$, then the sample of affected area is the following:

$$\begin{aligned} x &= 0 && u < f \\ &= \frac{-1}{L}\ln\frac{\left(1-u\right)}{\left(1-f\right)} && u \geq f \end{aligned} \tag{5}$$

The mean number of people trapped in the collapsed area can be estimated as n in equation 6 where the symbols $\lfloor\,\rfloor$ mean "floor," that is, the largest integer less than or equal to the value inside. The simulated number of people trapped in the collapsed area m can be taken as the inverse of a binomial cumulative distribution function with n trials and probability p, where p is another sample of a uniform distribution U(0,1). Common software can calculate m.

$$n = \lfloor x \cdot N \cdot E \rfloor \tag{6}$$

where N denotes the number of occupants in the building and E = 0.66. Alternatively, to account for building type, construct the cumulative distribution function of A from the probability mass functions in figure 3 and invert at u to simulate x, calculate n according to equation 6 using the value of E from table 2, and invert the binomial cumulative distribution function with parameters n and p, where p is again a sample of U(0,1).

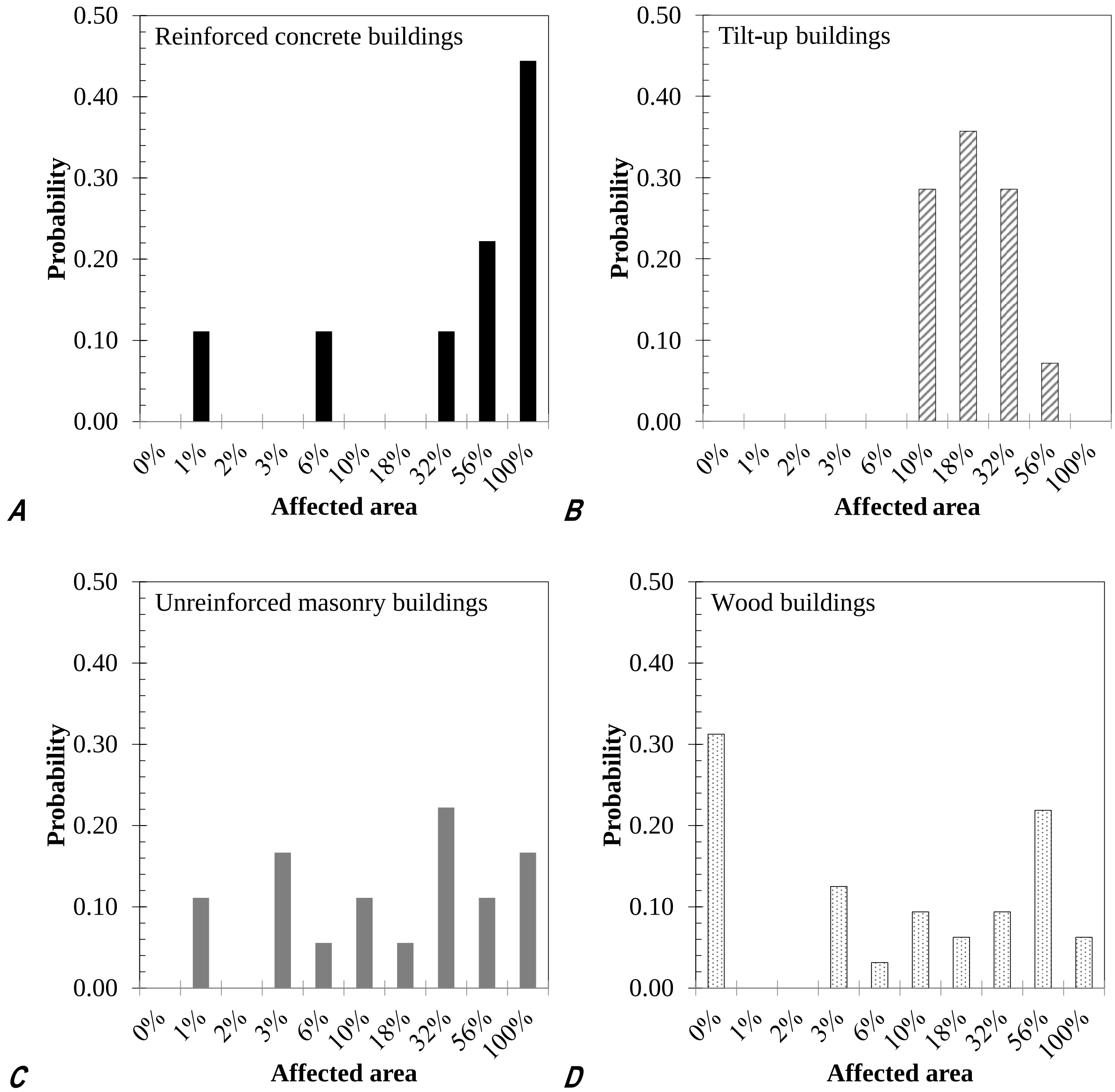


Figure 3. Graphs showing distribution of affected area by structural material: *A*, reinforced concrete except tilt-up; *B*, tilt-up concrete; *C*, URM; and *D*, wood.

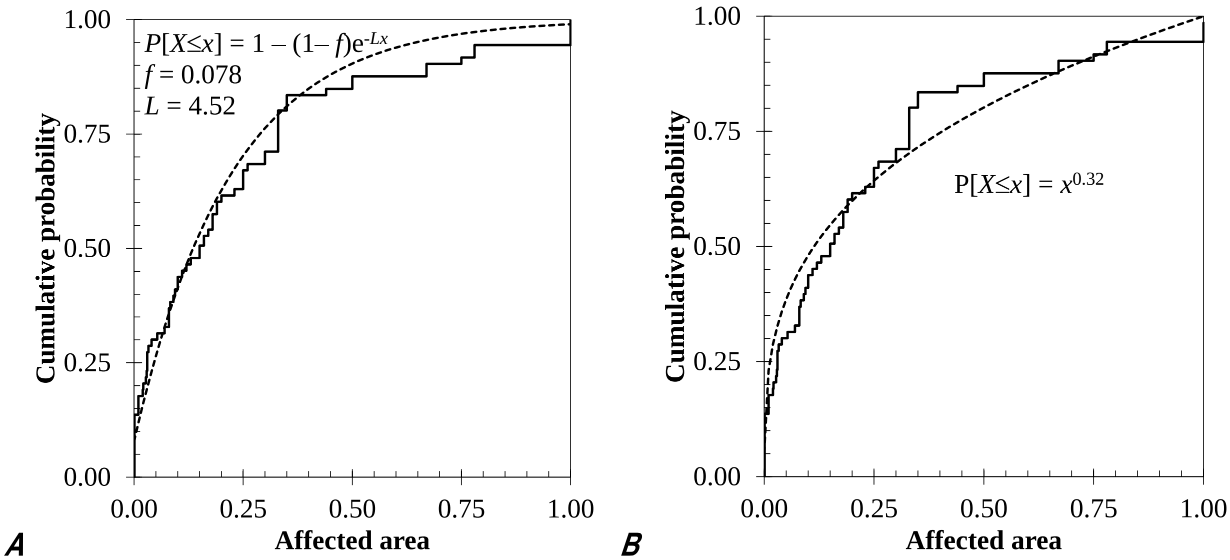


Figure 4. Graphs showing approximate parametric forms of the cumulative distribution function for affected area of all building types: *A*, frequency-and-exponential-severity; *B*, a simpler expression similar to a power law. The axis of affected area spans from 0.00 (no area affected) to 1.00 (100 percent of area affected).

If one wanted to use the data presented here for modeling future performance of buildings, one must assume that the past is indicative of the future. Is it? There does not appear to be a strong trend to the affected area in later earthquake years, as shown in figure 5. The trend line has almost no slope, and the coefficient of determination (R^2) is so low (0.0006) that one can be fairly confident that no trend actually exists. Because each earthquake affects an existing building stock that was built up over decades, the relationship would be a trailing indicator. But because approximately half the building stock was replaced over the 5 decades examined here, if newer buildings tended to experience lower collapse areas, one would expect to see a stronger downward trend. The implication is that, while collapse probability of an arbitrary building in the building stock may or may not change over time, if a building does collapse, its collapse area is not related to the year of collapse. One can reasonably assume that buildings in near-future earthquakes (the next several decades) will have approximately the same distribution of affected area as in the previous 5 decades. Note that the catalog does not indicate the age of the building that collapsed. Newer buildings presumably have a lower collapse probability than older buildings, all else being held equal, but that issue is separate from the one examined here.

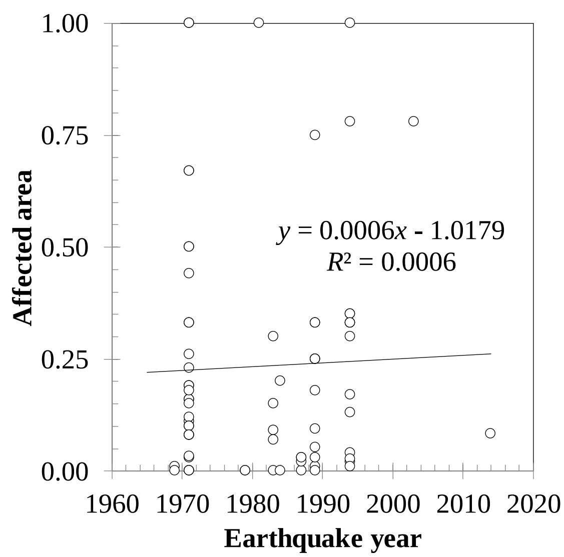


Figure 5. Graph showing affected area of all types of buildings versus year of the earthquake, 1965–2014.

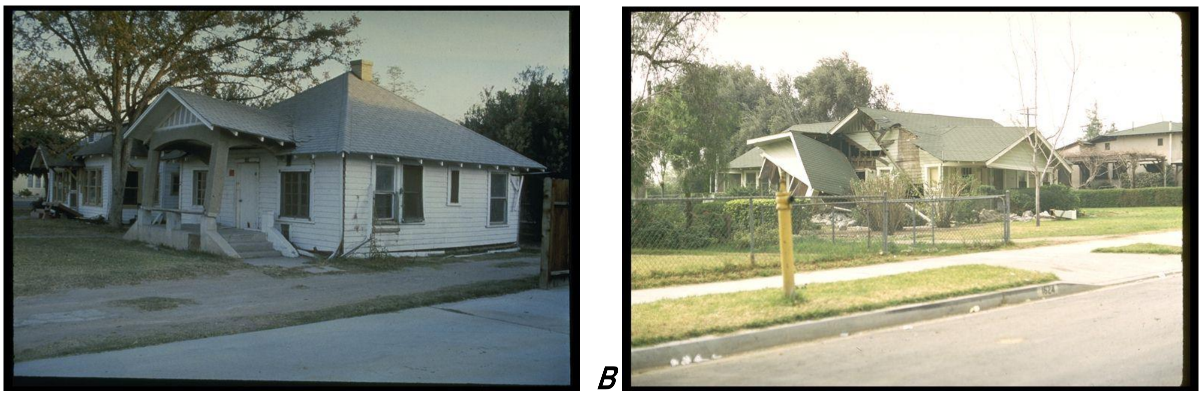
A few additional observations of the nature and extent of collapse follow.

- **Error! Reference source not found.** shows that collapse of buildings with bearing walls composed of wood or unreinforced masonry generally affected the least total area in these buildings, followed by tilt-up concrete, then other reinforced concrete.
- Most collapses involving wood frame buildings affect less than 10 percent of the building area, that is, the median affected area is less than 10 percent. Furthermore, 95 percent of collapses affect less than half the building area. More than 30 percent do not collapse into occupied space

at all. As shown in figure 3, the modal affected area (the tallest bar on the ¼-log-increment bar charts) for wood frame buildings was between 0 and 1 percent. A common example of a building with such an affected area is one in which the unbraced cripple wall collapsed, without the loss of load-bearing capacity supporting a ceiling or roof above an occupied space (fig. 6*A*). The median affected area (the value with 50 percent probability of being exceeded) was between 6 percent and 10 percent of building area, commonly the collapse of a chimney or porch roof (for example, fig. 6*B*). The distribution of affected area in wood frame collapses is likely biased high. The reason for this is that the collapse of brick chimneys was likely too widespread and too uninteresting for NISEE e-Library contributors to photograph instances in proportion to their actual occurrence within the population of wood frame buildings with collapse.

- Although the database includes instances of complete collapses of URM buildings, most URM collapses affect less than 18 percent of floor area. The modal affected area is between 18 and 32 percent of the building area, such as the collapse of brick parapets on the sidewalk, parking areas, and lower buildings adjacent to the URM building. That is, the URM collapses sampled here are commonly more dangerous to neighbors and passersby than to occupants. See figure 7 for representative examples.
- In the case of pre-1971 tilt-ups examined here, most collapses affected less than 18 percent of the building area. The modal affected area was between 10 and 18 percent of the building area, almost always just inside the building perimeter where roof-to-wall connection fractures occurred. The interior gravity system kept supporting interior subdiaphragms (away from the edge) even after perimeter subdiaphragms collapsed. See figure 8 for an example.
- Complete collapses of concrete buildings in California have occurred, but they are the exception rather than the rule. In most cases, less than 50 percent of the floor area is affected. The modal

affected area on this ¼-log-increment scale was between 32 and 56 percent of building area. In the specimens examined here, an example of such a modal collapse was that of a partial collapse of a parking structure, shown in figure 9. No obvious spatial pattern of collapse was observed in these images.



A *B*

Figure 6. *A*, An example of the modal affected area (0 percent) of a collapsed wood frame building. The cripple wall collapsed in this Imperial Valley home in 1979. *B*, An example of the median affected area (6–10 percent): collapse of a porch roof. Photo credits: M. Hopper, and V. Bertero, respectively. Courtesy of the National Information Service for Earthquake Engineering, PEER-NISEE, University of California, Berkeley.

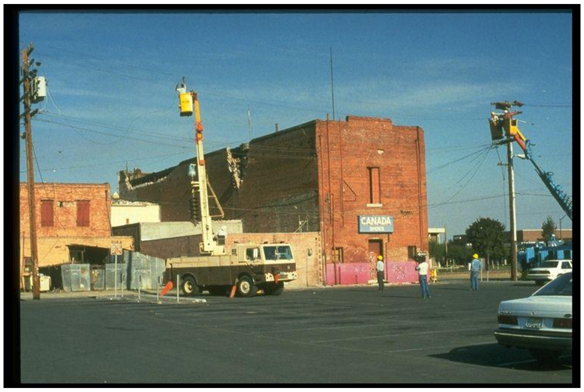
A  *B* 

Figure 7. Examples of modal (*A*) and median (*B*) affected areas in unreinforced masonry (URM) buildings. Photo credits: J. Blacklock and E. Schader, respectively. Courtesy of the National Information Service for Earthquake Engineering, PEER-NISEE, University of California, Berkeley.

Figure 8. Example of both modal and median collapse of tilt-up. Photo credit: V. Bertero, courtesy of the National Information Service for Earthquake Engineering, PEER-NISEE, University of California, Berkeley.

Figure 9. Example of a partially collapsed reinforced concrete structure: a parking structure at California State University, Northridge. Photo credit: P. Weigand. Permission for use granted per http://goo.gl/tmht1n.

Methodology for Estimating the Number of People Trapped in Elevators

It is reasonable to assume that electric power will go out across the Bay Area as soon as substation equipment and perhaps buildings in the area near the earthquake's epicenter are damaged. Hence, the vast majority of elevators in the Bay Area will lose power before P-waves trigger seismic switches or ring-on-a-string devices. How many people will be in elevators with doors closed and traveling between floors when power goes out? Let us take the number of elevators in a metropolitan area V_m as

$$V_m = \frac{P_m}{p} \tag{7}$$

where P_m is the population of the metropolitan area, and p is the average number of people per elevator, which as noted earlier is approximately 344 in the United States. The number of elevators in motion with people inside and no emergency power can be estimated as shown in equation 8.

$$V_0(t) = V_m \cdot f_o(t) \cdot f_c \cdot (1 - f_b) \tag{8}$$

where f_b denotes the fraction of elevators with emergency power, $f_o(t)$ is the estimated fraction of all elevators that are in use at time t, and f_c is the fraction of the time that an elevator in use with passengers in it is traveling between floors with the doors closed, which as noted earlier is on the order of 30 percent of the time. If the average elevator with passengers has d passengers, then the number of people that will be trapped in elevators N_e can be estimated as shown in equation 9.

$$\begin{aligned} N_e &= V_o(t) \cdot d \\ &= \frac{P_m}{p} \cdot f_o(t) \cdot f_c \cdot (1 - f_b) \cdot d \end{aligned} \tag{9}$$

Case Study: a Hypothetical Mw 7.0 Earthquake on the Hayward Fault

Selection of a Scenario Earthquake

With this new knowledge of area affected in mind, what can we say about urban search and rescue needs in a large urban earthquake? As a case study, let us consider one particular scenario: a M_w 7.0 rupture of the Hayward Fault in the San Francisco Bay Area. The Hayward Fault is perhaps the most urbanized active fault in the U.S. It runs through an urban core along a north-south axis that passes near the geographic centroid of the 7.2-million-person population of the Bay Area. According to the newest Uniform California Earthquake Rupture Forecast (UCERF3, Field et al. 2013), which now allows for fault-to-fault ruptures (i.e., ruptures involving two or more faults, potentially separated by several kilometers), the Hayward Fault is believed capable of participating in earthquakes as large as M_w 8.35. An M_w 7.05 rupture therefore is nowhere near a worst case for this fault. According to UCERF3, it has a mean annual recurrence interval of approximately 200 years, making it a large but not exceedingly rare event and a reasonable example of the earthquake the public thinks of as the Big One. In light of the fact that there are several other potential sources of the Big One in the San Francisco Bay Area, each with comparable return intervals, we can think of one of these Big Ones as a once-in-a-lifetime event, an earthquake that current residents, especially younger residents, can realistically anticipate experiencing in their lifetimes.

How shall we estimate the shaking in such an earthquake? Typically one would use a ground motion prediction equation, which is an empirical relationship derived from regression analyses of recorded ground motions from all over the world. Such relationships provide mean and standard deviation of the natural logarithm of many measures of ground motion. If one wished to depict a realistic map of ground motion, the simply mapping the median motion would tend be a poor choice, since nonlinearity in motion-damage relationships tend to be concave upward at realistic ground motion, resulting in a low bias for aggregate damage. One could apply a spatial correlation model such as that of Park et al. (2007) to simulate a realistic random field, i.e., one showing a realistic field of deviations from the median, and thus reduce the potential for an unrealistically low estimate of damage. Such an approach offers the advantage of (relative) simplicity and familiarity, but the disadvantage that ground motion prediction equations do not reflect regional variations from the worldwide average reflected in the database of ground motions on which the ground motion prediction equations are based. Frankel for example suggests that recent ground motion prediction equations tend to underpredict California ground motions at low periods.

An alternative is to use physics-based modeling, in which one applies a 3-dimensional mathematical model of the fault, crust, regional surficial geology, a spatially and temporally varying model of fault offset and stress drop along the rupture surface, and what structural engineers would recognize as a large nonlinear dynamic finite-element analysis of the resulting motion. The physics-based model offers the advantages of reflecting local geology, detailed characteristics of the fault and of the rupture, and avoids the potential biases inherent in applying a model derived from places that may differ greatly from the one in which we are interested. The disadvantage is that, as an analytical model, it lacks the built-in validation that an empirical model offers. A deciding advantage however is the availability of authoritative, well vetted, published ground motion maps developed by more than a dozen leading experts, in the form of the analyses offered by Aagaard et al. (2010a, b).

Those authors estimated motions from a wide variety of Hayward Fault earthquakes. Among the 39 hypothetical ruptures they examined, six include estimates of broadband motion (meaning motion that includes frequency content above 1 Hz) from a Hayward Fault earthquake. Three of these are relatively small (M_w 6.76), the other three large (M_w 7.05). It seems more useful to illustrate the model with a larger earthquake than a smaller one, especially since a 200-year mean recurrence interval seems more suited to be described and understood as the Big One. Of the three larger events, one originates at the north end of the Hayward Fault and ruptures south, the other at the south end rupturing north, and one in the middle rupturing bidirectionally. The middle one affects the entire Bay Area relatively equally, rather than aiming its directionality at Silicon Valley or Napa Valley. So let us consider that one, which Aagaard et al. (2010a, pg 2398) label "HS+HN G04 HypoO," meaning Hayward South and Hayward North segments, slip distribution model G04 (having to do with magnitude), and hypocenter under Oakland. Its ground motion, expressed in terms of 5% damped elastic spectral acceleration response at 0.3-second period, is shown in Figure 1.

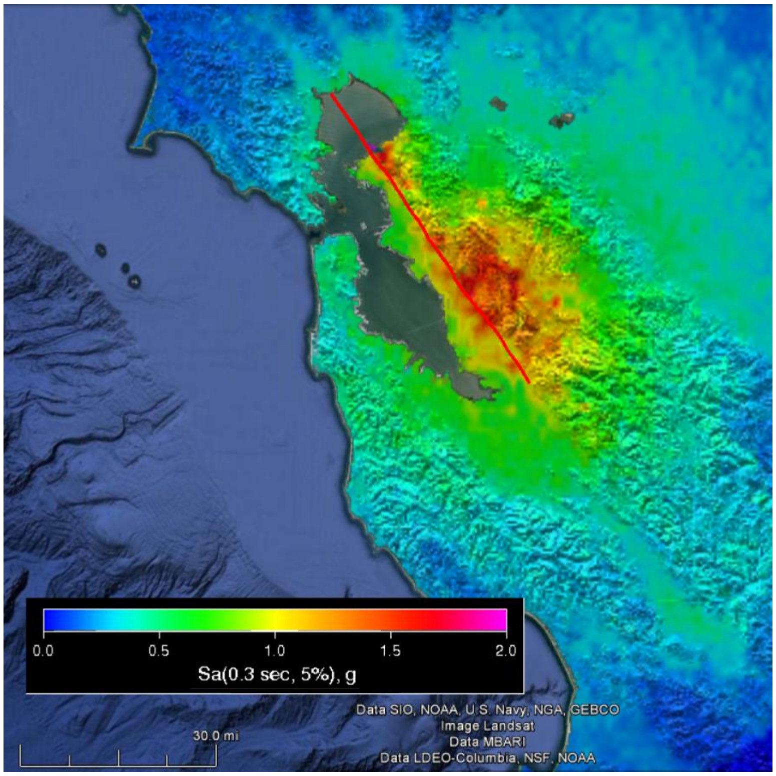


Figure 1. Scenario shaking in terms of 5% damped elastic spectral acceleration response at 0.3-second period

Building collapse

To estimate search and rescue demands, one must first estimate building collapse. How shall we do that? Two options present themselves: use Hazus-MH, or use the collapse model offered by Luco et al. (2007) and FEMA P-695 (Applied Technology Council 2009). Hazus-MH offers the advantages of relative familiarity and ease of use. But its collapse model draws heavily on expert opinion and largely lacks validation. The alternative relies on the common simplification of collapse capacity as lognormally distributed. Its parameters are derived from incremental dynamic analysis of a wide variety of hypothetical buildings, as in FEMA P-695. It offers the advantage of a strong and well documented analytical basis and much broader acceptance by the engineering community. It has, after all, formed the basis for the design maps that appeared in ASCE 7-10 (American Society of Civil Engineers 2010) and were adopted by reference in the International Building Code (International Code Council 2012). The disadvantage of the approach is that it only reflects modern, code-compliant buildings, not the actual mix of old and new that constitute the real building stock of the Bay Area. However, in light of the fact that the old mix will eventually be replaced with new (at a rate of about 1% per year), one could view an estimate of building collapse based on Luco et al. (2007) and FEMA P-695 as better reflecting real buildings in the coming decades. Let us choose that model therefore, in which collapse probability for any given building is estimated as in Equation (1):

$$P = \Phi\left(\frac{\ln\left(s/\theta\right)}{\beta}\right) \tag{1}$$

In the equation, Φ denotes the standard normal (Gaussian) cumulative distribution function of the value in parentheses, *s* denotes the ground motion (however measured) of at building's location, θ denotes the ground motion associated with 50% collapse probability, and β denotes the standard deviation of the natural logarithm of ground motion that causes collapse (sometimes called dispersion by other authors). Luco et al. (2007) examined a range of values for β and selected 0.8 as reasonable, and established FEMA P-695 suggests that collapse probability is below 10% at shaking equal to that of the maximum considered earthquake (MCE), or in terms of ASCE 7-10, the risk-targeted maximum considered earthquake (MCE_R). In other work (Porter 2015) I show that evidence from FEMA P-695 suggests a 6% expected collapse probability (as opposed to a 10% upper bound). Together, these two parameter values equate with a median collapse capacity $\theta = 3.47 \cdot s_{MCER}$, where s_{MCER} denotes the ground motion associated with MCE_R shaking, whether in terms of 5% damped spectral acceleration response at 0.2-second or 1.0-second period. It is available on a gridded basis from the US Geological Survey. One can adjust s_{MCER} to create a map of MCE_R that accounts for site soil conditions using maps of mean shearwave velocity in the upper 30 m of soil (Vs30) available from OpenSHA (www.opensha.org). FEMA has estimated California's current building stock (or at least that of 2010;

D. Bausch oral comm., 6 May 2016), which means an estimate of the number and quantity of buildings by census area.

To apply this information to the scenario earthquake, I created a map of soil-adjusted s_{MCER} in the Bay Area and normalized the shaking shown in Figure 1 by s_{MCER}. Let us refer to the ratio s/s_{MCER} as demand-to-design ratio, *DDR*. With ground motion measured in terms of DDR, θ = 3.47. Evaluating Equation (1) on a 0.02-degree grid produces the map of collapse probability shown in Figure 2.

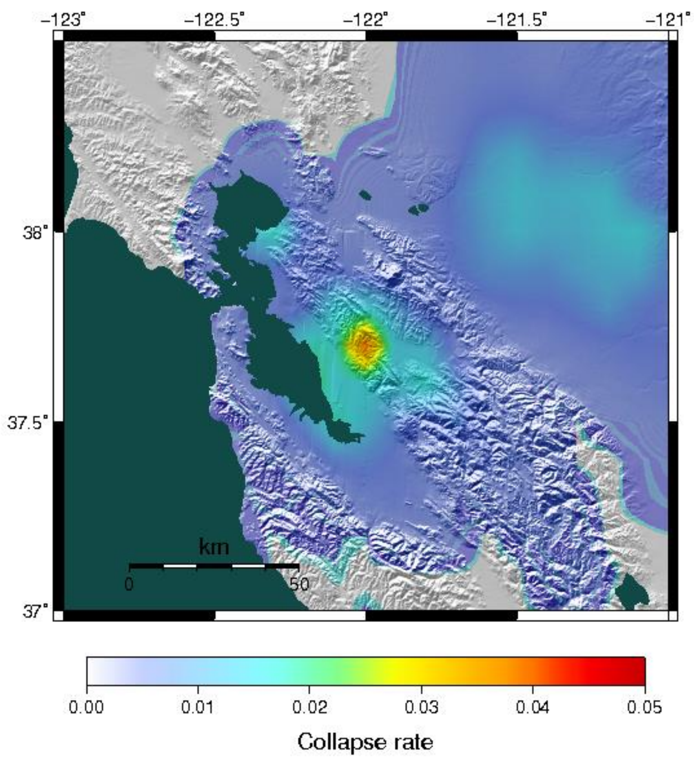


Figure 2. Collapse rate under Mw 7.0 Hayward Fault scenario

Bausch's inventory data. Let N_i denote the estimated number of buildings in census area i, and let s_i denote the ratio s/s_{MCER}, where s denotes the Using this latter approach therefore, I estimated the number of collapsed buildings in the scenario earthquakes to be N_b = 7,800, if all buildings were to perform as well as modern (code-compliant) buildings as estimated by a recent FEMA study (Applied Technology Council, 2009).

California is home to 38 million people and approximately 11 million buildings, or approximately 3.5 people per building. If 80 percent of people were indoors at the time of the earthquake (which seems realistic at 4:18 p.m. on a workday and consistent with Hazus-MH on an overall average basis), then there would be an average of about $O(t)$ = 2.8 occupants in each collapsed building at 4:18 p.m. As previously observed, the overall average fraction of building area that experiences collapse can be taken as $A \approx 0.25$. The overall average fraction of occupants in the collapsed area requiring USAR extrication can be taken as $E \approx 0.66$. Thus, if all buildings in the Bay Area just met current code requirements, equation 3 can estimate the number of people trapped in collapsed buildings.

$$
\begin{aligned}
N_c(t) &= N_b \cdot O(t) \cdot A \cdot E \\
&= 7{,}800\,\text{buildings} \cdot 2.8\,\tfrac{\text{people}}{\text{building}} \cdot 0.25 \cdot 0.66 \\
&= 3{,}600\,\text{people}
\end{aligned}
$$

That is, by the Safe Enough approach, I estimate 3,600 people trapped in 7,800 collapsed buildings. (Many buildings with collapse would not have people trapped in them requiring USAR assistance.)

People Trapped in Collapsed Buildings, Based on Hazus-MH

Hazus-MH does not estimate the number of people trapped in collapsed buildings, but it does estimate the number of buildings in the complete structural damage state and the fraction of their area that experiences collapse, the product of which we can take as $N_b \cdot A$. Applying the values of E, estimated here by structural material, and applying a uniform occupant load of 2.8 occupants per collapsed building, we can estimate

$$N_c(t) = O(t) \cdot \sum_i \left(\left(N_{b,i} \cdot A_i \right) \cdot E_i \right) \tag{10}$$

where i is an index for the structural materials, $N_{b,i} \cdot A_i$ is taken as the product of Hazus-MH's estimated number of buildings in the complete damage state and its estimate of the fraction of that building area that collapses, and E_i is the fraction of occupants requiring extrication for structural material i, from table 2. In unpublished work, Bausch used Hazus-MH to estimate the number of buildings in the complete structural damage state in this scenario earthquake (D. Bausch, written commun., 20 June 2014). See table 4 for results.

Table 4. People trapped in collapsed buildings, using Hazus-MH building damage estimates.

Material	Number in complete structural damage state	Fraction of area collapsed, given complete damage	E	$O(t)$	N_c
Wood	4,946	0.03	0.66	2.8	274
Steel	1,595	0.05	0.66	2.8	147
Concrete	1,241	0.10	0.94	2.8	327
Precast	71	0.15	0.10	2.8	3
RM	725	0.10	0.66	2.8	134
URM	639	0.15	0.98	2.8	263
MH	4,340	0.03	0	2.8	0
Total					**1,148**

How many buildings would Hazus-MH estimate had collapsed? Hazus-MH does not provide that estimate, but we can infer:

$$M_c = \sum_i \frac{M_{compl,i} \cdot f_{coll|compl,i}}{A_i} \tag{11}$$

where $M_{compl,i}$ denotes Hazus-MH's estimate of the number of buildings of structural material i in the complete structural damage state (column 2 in table 4); $f_{coll|compl,i}$ denotes the fraction of area collapsed, given that it is in the complete damage state (column 3 in table 4); A_i is the fraction of building area that collapses (from table 2); and i is an index for structural material. See table 5 for results.

Table 5. Number of collapsed buildings, using Hazus-MH building damage estimates.

Material	Number in complete structural damage state	Fraction of area collapsed, given complete damage	Fraction of area collapsed in collapsed buildings	Collapsed buildings
Wood	4,946	0.03	0.17	873
Steel	1,595	0.05	0.23	347
Concrete	1,241	0.10	0.50	248
Precast	71	0.15	0.17	63
RM	725	0.10	0.28	259
URM	639	0.15	0.28	342
MH	4,340	0.03	0.00	
Total				**2,132**

Thus, one can infer from the combination of Hazus-MH's damage estimates and the observations of collapsed buildings made here that a M_w 7.0 earthquake on the Hayward Fault would trap approximately 1,100 people in 2,100 collapsed buildings.

Scenario Estimate of People Trapped in Collapsed Buildings

Thus, using Hazus-MH damage estimates, 1,100 people are trapped in 2,100 collapsed buildings, whereas by the Safe Enough approach, 3,600 people are trapped in 7,800 collapsed buildings. That the two approaches differ by a factor of 3 essentially means that they agree within a half order of magnitude, which in the present state of loss modeling represents reasonable agreement.

The agreement is actually poorer than that, however, because the Safe Enough figures represent the expected behavior of post-1980 construction, and the Hazus-MH estimates are of the existing building stock, of which 60 to 70 percent predates 1980. One would expect the Safe Enough estimates to be less than those of Hazus-MH, if both were correct. (They use the same inventory of buildings.) However, let us use their estimates as benchmarks, their range representing two approaches to a realistic answer, and their medians, 2,500 people trapped in 5,000 collapsed buildings (in round numbers), as realistic estimates for a M_w 7.0 earthquake on the Hayward Fault.

Number of People Trapped in Stalled Elevators

Let us turn now to the question of people trapped in elevators. In a large Bay Area earthquake, power would be lost immediately throughout the Bay Area and return slowly as power plants are inspected, load is carefully restored, and damage is repaired. When power is lost, most elevators in the Bay Area (those that do not have emergency power) would stop, even before P-waves reached the elevators and triggered their ring-and-string safety devices. What would be the USAR impacts of that loss of power to elevators? How many people would be trapped in elevators with their doors closed, traveling between floors?

Considering a Bay Area population of 10 million, using the previously observed average of one elevator per 344 people, one can use equation 7 to estimate the number of elevators in the San Francisco Bay Area (V_m).

$$\begin{aligned} V_m &= \frac{P_m}{p} \\ &= \frac{10{,}000{,}000\,people}{344\,\frac{people}{elevator}} \\ &= 29{,}000\,elevators \end{aligned}$$

Subtracting 60 percent of the estimated 3,700 elevators in Bay Area high-rise buildings that have emergency power, and 2.5 percent of the remaining elevators and low- and mid-rise buildings with emergency power, an estimated 25,300 elevators in the Bay Area lack emergency power—let us estimate 25,000 in round numbers. Recall that the fraction of the time that an elevator that is in use with passengers in it is traveling between floors with the doors closed, $f_c \approx 0.3$. Let us assume that at peak hours (and 4:18 PM on a weekday seems like a peak hour), most elevators are in use and most are carrying passengers primarily in one direction, so let us assume $f_o(t) \approx 0.6$. Then by equation 8, the number of elevators stalled with people inside after a M_w 7.0 earthquake on the Hayward Fault can be estimated as

$$
\begin{aligned}
V_0(t) &= V_m \cdot f_o(t) \cdot f_c \cdot (1 - f_b) \\
&= 25{,}000 \cdot 0.6 \cdot 0.3 \\
&= 4{,}500\, elevators
\end{aligned}
$$

And as previously noted, the average elevator carries $d = 5$ people when occupied, so one can use equation 9 to estimate N_e, the number of occupants trapped in elevators by a M_w 7.0 earthquake on the Hayward Fault.

$$
\begin{aligned}
N_e &= V_o(t) \cdot d \\
&= 4{,}500\, elevators \cdot 5 \tfrac{occupants}{elevator} \\
&= 22{,}500\, occupants
\end{aligned}
$$

So in round numbers, it seems realistic that on the order of 22,000 people could be trapped in 4,500 elevators by the sudden loss of electric power after a M_w 7.0 earthquake on the Hayward Fault, requiring fire department assistance to escape. (Untrained first responders will be unable to assist the people trapped in elevators because technical skills and equipment are required to extract people from elevators.)

It is possible to retrofit some existing elevators with emergency power to reduce the demand for elevator rescue. Kornfield (written commun., 2015) estimates the cost of retrofitting elevators to be on the order of $20,000 per elevator, and only 30 to 40 percent of elevators in the Bay Area could be retrofitted, so retrofit could reduce elevator entrapment to 14,000 people in 3,000 stalled elevators.

Can nothing be done to enable those 14,000 people to escape older elevators? Elevators are equipped with devices called door interlocks that prevent the door from opening except at or very near a floor. Such devices prevent people falling down an open elevator shaft whether by entering the shaft from a floor through an open door, or by falling under the elevator while trying to exit an elevator that is not at floor level. They ensure that both inner and outer doors are closed before the elevator can move. Door interlocks vary between manufacturers and elevator models. They can be mechanical, electrical, or both, and can have two or more levels of redundancy so that a single electrical short circuit cannot result in the interlock being defeated and the elevator being allowed to move with the doors open, or the elevator door being opened when the elevator is not at a floor. Research is needed to deal with the variety of elevator door interlocks and the safety issues involved in allowing people to open elevator doors between floors.

Conclusions

USAR Demands Under As-Is Conditions

There are currently no public models of urban search and rescue demands for earthquakes. While engineers can estimate the number of buildings that collapse in an earthquake, we do not know what fraction of building area experiences collapse when at least some collapse occurs, nor do we know what fraction of occupants in those collapsed areas require extrication by urban search and rescue personnel.

To estimate the search-and-rescue demands in a M_w 7.0 earthquake on the Hayward Fault, I compiled a photographic database of 72 buildings known to have experienced at least some collapse (structural or nonstructural) in 10 California earthquakes in the last 50 years. These include all buildings with images in the NISEE e-Library whose description includes the word “collapse,” “fail,” “fell,” or “parapet,” plus 12 tilt-up buildings with roof collapse documented in a NOAA report on the 1971 San Fernando earthquake and one collapse from the 2014 South Napa earthquake. Slightly over half of these were wood frame buildings, 13 were unreinforced masonry, and 9 were of reinforced concrete. I found that on average, about 25 percent of the total square footage collapses, given that at least some collapse occurs. The fraction varies by structural material, from about 17 percent (tilt-up concrete and wood) to about 50 percent (cast-in-place reinforced concrete). I also estimated the fraction of occupants in the collapsed area who would require USAR assistance by various levels of technical expertise, based on CERT training guidelines. Applying the observations from these historic California building collapses, I estimated that on the order of 2,400 people could realistically require extrication from on the order of 5,000 collapsed buildings. Older buildings are generally more likely to collapse, so the trapped population will tend to be in older buildings.

There is no public model of USAR demands resulting from power loss to elevators. However, using relevant estimates of the total number of elevators nationwide and local experts’ observations that few Bay Area elevators have emergency power, I estimated that on the order of 22,000 people would be trapped in 4,500 stalled elevators.

USAR Demands Under Ideal-World Conditions

In other work that examines this hypothetical M_w 7.0 earthquake on the Hayward Fault, I estimated that the number of collapsed buildings could be reduced by a factor of four if all buildings were designed with an earthquake importance factor of $I = 1.5$ (as defined in American Society of Civil

Engineers 2010). Doing so would reduce the number of people trapped in collapsed buildings proportionately, from 2,500 people trapped in 5,000 collapsed buildings to perhaps 600 people trapped in 1,200 collapsed buildings. Retrofit of newer elevators with emergency power could reduce elevator entrapment to 14,000 people in 3,000 stalled elevators.

Limitations

Other buildings have collapsed in California earthquakes over the last 50 years that do not appear in the NISEE e-Library or the other sources examined here. The distribution of affected area in these images may be biased relative to the distribution of affected area in the population of collapsed buildings, for example, if photographers who contributed to the NISEE e-Library preferred to photograph buildings with more or less affected area than they would have done of they selected collapsed buildings at random to photograph. Absent a big California earthquake in which one can deliberately select collapsed buildings to examine in an unbiased way, I do not know how to test whether the photographers were biased in this way. However, the presence of numerous buildings with affected areas across the entire possible range of 0 to 100 percent shows that the observations are at least diverse, even if their representativeness cannot be known without more data. I find the database sufficiently useful for estimating the distribution of affected area, at least until better data—more definitely representative—come along. Some readers may object that the buildings shown here do not comprise an exhaustive list of collapsed California buildings, but few surveys are exhaustive. Samples commonly provide useful statistical information.

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Appendixes. National Information Service for Earthquake Engineering (NISEE) E-Library Images of Building Collapse in California, 1965–2014

This appendix presents images of building collapse caused by earthquakes in California in the past 50 years. The appendix is organized by earthquake in chronological order, beginning with the Borrego Mountain earthquake of 1968. Within each section, collapses are documented with their descriptions and the other metadata, followed by the author's estimate of the affected area, and then images of the collapse. Unless noted otherwise, metadata and images are copied from the NISEE e-Library. Permission for their use is granted at http://nisee.berkeley.edu/elibrary/about.html.

Abbreviations used in the appendixes—ft, feet; ft^2, square feet; in., inch; %, percent, Calif., California; St., Street, Ave., Avenue; Rd., Road.

Appendix 1. Santa Rosa (1969) Collapse Images

Image Metadata and Description

Karl V. Steinbrugge Collection: S3715, S3716

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Oct. 1, 1969; 5.59	Damage to wood frame house in the fault zone	Steinbrugge, Karl V.	1969-10-06	NORTH AMERICA/Sonoma County/United States/Santa Rosa/California	Two-story wood frame building off foundations. Foundations were rotted and poorly braced. Gas lines ruptured when house fell. 718 Beaver Street, Santa Rosa, California.

Author's Estimate of Affected Area

0%

Figure 1–1. Image showing two-story wood frame house collapsed in the 1969 Santa Rosa, California, earthquake.

Image Metadata and Description

Karl V. Steinbrugge Collection: S3726

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Oct. 1, 1969; 5.59	Damage to wood frame house in the fault zone	unknown	1969-10	Santa Rosa/California/NORTH AMERICA/Sonoma County/United States	Miramar Building. Collapsed portion of a wall fell on a car. 203 Old Courthouse Square, Santa Rosa, California.

Author's Estimate of Affected Area

Plan area ≈ 13,000 ft^2 × 3 stories. Area littered by bricks ≈ 25 ft × 15 ft = 1% of 39,000 ft^2.

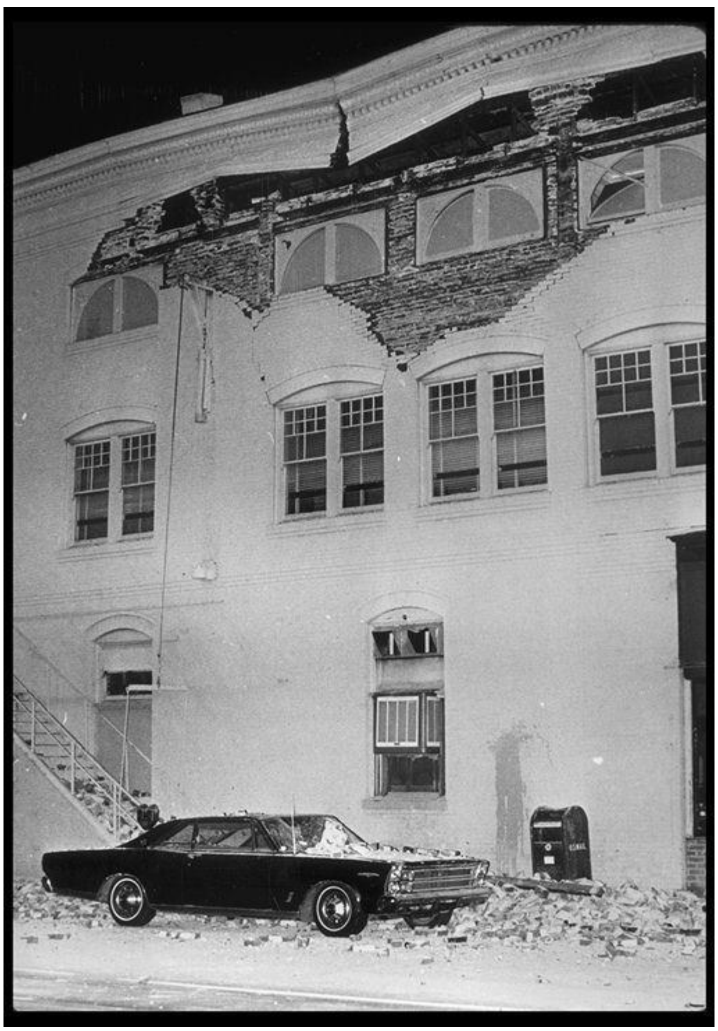


Figure 1–2. Image showing part of a wall collapsed onto a car in the 1969 Santa Rosa, California, earthquake.

Appendix 2. San Fernando (1971) Collapse Images

Image Metadata and Description

Karl V. Steinbrugge collection: S4473

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Feb. 9, 1971; 6.6	Damage to wood frame house in the fault zone	Steinbrugge, Karl V.	1971-02-16	NORTH AMERICA/Los Angeles County/United States/San Fernando/California	Damage to porches (probable cripple wall failure); chimney fell away from house. In the vicinity of Knox and Orange Grove Streets, in the fault zone.

Author's Estimate of Affected Area

Approximately (120 ft^2 porch)/(1,500 ft^2 house) = 8.0%.

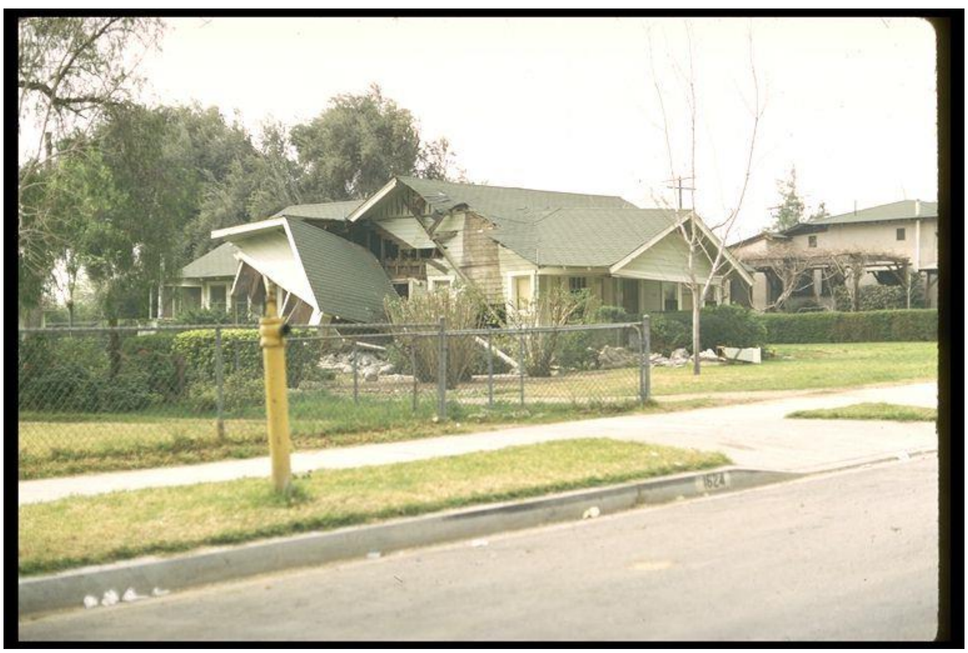


Figure 2–1. Image showing damage to a wood frame house in the 1971 San Fernando, California, earthquake.

Image Metadata and Description

Karl V. Steinbrugge Collection: S4533, S4534

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Feb. 9, 1971; 6.6	Chimney damage	Schader, Eugene E.	--	NORTH AMERICA/Los Angeles County/United States/California	Chimney fell towards otherwise undamaged wood frame house.

Author's Estimate of Affected Area

0%

Figure 2–2. Image showing chimney damage in the 1971 San Fernando, California, earthquake.

Image Metadata and Description

Karl V. Steinbrugge collection: S4581

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Feb. 9, 1971; 6.6	Furniture store	Schader, Eugene E.	1971-02-16	United States/San Fernando/California/NORTH AMERICA/Los Angeles County	Furniture store. Unreinforced masonry parapet has collapsed, dumping bricks into the street and on to the sidewalk. Large plate-glass windows are gone, presumably shattered by the earthquake. San Fernando, California.

Author's Estimate of Affected Area

Plan area ≈ 40 ft × 60 ft (?); area littered by bricks ≈ 30 ft × 15 ft = 19%.

Figure 2–3. Image showing furniture store damage in the 1971 San Fernando, California, earthquake.

Image Metadata and Description

Karl V. Steinbrugge collection: S4597, S4598, S4599, S4600, S4601, S4602.

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Feb. 9, 1971; 6.6	Apartments over retail space	Steinbrugge, Karl V.	--	United States/San Fernando/California/NORTH AMERICA/Los Angeles County	Apartments over retail space. Note that the failure of the nonreinforced bearing walls did not result in collapse. Unit masonry construction, built prior to 1933. Downtown San Fernando commercial area.

Author's Estimate of Affected Area

Plan area: 50 ft × 75 ft × 3 stories; masonry littering 250 ft (?) × 15 ft (?) = 3%.

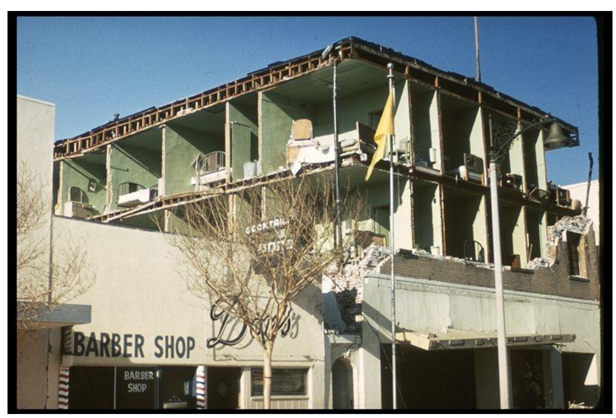


Figure 2–4. Images showing damage to apartments over retail space in the 1971 San Fernando, California, earthquake.

Image Metadata and Description

Karl V. Steinbrugge Collection: S4624, S4625

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Feb. 9, 1971; 6.6	Roof to the wall failed first	Steinbrugge, Karl V.	1971-02-18	NORTH AMERICA/Los Angeles County/United States/Los Angeles/California	Roof to the wall failed first. Ground cracks in the vicinity. Rear wall bulged out and rear roof fell. See S4625–4633. Light industrial buildings. Bradley Tract.

Author's Estimate of Affected Area

No long shots show the length of any wall, address, or way to estimate overall size of the building. Benfer and Coffman (1973, p. 123) show 14 tilt-up buildings in the Bradley Tract with this kind of failure, including the one pictured in S4624. Steinbrugge's photos seem to show a building on the north side of an east-west street, with failure on along the entire north wall and on the southwest bay. That only matches one building: 12884 Bradley Avenue, 131.5 ft wide (east-west) and 276 ft north-south, for a total floor area of 36,294 ft^2. Collapses appear to cover 26 ft × 26 ft on the southwest corner and 26 ft × 131 ft on the north wall. I estimate 26-ft bays because the panels look approximately square and 131 ft equals 5 bays plus two 6-inch panel thicknesses. Affected area: (6 × 26 ft × 26 ft)/(36,294 ft) = 11%. Other tilt-ups in the Bradley Tract: I extracted the map of tilt-up damage from Benfer and Coffman (1973, p. 123) and overlaid it in Google Earth Pro, measuring the collapsed area with Google Earth Pro's ruler tool. Results are shown in table 2–1.

Table 2–1. Collapsed tilt-up roofs in Bradley Tract, Los Angeles, in the 1971 San Fernando, California, earthquake.

[%, percent]

Address	Collapsed area, in square feet	Plan area, in square feet	Affected area, in percent
12840 Bradley Avenue	21,461	48,400	44%
12874 Bradley Avenue	2,460	21,000	12%
12884 Bradley Avenue	4,056	36,294	11%
12950 Bradley Avenue	3,060	30,240	10%
12881 Bradley Avenue	5,678	58,500	10%

Address	Collapsed area, in square feet	Plan area, in square feet	Affected area, in percent
12975 Bradley Avenue	18,180	77,600	23%
13001 Bradley Avenue	6,400	85,050	8%
13069 Bradley Avenue	7,030	45,000	16%
15200 Bledsoe Street	3,700	19,800	19%
15151 Bledsoe Street	4,050	51,800	8%
12860 San Fernando Road	4,650	29,340	16%
12806 San Fernando Road	11,260	63,400	18%
12744 San Fernando Road	26,600	101,400	26%
12814 Bradley Avenue	2,400	15,600	15%








Figure 2–5. Images showing damage to industrial buildings in Bradley Tract, Los Angeles, in the 1971 San Fernando, California, earthquake.

Image Metadata and Description

Karl V. Steinbrugge Collection: S4489

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Feb. 9, 1971; 6.6	Older wood frame house	Steinbrugge, Karl V.	1971	United States/San Fernando/California/NORTH AMERICA/Los Angeles County	Porch partial collapse on older wood frame house, probable cripple wall failure of house. Between Glen Oaks and Hubbard Streets.

Author's Estimate of Affected Area

Plan area ≈ 1,500 ft^2 (?); collapsed area where people could be trapped = 0%.

Figure 2–6. Image showing damage to industrial buildings in Bradley Tract, Los Angeles, in the 1971 San Fernando, California, earthquake.

Image Metadata and Description

Karl V. Steinbrugge collection: S4491, S4492

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Feb. 9, 1971; 6.6	Soft-story failure	Steinbrugge, Karl V.	--	United States/San Fernando/California/NORTH AMERICA/Los Angeles County	Pink structure at the rear was a residence over a garage. The first story collapsed, note remains of automobile under the building.

Author's Estimate of Affected Area

Building area = 30 ft × 20 ft (?) × 2; collapsed area = 30 ft × 20 ft (?) × 1 = 50%.

Figure 2–7. Images showing soft-story failure in the 1971 San Fernando, California, earthquake.

Image Metadata and Description

William G. Godden (Vol 4) Collection: GoddenJ53

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Feb. 9, 1971; 6.6	Split-level house, San Fernando Valley	Bertero, Vitelmo V.	--	United States/California/NORTH AMERICA	Collapse of a split-level wooden home. Large numbers of these split-level homes suffered significant damage because of a lack of adequate ties between the two levels. The upper level ripped away and crushed the lower garage walls, which did not have adequate lateral bracing.[1]

[1]Additional discussion of this image is available in Godden Set J: V. V. Bertero Introduction to Earthquake Engineering.

Author's Estimate of Affected Area

Building area ≈ 15 ft × 30 ft × 3; collapsed area ≈ 15 ft × 30 ft × 1 = 33%.

Figure 2–8. Image showing damage to a split-level house in the 1971 San Fernando, California, earthquake.

Image Metadata and Description

Karl V. Steinbrugge Collection: S4195

Earthquake date and magnitude	Title	Date	Source	Location	Description
Feb. 9, 1971; 6.6	Severe damage to masonry building	1971-02	Newsweek (copyright restricted)	United States/Los Angeles/California/NORTH AMERICA/Los Angeles County	Collapsed Semi-Ambulent Building, built in 1925, masonry construction. Structure: Veterans Administration Hospital (Sylmar).

Author's Estimate of Affected Area

Collapsed area: from this photo, it looks as if the lower story collapsed, so 50%.

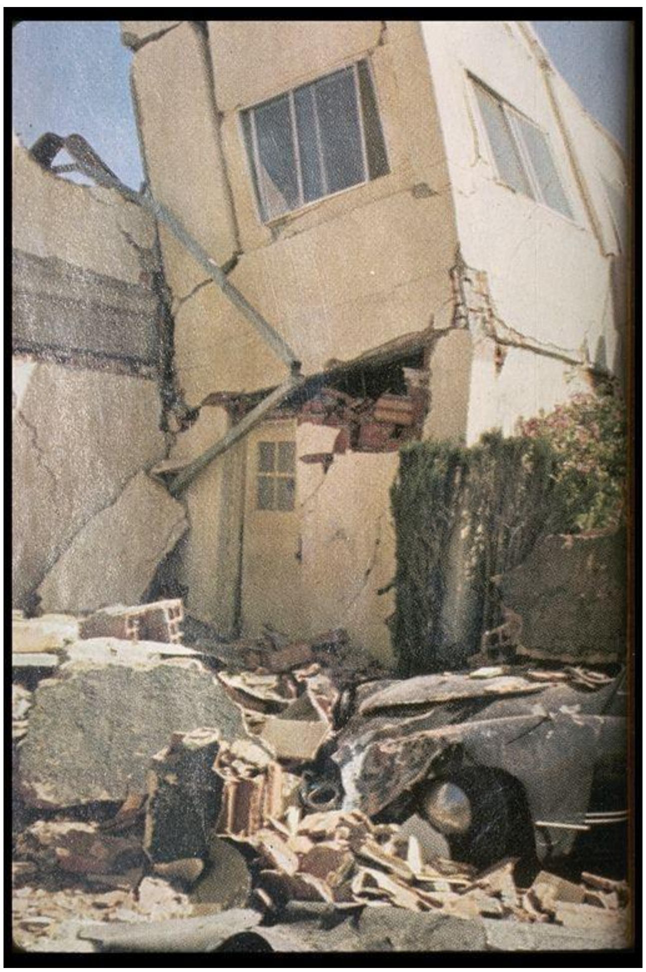


Figure 2–9. Image showing severe damage to masonry building at the Veterans Administration Hospital (Sylmar) in the 1971 San Fernando, California, earthquake.

Image Data and Description

The 1971 San Fernando earthquake (magnitude 6.7) collapsed four buildings at the San Fernando Veterans Administration Hospital complex, killing 47 people. The buildings had been built in 1925, before building codes were in effect. Image and description are from Wikimedia, accessed on December 19, 2005. Authors are Mehmet Çelebi and Robert Page of the U.S. Geological Survey.

Author's Estimate of Affected Area

The view is from the west. The Semi-Ambulent Building was a long building oriented east to west, the second building from the south (that is, second from right), in the middle of the photo. Portions of the building are leaning at various angles to the north. The wing is a complete loss, but it appears as if it did not pancake. The estimate of 50% from NISEE S4195 seems reasonable.

Figure 2–10. Images showing four collapsed buildings at the San Fernando Veterans Administration Hospital complex in the 1971 San Fernando, California, earthquake.

Image Metadata and Description

Karl V. Steinbrugge Collection: S4529

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Feb. 9, 1971; 6.6	Damage to older dwellings	Olson, Robert A.	--	United States/California/NORTH AMERICA/Los Angeles County	Damage to older house caused by cripple wall collapse.

Author's Estimate of Affected Area

Although the cripple wall collapsed, the living space does not appear to have experienced any drop in a roof or ceiling relative to the floor, so 0%.

Figure 2–11. Image showing damage to older dwellings in the 1971 San Fernando, California, earthquake.

Image Metadata and Description

Karl V. Steinbrugge Collection: S4065

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Feb. 9, 1971; 6.6	Collapsed tower at southeast corner	Steinbrugge, Karl V.	--	United States/Sylmar/California /NORTH AMERICA/Los Angeles County	Collapsed tower at southeast corner. Olive View Hospital. Rear (east) elevation of Medical Treatment Building. Structure: Olive View Medical Treatment Building.

Author's Estimate of Affected Area

See next image.

Figure 2–12. Image showing collapsed tower at Olive View Hospital, Sylmar, in the 1971 San Fernando, California, earthquake.

Image Data and Description

San Fernando earthquake, February 1971, California. Fallen, structurally separated stair tower and leaning north stair tower (left) at Olive View Hospital. Emergency vehicles are visible in the foreground. View is from the west. Image and description are from Wikimedia, accessed on June 24, 2003.

Author's Estimate of Affected Area

Each wing appears to be approximately 240 ft × 50 ft × 5 stories × 4 wings = 240,000 ft^2. The collapsed stair towers appear to be approximately 20 ft × 40 ft × 5 stories × 2 towers = 8,000 ft^2, or 3.3%.

Figure 2–13. Image showing collapsed and leaning stair towers at Olive View Hospital, Sylmar, in the 1971 San Fernando, California, earthquake.

Image Metadata and Description

Karl V. Steinbrugge collection: S4070,

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Feb. 9, 1971; 6.6	Ambulance garage collapsed	Steinbrugge, Karl V.	--	United States/Sylmar/California/ NORTH AMERICA/Los Angeles County	Ambulance garage collapsed. Olive View Hospital. Southern elevation of Medical Treatment Building. See also S4139–44. Structure: Olive View ambulance garage.

Author's Estimate of Affected Area

By inspection (an engineering term meaning "just by looking at it"), 100%.

Figure 2–14. Image showing a collapsed ambulance garage at Olive View Hospital, Sylmar, in the 1971 San Fernando, California, earthquake.

Image Metadata and Description

Karl V. Steinbrugge Collection: S4115

Earthquake date and magnitude	Title	Creator	Location	Description
Feb. 9, 1971; 6.6	Olive View Psychiatric Building	Steinbrugge, Karl V.	United States/Sylmar/California/ NORTH AMERICA/Los Angeles County	Soft-story collapse, most evident at upper right of photo. Originally a one- and two-story building, irregular in plan, the first story collapsed in the earthquake. Structure: Olive View Medical Center, Calif.

Author's Estimate of Affected Area

Collapsed area: it appears as of the first story was about twice the area of the second, and all of the area of the first story has collapsed, so 67%.

Figure 2–15. Image showing soft-story collapse of Psychiatric Building at Olive View Hospital, Sylmar, in the 1971 San Fernando, California, earthquake.

Image Metadata and Description

Karl V. Steinbrugge Collection: S4117

Earthquake date and magnitude	Title	Creator	Location	Description
Feb. 9, 1971; 6.6	Psychiatric Building collapsed	Olson, Robert A.	United States/Sylmar/California/ NORTH AMERICA/Los Angeles County	West elevation, Psychiatric Building. This was a two-story building—the first story collapsed. Olive View. Structure: Olive View Medical Center, Calif.

Author's Estimate of Affected Area

This is another view of the previous building.

Figure 2–16. Image showing first story collapse of Psychiatric Building at Olive View Hospital, Sylmar, in the 1971 San Fernando, California, earthquake.

Image Metadata and Description

Karl V. Steinbrugge collection: S4519

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Feb. 9, 1971; 6.6	Collapsed wood frame house	Steinbrugge, Karl V.	1971-02-16	United States/Sylmar/California/ NORTH AMERICA/Los Angeles County	Collapsed wood frame house under construction on Tucker Street near Pacoima Dam.

Author's Estimate of Affected Area

There is no other view of this house. It looks as if the garage (front left) and perhaps half of the living space (in the rear) at least partially collapsed, so say 67%.

Figure 2–17. Image showing a collapsed wood frame house in the 1971 San Fernando, California, earthquake.

Image Metadata and Description

Karl V. Steinbrugge collection: S4501

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Feb. 9, 1971; 6.6	Soft-story failure	Steinbrugge, Karl V.	1971	United States/Sylmar/California/ NORTH AMERICA/Los Angeles County	Two-story section over garage of this wood frame house on Almetz Street has collapsed in the first story. In a new housing tract in Sylmar at base of hills and between Olive View and Veterans Administration Hospitals.

Author’s Estimate of Affected Area

There are no other views of this house. Judging by the description, this building resembled S4514 in layout, so say again 33%.

Figure 2–18. Image showing soft-story failure in a wood frame house in the 1971 San Fernando, California, earthquake.

Image Metadata and Description

Robert A. Olson Collection: R0070

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Feb. 9, 1971; 6.6	VA Hospital	--	1971	--	Veterans Administration Hospital (Sylmar). Old masonry building in upper center of photo has completely collapsed. Constructed in 1925–1926, with major additions in 1938 and 1949, the entire complex was demolished after the 1971 earthquake, and the entire 97 acres were dedicated in 1977 as Veterans Memorial Park. Structure: Veterans Administration Hospital (Sylmar).

Author's Estimate of Affected Area

The collapsed building is the gray-roofed one, which appears to have been a one-story building whose entire area collapsed. 100%.

Figure 2–19. Image showing damage to the Veterans Administration Hospital, Sylmar, in the 1971 San Fernando, California, earthquake.

Appendix 3. Imperial Valley (1979) Collapse Images

Image Metadata and Description

Image Metadata and Description

Karl V. Steinbrugge Collection: S5584

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Oct. 15, 1979; 7.0	Cripple wall collapse	Hopper, Margaret G.	1979-10	United States/California/NORTH AMERICA/Imperial County	Cripple wall collapse—wood frame house on G Street.

Author's Estimate of Affected Area

By inspection, 0%.

Figure 3–2. Image showing cripple wall collapse on a wood frame house in the 1979 Imperial Valley, California, earthquake.

Image Metadata and Description

Karl V. Steinbrugge Collection: S5585

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Oct. 15, 1979; 7.0	Cripple wall collapse	Hopper, Margaret G.	1979-10	Brawley, Imperial County, Calif.	Cripple wall collapse—wood frame house on G Street.

Author's Estimate of Affected Area

By inspection, 0%.

Figure 3–3. Image showing cripple wall collapse on a wood frame house in the 1979 Imperial Valley, California, earthquake.

Appendix 4. Westmorland (1981) Collapse Images

Image Metadata and Description

National Oceanic and Atmospheric Administration National Centers for Environmental Information

Geologic Hazards Photos Volume 2 Earthquake Events

Earthquake date and magnitude	Title	Creator	Date	Location	Description
April 26, 1981; 5.6 (ML)	Westmorland 1981	Olsen, Robert O.	--	NORTH AMERICA/United States/California	View of a two-story building which partially collapsed in the earthquake. Note the undamaged one story building on the left. [Photo credit: California Governor's Office of Emergency Services Earthquake Program]

Author's Estimate of Affected Area

100%

Figure 4–1. View of a two-story building on West Main St, Westmorland after the April 26, 1981 Westmorland earthquake

Appendix 5. Coalinga (1983) Collapse Images

Image Metadata and Description

William G.Godden (Vol 4) Collection: GoddenJ19

Earthquake date and magnitude	Title	Creator	Date	Location	Description
May 2, 1983; 6.5	2-story building, Coalinga	Bertero, Vitelmo V.	--	NORTH AMERICA/United States/California	This two-story wood frame dwelling underwent a lateral displacement of more than half a meter, as illustrated by the slant in the porch columns, and also fell more than half a meter from its foundation, owing to lack of adequate anchorage and support.

Author’s Estimate of Affected Area

0%

Figure 5–1. Image showing lateral displacement of two-story wood frame dwelling in the 1983 Coalinga, California, earthquake.

Image Metadata and Description

William G.Godden (Vol 4) Collection: GoddenJ52

Earthquake date and magnitude	Title	Creator	Date	Location	Description
May 2, 1983; 6.5	Chimney collapse, Coalinga	Bertero, Vitelmo V.	--	United States/Coalinga/California/NORTH AMERICA/Fresno County	Chimney collapse of a modern house, 1983 Coalinga earthquake. Most of the chimneys were thrown down because of the lack of proper connections (straps) to the building.[1]

[1]Additional discussion of this image is available in Godden Set J: V. V. Bertero Introduction to Earthquake Engineering.

Author's Estimate of Affected Area

There are no other views of this building. Typical single-family dwelling is approximately 1,500 ft^2, but this one looks a little larger, say 50% larger or 2,250 ft^2. Bricks litter an area approximately 20 ft × 10 ft = 200 ft^2, or 9%.

Figure 5–2. Image showing chimney collapse of a modern house in the 1983 Coalinga, California, earthquake.

Image Metadata and Description

William G.Godden (Vol 4) Collection: GoddenJ23

Earthquake date and magnitude	Title	Creator	Date	Location	Description
May 2, 1983; 6.5	Collapse of wooden porch, Coalinga	Bertero, Vitelmo V.	--	United States/California/NORTH AMERICA	Collapse of a wooden porch (owing to lack of proper anchorage to the wooden frame of the house and of a proper later-resistant supporting system) was due to vibratory response during the 1983 Coalinga earthquake.[1]

[1]Additional discussion of this image is available in Godden Set J: V. V. Bertero Introduction to Earthquake Engineering.

Author's Estimate of Affected Area

There are no other views of this building. Typical single-family dwelling is approximately 1,500 ft^2.

This porch appears to have measured 12 ft × 20 ft, so 200 ft^2 / 1,500 ft^2 ≈ 15%.

Figure 5–3. Image showing collapse of a wooden porch in the 1983 Coalinga, California, earthquake.

Image Metadata and Description

William G.Godden (Vol 4) Collection: GoddenJ29

Earthquake date and magnitude	Title	Creator	Date	Location	Description
May 2, 1983; 6.5	Unreinforced brick building, Coalinga	Bertero, Vitelmo V.	--	United States/California/NORTH AMERICA	The second story, 8-in., unreinforced solid brick masonry walls of this commercial building in Coalinga collapsed, owing to inadequate tying at the floor, roof, and transverse walls.[1]

[1]Additional discussion of this image is available in Godden Set J: V. V. Bertero Introduction to Earthquake Engineering.

Author's Estimate of Affected Area

There are no other views of this building. It looks as if about half of the upper story of a two-story building collapsed (25%), plus bricks litter the perimeter, so say 30%.

Figure 5–4. Image showing collapse of an unreinforced brick building in the 1983 Coalinga, California, earthquake.

Image Metadata and Description

Robert A. Olson Collection: R0321

Earthquake date and magnitude	Title	Creator	Date	Location	Description
May 2, 1983; 6.5	Heavy wooden overhang fell on sidewalk	--	--	--	Heavy wooden overhang fell from storefront on to the sidewalk. Damaged concrete block wall at the right.

Author’s Estimate of Affected Area

No long shot to show how long the building is. No address. No estimate of affected area.

Figure 5–5. Image showing a heavy wooden overhang fallen onto sidewalk in the 1983 Coalinga, California, earthquake.

Image Metadata and Description

Robert A. Olson Collection: R0323

Earthquake date and magnitude	Title	Creator	Date	Location	Description
May 2, 1983; 6.5	Porch pulled away from church building	--	--	--	Porch running the full width of the church simply pulled away from the rest of the building. Built in 1946, the stabilized adobe building was heavily damaged, but did not collapse. On the corner of Jefferson St.

Author's Estimate of Affected Area

There are no other views of this building. Guess building area ≈ 30 ft × 00 ft = 2,700 ft^2, guess porch measured 20 ft × 10 ft = 7%.

Figure 5–6. Image showing porch pulled away from church building in the 1983 Coalinga, California, earthquake.

Image Metadata and Description

Karl V. Steinbrugge Collection: S5765

Earthquake date and magnitude	Title	Creator	Date	Location	Description
May 2, 1983; 6.5	Veneer also fell into the first story	Steinbrugge, Karl V.	1983-05-03	NORTH AMERICA/Fresno County/United States/Coalinga/California	Veneer also fell into the first story. All reinforced brick buildings in the downtown Coalinga area were demolished.

Author's Estimate of Affected Area

No long shots, no address, no estimate of affected area.

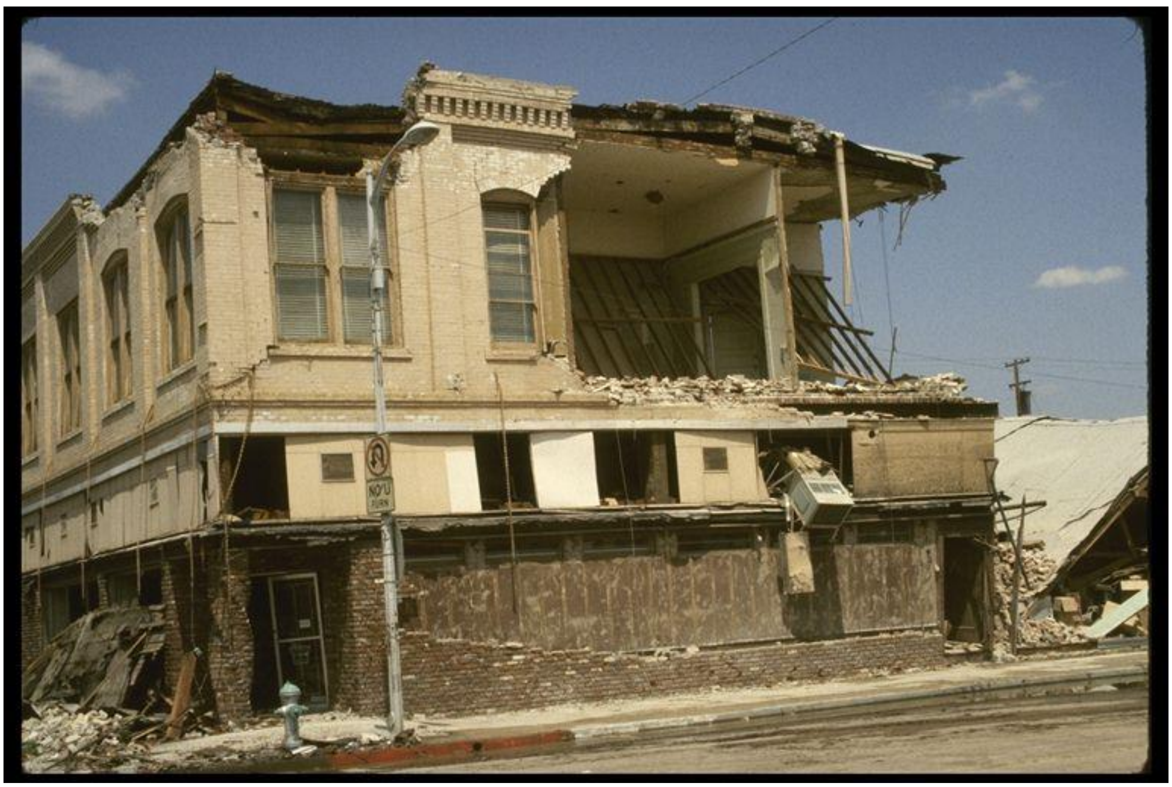


Figure 5–7. Image showing veneer fallen into first story of downtown building in the 1983 Coalinga, California, earthquake.

Image Metadata and Description

Karl V. Steinbrugge Collection: S5773

Earthquake date and magnitude	Title	Creator	Date	Location	Description
May 2, 1983; 6.5	Parapet damaged	Steinbrugge, Karl V.	1983-05-03	NORTH AMERICA/Fresno County/United States/Coalinga/California	Parapet damage. All reinforced brick buildings in the downtown Coalinga area were demolished. See S5828–5830 for "after" views.

Author's Estimate of Affected Area

Building was at E. Durian Avenue and Coalinga Plaza, Coalinga, Calif. (https://goo.gl/xddM2R), possibly 286 Coalinga Plaza. No old satellite imagery. No estimate of plan area. No estimate of effected area.

Figure 5–8. Image showing parapet damage to a building in downtown Coalinga in the 1983 Coalinga, California, earthquake.

Appendix 6. Morgan Hill (1984) collapse images

Image Metadata and Description

Karl V. Steinbrugge Collection: S5840

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Apr. 24, 1984; 6.19	Most severely damaged dwelling	Steinbrugge, Karl V.	1984-04-28	United States/Morgan Hill/California/NORTH AMERICA/Santa Clara County	Most severely damaged dwelling. Sheathing between first floor and foundation was fibreboard with little strength. Morgan Hill, Calif. Anderson Lake area.

Author's Estimate of Affected Area

By inspection, 0%.

Figure 6–1. Image showing the most severely damaged dwelling in the 1984 Morgan Hill, California, earthquake.

Image Metadata and Description

Karl V. Steinbrugge Collection: S5839

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Apr. 24, 1984; 6.19	Dwelling on the left moved due to landslide	Steinbrugge, Karl V.	1984-04-28	Morgan Hill/California/NORTH AMERICA/Santa Clara County/United States	Dwelling on the left moved, owing to landsliding from the earthquake. Morgan Hill, California. Anderson Lake area.

Author's Estimate of Affected Area

The right-hand image is from the FEMA National Earthquake Technical Assistance Training Program training slideset, entitled "Postearthquake Safety Evaluation of Buildings." Plan area from top to bottom floors appear to be 2:2:1. The bottom floor experienced some collapse, so say 20%.

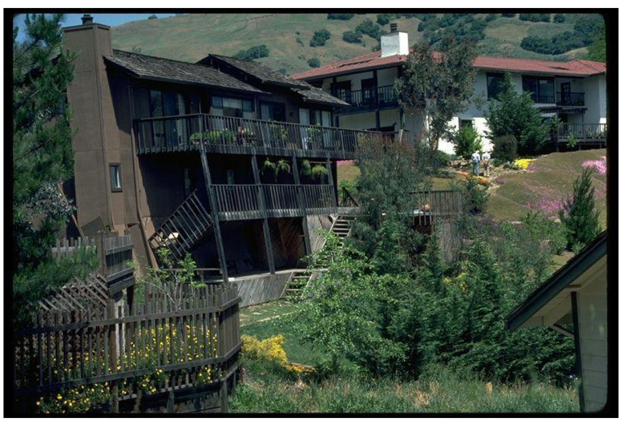


Figure 6–2. Images showing dwellings that have moved, owing to landslide. Left image shows dwelling movement in the 1984 Morgan Hill, California, earthquake. Right image is from the Federal Emergency Management Agency (FEMA) National Earthquake Technical Assistance Training Program training slide set, entitled "Postearthquake Safety Evaluation of Buildings." It is in the public domain.

Appendix 7. Whittier Narrows (1987) Collapse Images

Image Metadata and Description

Karl V. Steinbrugge Collection: S6014

Earthquake	Title	Creator	Date	Location	Description
Oct. 1, 1987; magnitude 6.0	Chimney collapsed	Steinbrugge, Karl V.	1987-10-03	United States/Whittier/California/ NORTH AMERICA/Los Angeles County	Damage to roof from chimney collapsing. Whittier, California.

Author's Estimate of Affected Area

By inspection, 0%.

Figure 7–1. Image showing damage to roof from collapsed chimney in the 1987 Whittier Narrows, California, earthquake.

Image Metadata and Description

Karl V. Steinbrugge Collection: S6023

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Oct. 1, 1987; 6.0	Chimney collapsed	Steinbrugge, Karl V.	1987-10-03	United States/Whittier/California/ NORTH AMERICA/Los Angeles County	Chimney collapsed away from the house. Whittier, California.

Author's Estimate of Affected Area

There are no other views of this house in adjacent records, so assume typical area 1,500 ft^2 and that bricks litter an area 5 ft × 10 ft = 3%.

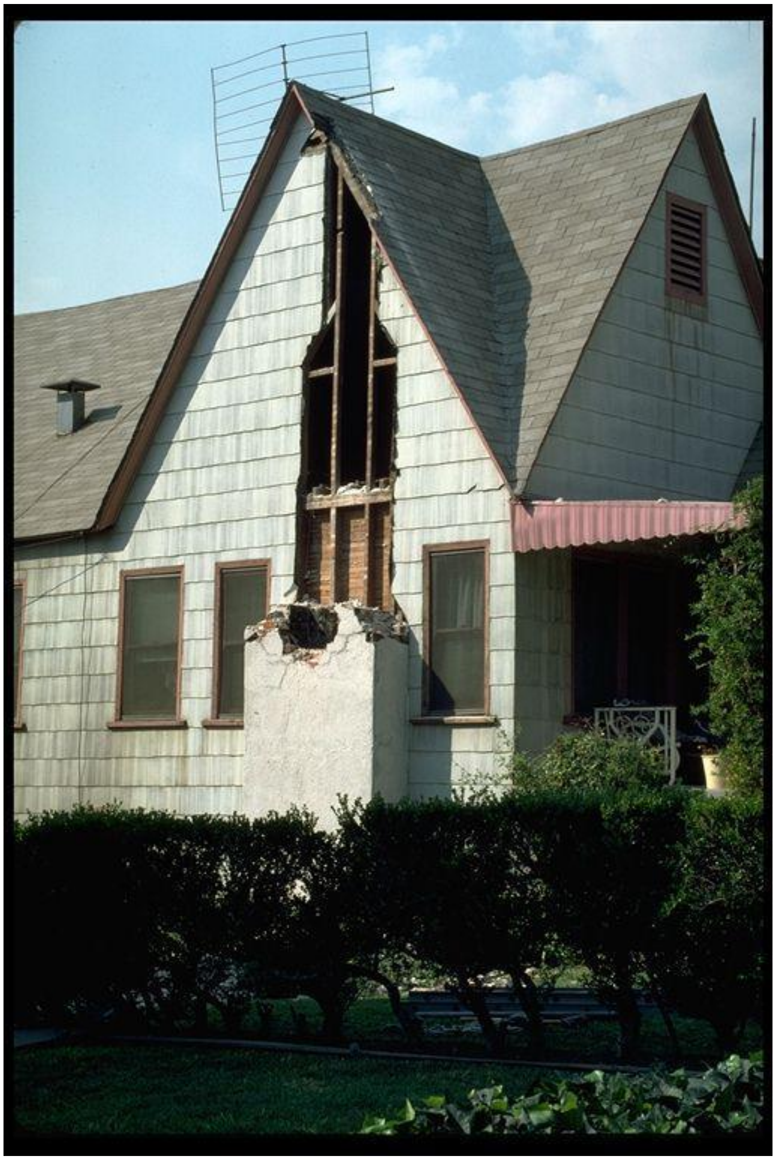


Figure 7–2. Image showing collapsed chimney in a house in Whittier in the 1987 Whittier Narrows, California, earthquake.

Image Metadata and Description

Karl V. Steinbrugge Collection: S6020

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Oct. 1, 1987; 6.0	Chimney collapsed	Steinbrugge, Karl V.	1987-10-03	United States/Whittier/California/NORTH AMERICA/Los Angeles County	Chimney fell through porch roof. See S6021 and s6040. Whittier, California.

Author's Estimate of Affected Area

House looks larger than typical: assume 3,000 ft^2. Bricks litter an area 8 ft × 8 ft = 2%.

Figure 7–3. Image showing collapsed chimney in the 1987 Whittier Narrows, California, earthquake.

Image Metadata and Description

Karl V. Steinbrugge Collection: S6022

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Oct. 1, 1987; 6.0	Chimney damage	Steinbrugge, Karl V.	1987-10-03	United States/Whittier/California/NORTH AMERICA/Los Angeles County	One chimney collapsed, but not the other. Whittier, California.

Author's Estimate of Affected Area

Assume typical plan area for single-family dwelling of 1,500 ft^2. Bricks litter an area approximately 5 ft × 10 ft = 3%.

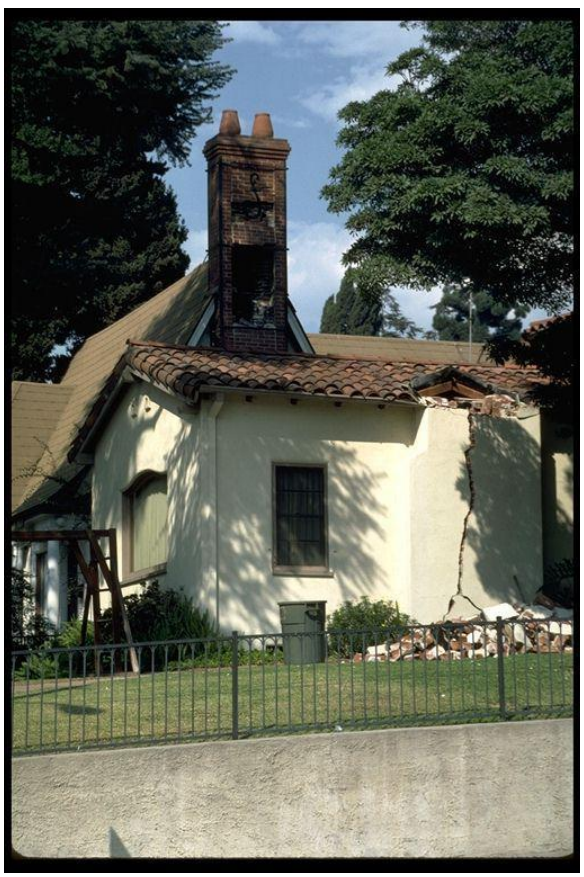


Figure 7–4. Image showing chimney damage in the 1987 Whittier Narrows, California, earthquake.

Image Metadata and Description

Karl V. Steinbrugge Collection: S6024–S6029

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Oct. 1, 1987; 6.0	May Company parking	Steinbrugge, Karl V.	1987-10-03	NORTH AMERICA/Los Angeles County/United States/Whittier/California	May Company parking structure. Roof failed; damage shown is from demolition. Whittier, California.

Author's Estimate of Affected Area

No long shots. Google Earth imagery does not date back to 1987, so there is no way to estimate total area of lot. No estimate of affected area.

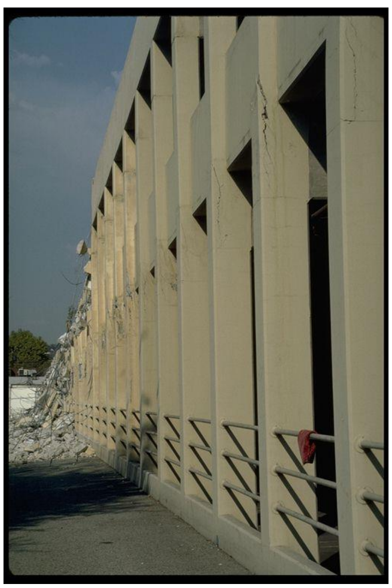


Figure 7–5. Image showing failure of parking structure roof in the 1987 Whittier Narrows, California, earthquake.

Appendix 8. Loma Prieta (1989) Collapse Images

Image Metadata and Description

Loma Prieta Blacklock Collection: LP0042

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Oct. 17, 1989; 7.09	Wall collapse in unreinforced masonry	Blacklock, James R.	1989	United States/Santa Cruz/California/NORTH AMERICA/Santa Cruz County	Wall collapse in unreinforced masonry (URM) building. Santa Cruz, California.

Author's Estimate of Affected Area

This is the historic Hihn Building, 1205 Pacific Avenue, Santa Cruz, CA 95060. The parcel (APN 00507517000) covers 8,180 ft^2 according to Google Earth. The building stood two stories tall in 1989. Total building area = 16,360 ft^2. Bricks litter an area about 16 ft × 12 ft, or 1%.

Figure 8–1. Photographs showing wall collapse in an unreinforced masonry (URM) building in the 1989 Loma Prieta, California, earthquake. Left image is from the Loma Prieta Blacklock Collection: LP0042. Right image shows a longer shot of the same building, copied from an article in the Press Democrat by Derek Moore, Oct 16, 2014, titled "Loma Prieta's legacy, 25 years later (w/video)" (http://www.pressdemocrat.com/news/2983451-181/loma-prietas-legacy-25-years).

Image Metadata and Description

Loma Prieta Blacklock Collection: LP0066

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Oct. 17, 1989; 7.09	Parapet and wall failures in bakery building	Blacklock, James R.	1989	NORTH AMERICA/Santa Cruz County/United States/Watsonville/California	Parapet and wall failures in bakery building. Watsonville, California.

Author's Estimate of Affected Area

15 E Beach Street (at Union Street), Watsonville, Calif. No long shot. No 1989 satellite imagery exists, so no there is no estimate of shape or size of the damaged building. No estimate of affected area.

Figure 8–2. Image showing parapet and wall failures in Watsonville in the 1989 Loma Prieta, California, earthquake.

Image Metadata and Description

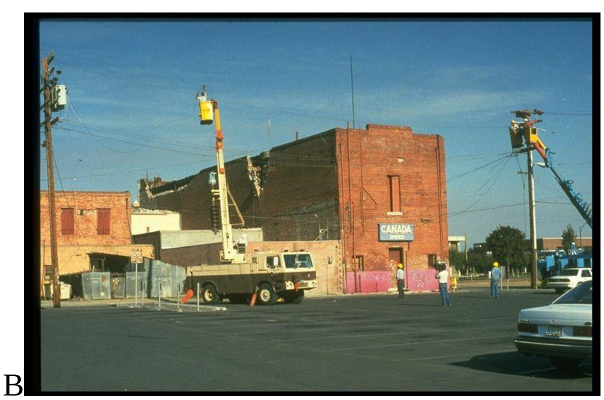
Loma Prieta Blacklock Collection: LP0070–LP0074

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Oct. 17, 1989; 7.09	Failed parapets on Main Street	Blacklock, James R.	1989	NORTH AMERICA/Santa Cruz County/United States/Watsonville/California	Older building with failed parapets on Main Street. Watsonville, California.

Author's Estimate of Affected Area

Two buildings area addressed here. The tall building labeled "Canada" on front and back appears to be 307 Main Street, Watsonville (see http://goo.gl/0TZmK5). According to Google Earth Pro, the lot at 307 Main Street measures 30 ft × 125 ft. The building (now removed) appears to fill the parcel, with a total building area of 7,500 ft^2. Collapsed parapet and second story wall appears to litter an area about 90 ft long (counting collapsed portions of both long walls, on the north and south sides) and perhaps 15 ft wide, for total affected area = (90 ft × 15 ft)/(7,500 ft^2) = 18%. The building with the collapsed parapet on its front facade appears to be located at what is now 311 Main Street, Watsonville, the middle one of three buildings on what is now one parcel. The center building appears to be about 65 ft wide, with the front 35 ft or so occupying two stories and the back 90 ft a single story. Bricks litter the 65 length by 15 ft, for an affected area of (65 ft × 15 ft)/(65 ft × 125 ft + 65 ft × 35 ft) = 9.4%.

A


B


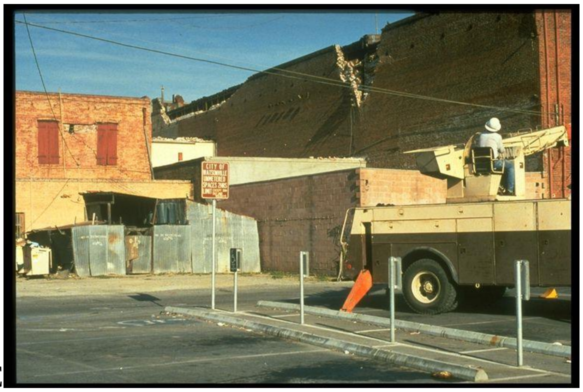
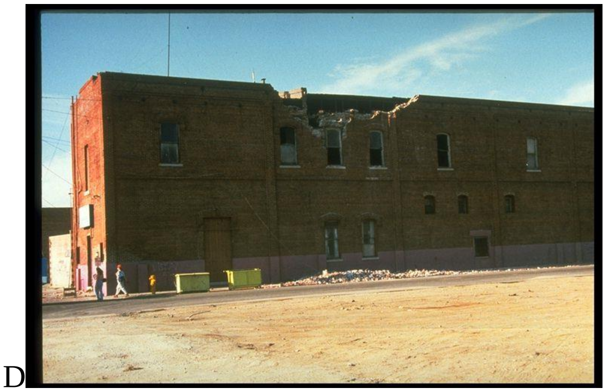
C  D 

Figure 8–3. Images showing failed parapets in Watsonville the 1989 Loma Prieta, California, earthquake: *A* The building at the far left is 307 Main Street; the building in the foreground is 311 Main Street. *B, C, D:* three views of the sides and rear of 307 Main Street

Image Metadata and Description

Loma Prieta Blacklock Collection: LP0080

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Oct. 17, 1989; 7.09	Failed brick parapet fell on sidewalk	Blacklock, James R.	1989	NORTH AMERICA/Santa Cruz County/United States/Watsonville/California	Damaged building near Main Street. Failed brick parapet fell on sidewalk

Author's Estimate of Affected Area

No address, no long shots. There is no way to tell how long this wall is or how deep the building is perpendicular to this wall. No estimate of affected area.

Figure 8–4. Image showing failed brick parapet fallen onto sidewalk in Watsonville in the 1989 Loma Prieta, California, earthquake.

Image Metadata and Description

Loma Prieta Blacklock Collection: LP0081–LP0085

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Oct. 17, 1989; 7.09	St. Patrick's Church	Blacklock, James R.	1989	NORTH AMERICA/Santa Cruz County/United States/Watsonville/California	Front view of damaged St. Patrick's Church. Watsonville, California.

Author's Estimate of Affected Area

Littered area ≈ 200 ft^2 at front (east) entrance, about 200 ft^2 at south transept, and 50 ft^2 at east end of north facade. Plan area ≈ 9,070 ft^2, and assume 1,000 ft^2 of additional galleries. Affected area ≈ (450 ft^2)/(10,000 ft^2) = 4.5%.



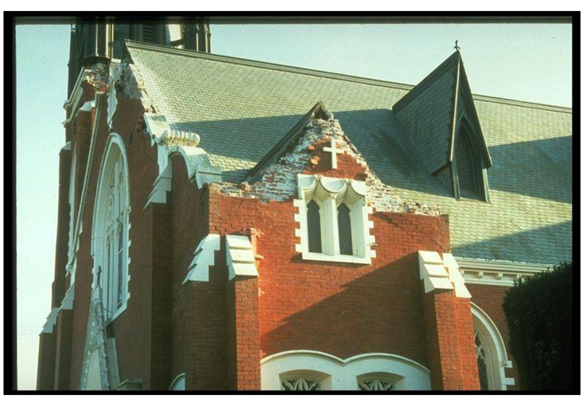



Figure 8–5. Images showing damage to St. Patrick's Church, Watsonville, in the 1989 Loma Prieta, California, earthquake.

Image Metadata and Description

Loma Prieta Blacklock Collection: LP0087

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Oct. 17, 1989; 7.09	Damaged bike store with failed parapet	Blacklock, James R.	Late 1989	NORTH AMERICA/Santa Cruz County/United States/Watsonville/California	Damaged bike store with failed parapet. Watsonville, California.

Author's Estimate of Affected Area

No other shots. No street name. Watsonville Cyclery is no longer at 202 anything. 202 Main Street does not look like this. Littered area ≈ 50 ft × 12 ft. Plan area ≈ 40 ft × 60 ft. Affected area ≈ 25%.

Figure 8–6. Image showing damaged bike store in Watsonville with failed parapet in the 1989 Loma Prieta, California, earthquake.

Image Metadata and Description

Loma Prieta Blacklock Collection: LP0090

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Oct. 17, 1989; 7.09	Wood frame house with failed foundation	Blacklock, James R.	Late 1989	NORTH AMERICA/Santa Cruz County/United States/Watsonville/California	Pink frame house with failed foundation. Watsonville, California.

Author's Estimate of Affected Area

By inspection, 0%.

Figure 8–7. Image showing house with failed foundation in Watsonville in the 1989 Loma Prieta, California, earthquake.

Image Metadata and Description

Loma Prieta Collection: LP0462

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Oct. 17, 1989; 7.09	6th and Bluxome St.	Dickenson, Stephen E.	1989	United States/California/NORTH AMERICA/San Francisco	Collapse of fourth story wall from unreinforced brick building at 6th and Bluxome Streets, San Francisco, South of Market.

Author's Estimate of Affected Area

Also see LP0460. The location is sometimes reported as near 5th and Townsend Streets, sometimes on Bluxome Street near 6th and Townsend Streets. If the latter, the building appears to be 178 Bluxome Street, at the south end of Bluxome, north side of the street, APN 3785135, with parcel area 15,300 ft^2 according to Google Earth Pro. With four stories, the total building area would be 61,200 ft^2. The debris runs the length of the facade (135 ft) and twice as wide as the sidewalk, perhaps 24 ft. Five people were killed by the wall collapse. Affected area = $(135 \times 24)/(61,200) = 5.3\%$.

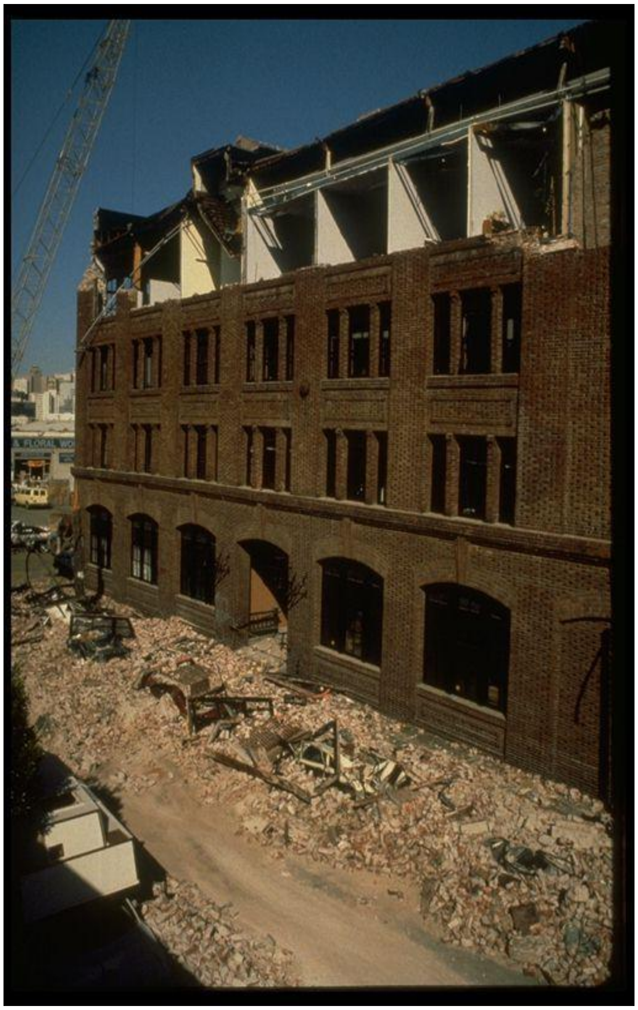


Figure 8–8. Image showing collapse of fourth story wall from unreinforced brick building in the 1989 Loma Prieta, California, earthquake.

Image Metadata and Description

Loma Prieta Collection: LP0460

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Oct. 17, 1989; 7.09	Unreinforced brick building	Kayen, Robert E.	Late 1989	United States/California/NORTH AMERICA/San Francisco	6th and Bluxome Streets, south of Market. Collapse of unreinforced brick wall.

Author's Estimate of Affected Area

Same as LP0462.

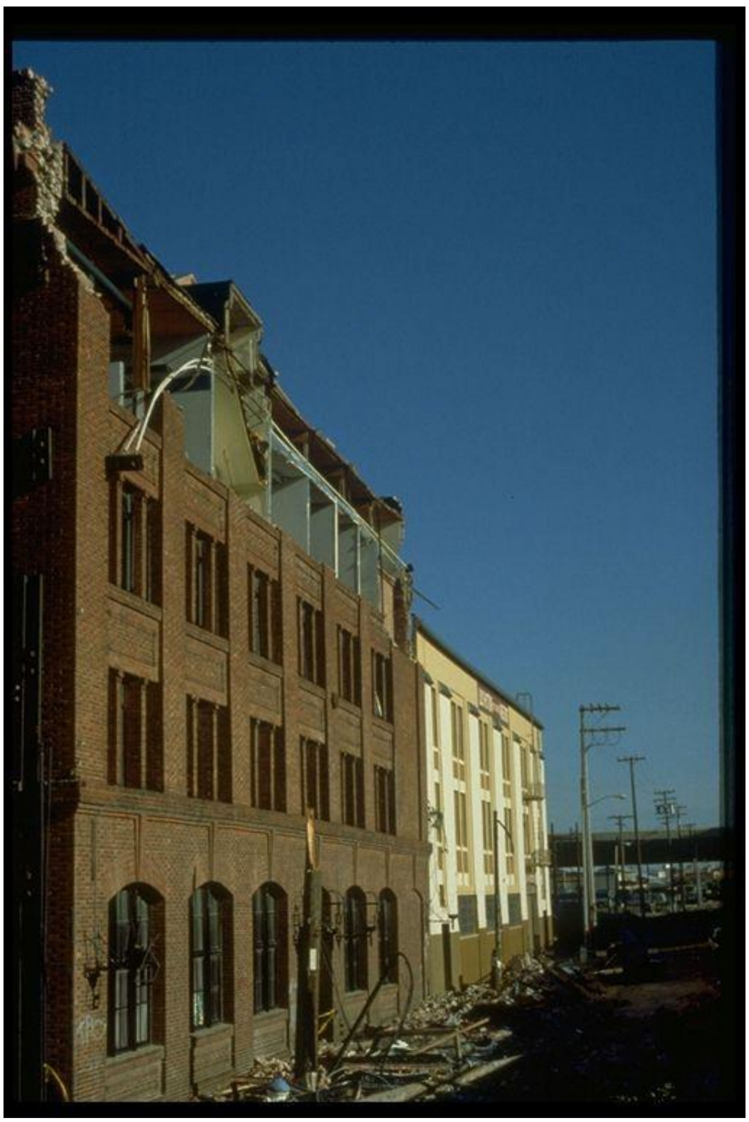


Figure 8–9. Image showing collapse of unreinforced brick wall in the 1989 Loma Prieta, California, earthquake.

Image Metadata and Description

Loma Prieta Collection: LP0375

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Oct. 17, 1989; 7.09	Collapse of apartment buildings	Seed, Raymond B.	Late 1989	United States/California/NORTH AMERICA/San Francisco	Collapse of two four-story apartment buildings (soft ground floors). Marina District, San Francisco, California.

Author’s Estimate of Affected Area

By inspection, two buildings, each with 25% collapse.

Figure 8–10. Image showing collapse of apartment buildings with soft ground floors in the Marina District of San Francisco in the 1989 Loma Prieta, California, earthquake.

Image Metadata and Description

Loma Prieta Collection: LP0499

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Oct. 17, 1989; 7.09	Collapsed building in Marina District	Harris, S. P.	1989-10-17	United States/California/NORTH AMERICA/San Francisco	Collapsed apartment building at 2090 Beach Street, after the fire was much advanced. Note firefighter directing water onto exposed side of building. Marina District, San Francisco, California.

Author's Estimate of Affected Area

This had been a four-story building, now with only one story remaining somewhat intact, so 75% collapse. (This was the building from which Sherra Cox was rescued.)

Figure 8–11. Image showing collapsed four-story building in the Marina District, San Francisco, in the 1989 Loma Prieta, California, earthquake. [Source: Scawthorn et al. 1992, p.204, fig. 11.]

Image Metadata and Description

Karl V. Steinbrugge Collection: S6144

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Oct. 17, 1989; 7.09	Soft-story collapse	unknown	--	United States/California/NORTH AMERICA/San Francisco	Soft-story collapse of apartment building in the Marina District, San Francisco, California.

Author's Estimate of Affected Area

This had been a three-story building, according to http://goo.gl/PBOKiA, so affected area = 33%. What is remarkable about this building is that it appears in many photos of the Marina District, almost entirely without identifying information other than the neighborhood. One photo caption says the building was at Beach Street and Divisadero Street. The view of the Golden Gate Bridge tower in the background tells us that it was at the northwest corner, apparently 3700 Divisadero Street, San Francisco, CA 94123-1000, APN 0913037.

Figure 8–12. Image showing soft-story collapse of an apartment building in the Marina District, San Francisco, in the 1989 Loma Prieta, California, earthquake. Karl V. Steinbrugge Collection: S6144, copyright restricted.

Image Metadata and Description

Loma Prieta Collection: LP0459

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Oct. 17, 1989; 7.09	Front and Davis St.	Dickenson, Stephen E.	Late 1989	United States/California/NORTH AMERICA/San Francisco	Front and Davis Streets. Collapse of unreinforced masonry wall from third floor of building. Embarcadero/Financial District, San Francisco.

Author's Estimate of Affected Area

Front Street is parallel to Davis Street, so the location makes no sense. Matching the background buildings, the address seems to be 235 Front Street, San Francisco, Calif., on the northwest corner of Front Street and Halleck Street. The view is toward the northwest. The building appears to be on assessor's parcel number 0237047, whose area is 4,960 ft^2. Google Earth Pro imagery from 1938 shows a building of uniform height covering the entire parcel, suggesting a total building area of 14,880 ft^2. The collapsed wall faces Front Street. The facade length is 72 ft, so the affected area appears to be 36 ft. I can find no images of the masonry on the sidewalk. Let us assume it litters an area 36 ft × 16 ft wide, for an affected area of (36 ft × 12 ft)/(14,880 ft^2) = 2.9%.

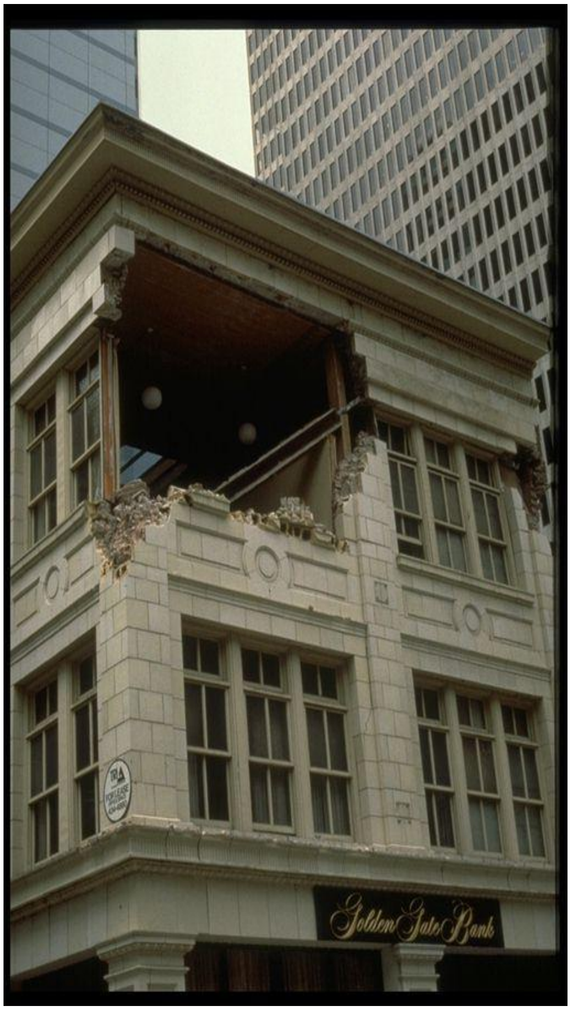


Figure 8–13. Image showing collapse of unreinforced masonry wall in the Embarcadero/Financial District, San Francisco, in the 1989 Loma Prieta, California, earthquake.

Image Metadata and Description

Loma Prieta Blacklock Collection: LP0041

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Oct. 17, 1989; 7.09	Interior structural failures at department store	Blacklock, James R.	Late 1989	NORTH AMERICA/Santa Cruz County/United States/Santa Cruz/California	Interior structural failures at department store. Santa Cruz, California.

Author's Estimate of Affected Area

This may be Ford's Department Store, the only department store mentioned in connection with collapse in Santa Cruz in the Loma Prieta earthquake. The building was located at the corner of Pacific Avenue and Cathcart Street, Santa Cruz, Calif. (http://goo.gl/fnczyK). The address is 1101 Pacific Avenue, Santa Cruz, Calif., APN 00514120000, on the northwest corner of Pacific Avenue and Cathcart Street (see http://goo.gl/0frVnb). The parcel measures 20,900 ft^2, according to Google Earth Pro. One can see an exhaust vent on above the truss in the background, so Ford's Department Store must have been one story tall in this portion of the building. The affected area here appears to be perhaps 1,000 ft^2. This site (http://goo.gl/ZQjZ5J) says that the "back of the Ford's Department Store collapsed," indicating that it was not the entire interior that collapsed. More images here (https://goo.gl/ULOUmp) and here (http://goo.gl/tpDTTV) suggest that something like the back one-third of the store collapsed. Say 33%.

Figure 8–14. Image showing interior structural failure in a department store in Santa Cruz in the 1989 Loma Prieta, California, earthquake.

Appendix 9. Northridge (1994) Collapse Images

Image Metadata and Description

Northridge Collection: NR327

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Jan. 17, 1994; 6.69	Collapsed apartment building	unknown	1994	Northridge/California/NORTH AMERICA/Los Angeles County/United States	Collapsed apartment building, three-story wood frame. Northridge, California.

Author's Estimate of Affected Area

According to Todd et al. (1994, p. 23; see figure 9–2), there were four collapsed three-story buildings. The ground story of two of the buildings completely collapsed, the ground story of about half of a third three-story building collapsed, and approximately one-eighth of a fourth. Thus, the affected areas are 33%, 33%, 17%, and 4%.

Figure 9–1. Image showing collapsed apartment building in the 1994 Northridge, California, earthquake.

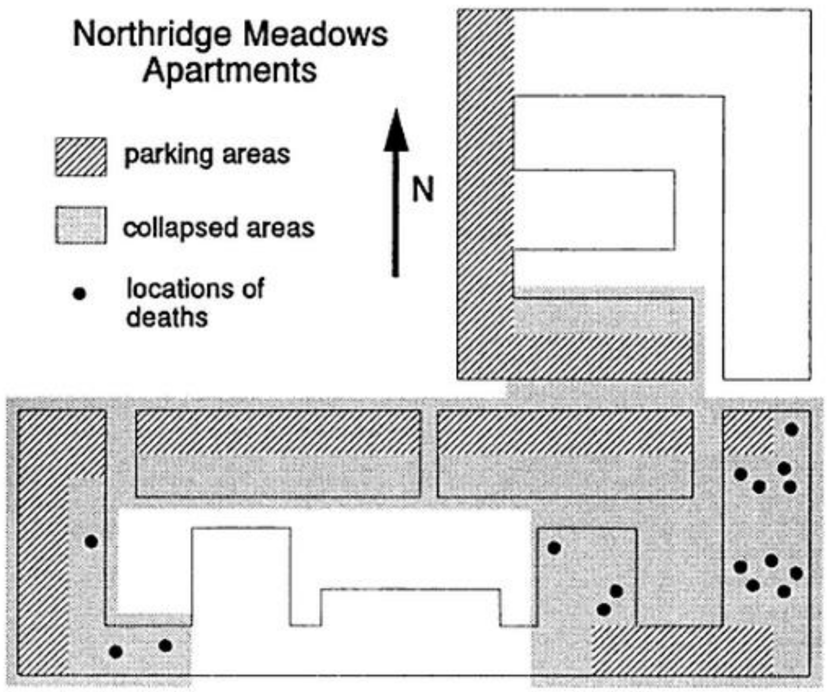


Figure 3.3. This plan of the Northridge Meadows apartment complex shows the distribution of parking and living spaces at the first level, and locations of deaths (source: Los Angeles Times, January 24, 1994). The shaded areas indicate the portions of the complex which collapsed.

Figure 9–2. Parking areas, collapsed areas, and locations of deaths on the first level of Northridge Meadows Apartments in the 1994 Northridge, California, earthquake (Todd et al., 1994, p. 23).

Image Metadata and Description

Northridge Collection: NR335

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Jan. 17, 1994; 6.69	Building components fell onto off-ramp	Aschheim, Mark A.	1994-01-19	NORTH AMERICA/Los Angeles County/United States/Los Angeles/California	Building at eastbound off-ramp of Route 101 south at Van Nuys exit. View to south. Failed building components fell onto off-ramp. Los Angeles, California.

Author's Estimate of Affected Area

This building was repaired. It is located at 4717 Van Nuys Boulevard, Sherman Oaks, CA 91403. According to Google Earth Pro, building area is 16,094 ft^2. There are no long shots or aerial shots to show the extent of the roof collapse. No estimate of affected area.

Figure 9–3. Image showing building components fallen onto off-ramp in the 1994 Northridge, California, earthquake.

Image Metadata and Description

Northridge Collection: NR353

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Jan. 17, 1994; 6.69	Northridge Meadows Apartments	Reitherman, Robert K.	1994-02-12	Northridge/California/NORTH AMERICA/Los Angeles County/United States	Collapse of ground story in Northridge, California. Structure: Northridge Meadows Apartments.

Author's Estimate of Affected Area

Same as fig. 9-1.

Figure 9–4. Image showing collapse of ground story at Northridge Meadows Apartments in the 1994 Northridge, California, earthquake.

Image Metadata and Description

Northridge Collection: NR357

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Jan. 17, 1994; 6.69	Northridge Meadows Apartment	Reitherman, Robert K.	1994-02-12	Northridge/California/NORTH AMERICA/Los Angeles County/United States	Northridge Meadows Apartments. Collapse of ground story. Northridge, California. Structure: Northridge Meadows Apartments.

Author's Estimate of Affected Area

Same as fig. 9-1.

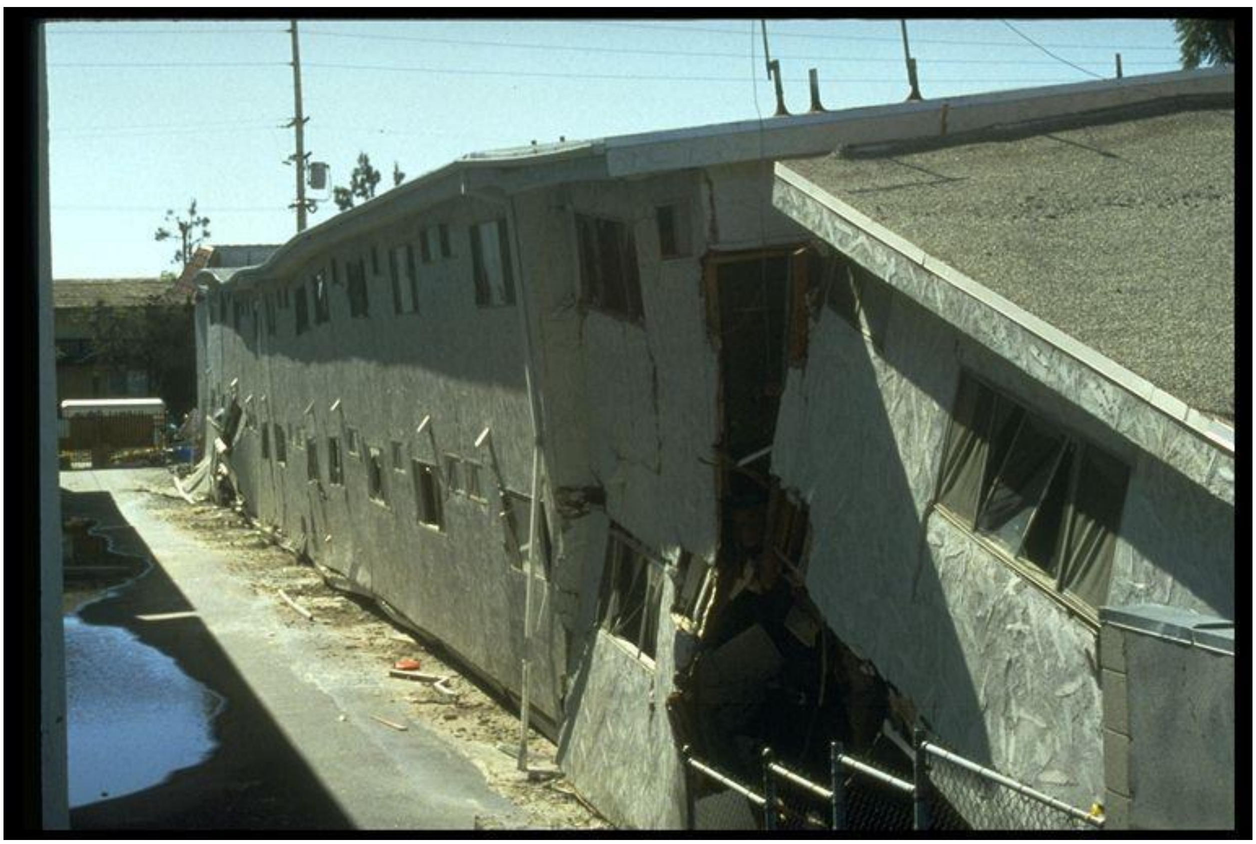


Figure 9–5. Image showing collapse of ground story at Northridge Meadows Apartments in the 1994 Northridge, California, earthquake.

Image Metadata and Description

Northridge Collection: NR358

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Jan. 17, 1994; 6.69	Northridge Meadows Apartment	Reitherman, Robert K.	1994-02-12	United States/Northridge/California /NORTH AMERICA/Los Angeles County	Northridge Meadows Apartments. Collapse of ground story. Northridge, California. Structure: Northridge Meadows Apartments.

Author's Estimate of Affected Area

Same as fig. 9-1.

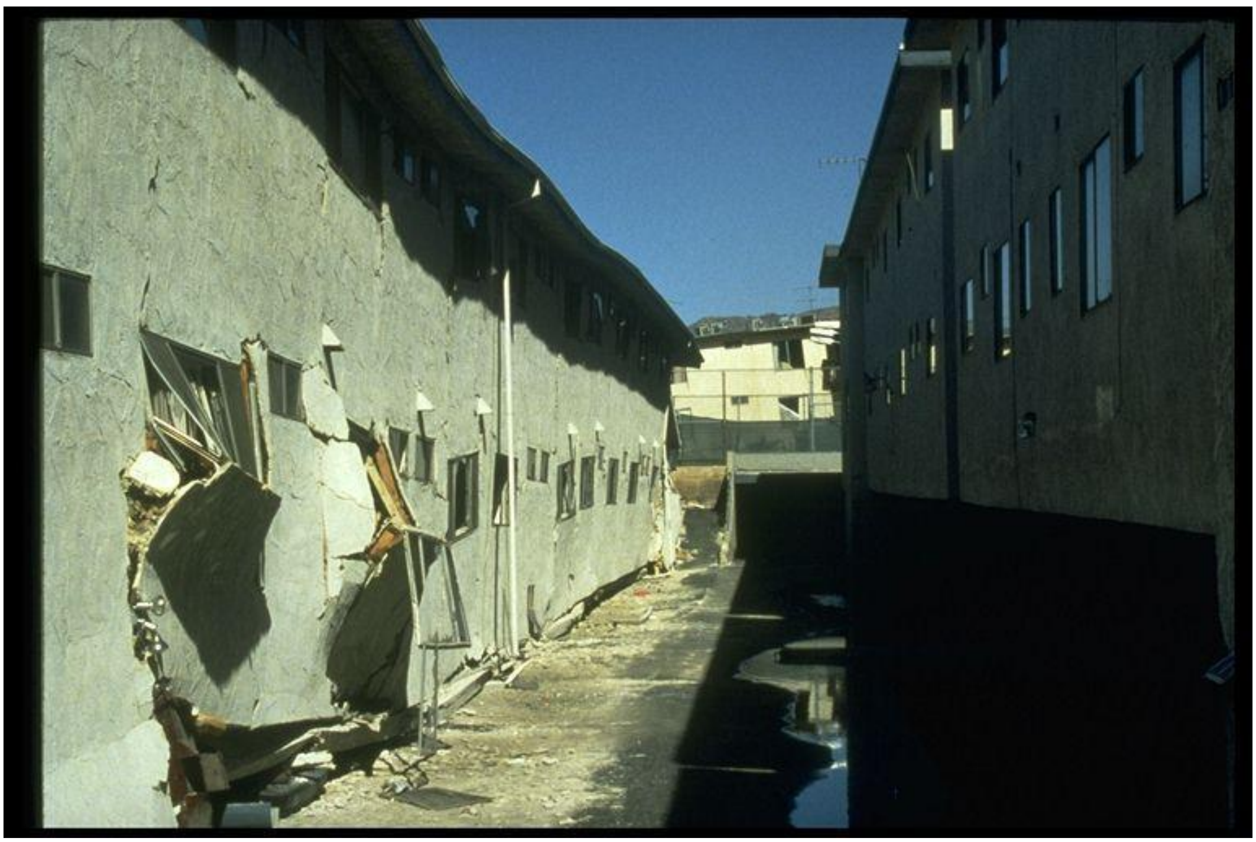


Figure 9–6. Image showing collapse of ground story at Northridge Meadows Apartments in the 1994 Northridge, California, earthquake.

Image Metadata and Description

Northridge Collection: NR408–NR409

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Jan. 17, 1994; 6.69	2-story masonry building	Stojadinovic, Bozidar	1994-01-19	NORTH AMERICA/Los Angeles County/United States/Santa Monica/California	1004 West Channel Road at Pacific Coast Highway (near Pacific Palisades). Damage to two-story masonry building. Heavy shear cracking on side walls. Out of plane failure of the second story. State Beach Cafe, Santa Monica, California.

Author's Estimate of Affected Area

Affected area: The address appears to be 108 W Channel Road, Santa Monica, which is adjacent to 112 (it is not 1004). From size of replacement building, which fills the lot, the damaged building appears to be 1,500 ft^2 in plan, or 3,000 ft^2 total. Bricks litter 40 ft of facade × 10 ft across sidewalk. Affected area is therefore approximately 400 ft^2/3,000 ft^2 = 13%.

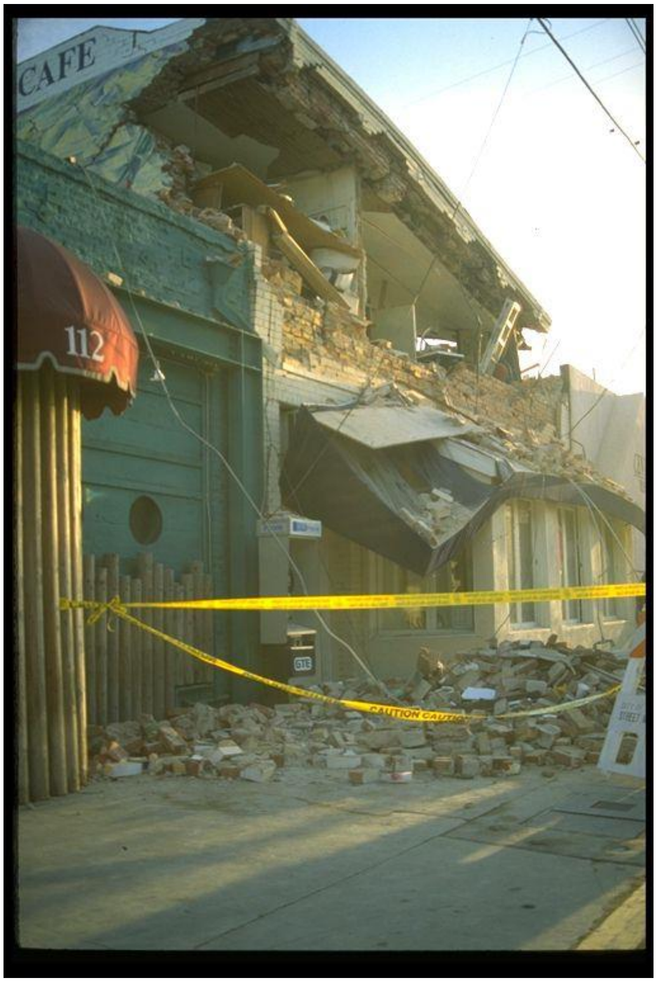


Figure 9–7. Image showing damage to two-story masonry building in Santa Monica in the 1994 Northridge, California, earthquake.

Image Metadata and Description

Northridge Collection: NR412–NR414

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Jan. 17, 1994; 6.69	Four-story masonry building	Stojadinovic, Bozidar	1994-01-19	NORTH AMERICA/Los Angeles County/United States/Santa Monica/California	Four-story masonry building, 827 Fourth St. Damage to the fourth and third floor of the building. The masonry facade fell out of plane and took with it the fourth floor terrace. This building had been scheduled for a retrofit to begin on Monday, Jan. 17, 1994.. Three layers thick unreinforced masonry. Damage in the top story and balcony. Little damage on the sides and below the third story. See also NR412–414. Santa Monica, California.

Author's Estimate of Affected Area

Building still exists and has been repaired. Google Earth Pro says building area = 31,314 ft^2. Affected area looks like (55 ft · 12 ft)/(31,314 ft^2) = 2.1%.

Figure 9–8. Image showing damage to four-story masonry building in Santa Monica in the 1994 Northridge, California, earthquake.

Image Metadata and Description

Northridge Collection: 201012024

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Jan. 17, 1994; 6.69	Collapsed unreinforced chimney	Reitherman, Robert K.	2010	Northridge, California earthquake, Jan. 17, 1994. Magnitude: 6.69	This residential chimney of unreinforced blocks collapsed during the 1994 Northridge earthquake.

Author's Estimate of Affected Area

Masonry litters an area about 10 ft × 4 ft, or 40 ft^2. Assuming a typical 1,500 ft^2 home, the affected area is 2.7%.

Figure 9–9. Image showing collapsed unreinforced chimney in the 1994 Northridge, California, earthquake.

Image Metadata and Description

Northridge Collection: NR559

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Jan. 17, 1994; 6.69	Parking structure on Cal State Northridge campus	unknown	1994	Northridge/California/NORTH AMERICA/Los Angeles County/United States	Parking structure on Zelzah Ave., California State University, Northridge, campus. This is a three-story precast concrete parking structure. Overall view showing collapse at east end of the structure. Structure: Cal State Northridge Parking

Author's Estimate of Affected Area

From an LA Times image here (http://goo.gl/7nnTu5), looks like about 35%.

Figure 9–10. Image showing collapse of a parking structure on the California State University, Northridge, campus in the 1994 Northridge, California, earthquake.

Figure 9–11. Photograph from the 1994 Northridge, California, earthquake. Image is taken from Earth Science World Image Bank (http://goo.gl/gdASRH), which describes it as follows: “California State University, Northridge parking structure that partially collapsed during the 1994 earthquake. Scientists believe it was the lack of shear walls, being precast, and lack of extra steel reinforcements in vertical columns that led to the damage seen here. This is 5km northeast of the epicenter.” Photo by P.W. Weigand. Copyright California State University, Northridge, Geology Department. Permission granted per http://goo.gl/tmht1n.

Image Metadata and Description

Northridge Collection: NR579

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Jan. 17, 1994; 6.69	Fashion Center parking garage	Reitherman, Robert K.	1994-02-12	Northridge/California/NORTH AMERICA/Los Angeles County/United States	Collapse of parking garage floors. See NR459–461 for damage to Broadway department store. Fashion Center, Northridge, California. Structure: Northridge Fashion Center Parking.

Author's Estimate of Affected Area

From an Atlantic Magazine image here (http://goo.gl/QQYVQ7), looks like about 35%.

Figure 9–12. Image showing collapse of floors in the Northridge Fashion Center parking garage in the 1994 Northridge, California, earthquake.

Image Metadata and Description

Northridge Collection: NR221

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Jan. 17, 1994; 6.69	Bullock's retail store	unknown	1994	Northridge/California/NORTH AMERICA/Los Angeles County/United States	Northridge Fashion Island Center. Interior reinforced concrete columns remain standing following collapse of second- and third-floor concrete waffle slabs. Intact portion of waffle slab roof shows typical slab construction. Structure: Bullock’s Department Store.

Author’s Estimate of Affected Area

A plan of Bullock’s can be found at https://goo.gl/BR34F7. The building has 8 × 8 bays and three stories. It appears that the second floor collapsed onto the first floor in all but about 14 square bays: the one on the left and the one in the rear as viewed from the photographer’s viewpoint, so 150 out of 192 floor-bays collapsed, or 78%.

Figure 9–13. Image showing collapse of second- and third-floor concrete waffle slabs at Bullock's retail store in the 1994 Northridge, California, earthquake.

Image Metadata and Description

Northridge Collection: NR303

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Jan. 17, 1994; 6.69	Oviatt Library, Cal State campus	McMullin, Kurt M.	1994-01-20	Northridge/California/NORTH AMERICA/Los Angeles County/United States	View of partial roof collapse. South elevation, east of front entry. View from east. Taken at 3 p.m. California State University, Northridge. Structure: Oviatt Library.

Author's Estimate of Affected Area

See also NR299, NR300, and NR302, showing about 4×1 bays of roof collapse. The floor plan at http://goo.gl/Fzv7Og shows 14 bays east to west and 6 bays north to south. The building has five floors (see http://goo.gl/Z2Ib5R). Thus, (4×1)/(5×14×6) = 1.0%

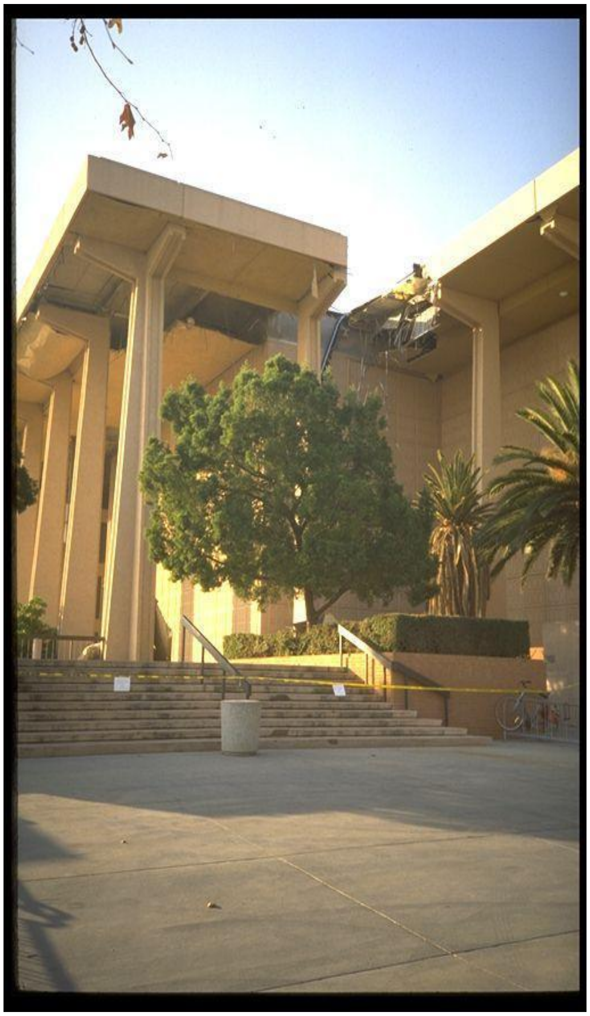


Figure 9–14. Image showing partial roof collapse of Oviatt Library, California State University, in the 1994 Northridge, California, earthquake.

Image Metadata and Description

Northridge Collection: NR543

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Jan. 17, 1994; 6.69	Kaiser parking structure	Reitherman, Robert K.	1994-01-19	Los Angeles/California/NORTH AMERICA/Los Angeles County/United States	Complete collapse of parking structure. Los Angeles, California. Structure: Kaiser Hospital parking.

Author's Estimate of Affected Area

See also NR519, NR528, NR530, NR539, NR540, NR542, NR544, NR545, NR546, NR549, NR551, NR552, NR543, and NR544. All the photo descriptions say they are talking about the Kaiser Hospital parking structure, but it appears there were two parking structures. Some descriptions say “complete collapse” and other photos such as NR519, NR528, and NR530 show a parking structure that has not collapsed. Reitherman, in NR549, names the location “Kaiser West Los Angeles Medical Center,” which Google says is located at “6041 Cadillac Avenue, Los Angeles, CA 90034,” which Google Earth locates at lat 34.0384 N., long –118.3757 E. Three satellite images from August 1989, April 1994, and March 2002, and shown in Google Earth, show two parking structures near here: one with a center near lat 34.0391 N., long –118.3759 E. appears to be the one that did not collapse. Another with a center at lat 34.0389 N., long –118.3733 E. appears in 1989 but is absent in April 1994 (after the earthquake), and it reappears (a replacement) in 2002. I can find no aerial images of the latter collapsed structure or long shots to show the extent of the collapse, so let us take the affected area as 100%.

Figure 9–15. Image showing complete collapse of the Kaiser parking structure, Los Angeles, in the 1994 Northridge, California, earthquake.

Image Metadata and Description

Northridge Collection: NR328

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Jan. 17, 1994; 6.69	Soft-story collapse of apartment building	unknown	1994	Sherman Oaks/California/NORTH AMERICA/Los Angeles County/United States	Soft-story collapse of apartment building, at Hazeltine Ave. and Milbank St., Sherman Oaks, California.

Author's Estimate of Affected Area

By inspection, 33%.

Figure 9–16. Image showing soft-story collapse of apartment building in Sherman Oaks in the 1994 Northridge, California, earthquake.

Image Metadata and Description

Northridge Collection: NR160

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Jan. 17, 1994; 6.69	Kaiser office building	unknown	1994	Granada Hills/California/NORTH AMERICA/Los Angeles County/United States	Over all view of Kaiser Permanente office building looking toward the northeast. The brick facades at either end of the structure have separated from the concrete frame, and the second floor of the structure has completely collapsed. The bays at the north and south ends of the building are also partially collapsed from the second to the fifth floor. Granada Hills, California. Structure: Kaiser Permanente Building.

Author's Estimate of Affected Area

See also NR162. The collapsed second floor amounts to 20% of the building area. The partially collapsed north and south end bays from floors three to five add another 10%, for a total of 30%.

Figure 9–17. Image showing second-floor collapse at Kaiser Permanente office building, Granada Hills, in the 1994 Northridge, California, earthquake.

Appendix 10. San Simeon (2003) Collapse Images

Image Metadata and Description

NISEE misc. Collection: NM0008

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Dec. 22, 2003; 6.6	View of collapsed building from intersection of 12th and Park Streets	Sakai, Junichi	2003-12-23	Paso Robles/California/NORTH AMERICA/San Luis Obispo County/United States	This unreinforced masonry building was built in 1892, and its clock tower became a symbol for the town of Paso Robles. The second story of the building collapsed during the earthquake, killing two employees of Ann's Dress Shop as they tried to flee onto Park Street. The roof of the building collapsed directly westward onto Park Street and landed on a row of parked cars. Debris from the north wall went through the roof of an adjacent shop at 1220 Park Street, Paso Robles, California. Structure: Mastagni Building.

Author's Estimate of Affected Area

Also see NM0009 and NM0012 for this building and NM0001–NM0004 for 1220 Park Street. The building at the west end of the 800 block of 12th Street (807 12th Street is mentioned in the description of NM0009) and the south end of the 800 block of Park Street (1220 is mentioned here) appears in September 1994 satellite imagery in Google Earth. It has a plan area of approximately 5,960 ft^2, so a total area of approximately 11,920 ft^2. The collapse of the second floor constitutes 5,960 ft^2. In addition, the roof collapsed onto 12th Street. The building was approximately 120 ft long north to south, and it looks as if the roof covered the sidewalk and half the depth of the diagonal street parking, about 19 ft total, so another 120 ft·19 ft = 2,280 ft^2. The building at 1220 Park Street, just to the north, was a one-story building that appears from NM0009 to have had its roof completely collapse when debris from the Mastagni Building went through the roof of 1220 Park Street. The floor area of 1220 Park Street looks like 50 ft deep by perhaps 20 ft wide. The total affected area is therefore approximately (5,960 ft^2 + 2280 ft^2 + 1,000 ft^2)/(11,920 ft^2) = 78%.

Figure 10–1. Image showing collapsed building from intersection of 12th and Park Streets in Paso Robles in the 2003 San Simeon, California, earthquake.

Image Metadata and Description

NISEE misc. Collection: NM0012

Earthquake date and magnitude	Title	Creator	Date	Location	Description
Dec. 22, 2003; 6.6	Old Clocktower	unknown	2003-12-23	Paso Robles/California/ NORTH AMERICA/San Luis Obispo County/United States	Before and after images of the Old Clocktower. This unreinforced masonry building was built in 1892, and its clock tower had become a symbol of Paso Robles. The second story of the building collapsed directly westward onto Park Street. Paso Robles, California.

Author's Estimate of Affected Area

?

Figure 10–2. Before (right) and after (left) photographs of the Old Clock Tower, Paso Robles, in the 2003 San Simeon, California, earthquake. This unreinforced masonry building was built in 1892, and its clock tower had become a symbol of Paso Robles. The second story of the building collapsed directly westward onto Park Street.

Appendix 11. South Napa (2014) Collapse Images

Image Metadata and Description

Photos P9050177 (outside) and P9080152 (inside) were provided by Sarah Durphy. She describes them as showing Don Perico's Restaurant in Napa.

Author's Estimate of Affected Area

At the time of the earthquake, the restaurant was located at 1025 1st Street, Napa, Calif., in the west end of the building at lat 38.299029 N., long –122.285868 E. That address seems to occupy approximately 60 ft × 60 ft. The collapsed wall appears to fill 25 ft by 12 ft, suggesting an affected area of 8.3%.

Figure 11–1. Image showing damage to Don Perico's Restaurant in Napa in the 2014 South Napa, California, earthquake.

Appendix 11. Earthquakes with No Available Collapse Images

Borrego Mountain (1968)
Livermore (1980)
Mammoth Lakes (1980)
Cape Mendocino (1980)
Humboldt County (1980)
North Palm Springs (1986)
Oceanside (1986)
Chalfant Valley (1986)
Superstition Hills (1987)
Lake Elsman (1989)
Sierra Madre (1991)
Joshua Tree (1992)
Cape Mendocino (1992)
Landers (1992)
Big Bear (1992)
Eureka Valley (1993)
Hector Mine (1999)
Yountville (2000)
Parkfield (2004)
Anza (2005)
Cape Mendocino (2005)
Alum Rock (2007)
Chino Hills (2008)
Inglewood (2009)
Eureka (2010)
Pico Rivera (2010)
El Mayor-Cucapah (2010)
Borrego Springs (2010)
Brawley swarm (2012)
Avalon (2012)