U.S. Department of Housing and Urban Development
Office of Policy Development and Research

# Assessment of Damage to Residential Buildings Caused by the Northridge Earthquake

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**July 30, 1994**

Prepared for:

**The United States Department of Housing and Urban Development**
**Office of Policy Development and Research**
Washington, DC
Cooperative Agreement DU100K000005911

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Notice

# Acknowledgements

This report was prepared by the NAHB Research Center for the U.S. Department of Housing and Urban Development. Research Center staff responsible for the production of this report were Jay H. Crandell, P.E., principal author and project manager; Mark Gibson, survey designer and statistics analyst; Mark Nowak, technical reviewer; David J. Dacquisto, statistics reviewer; Edward M. Laatsch, P.E., advance team and survey team leader; Timothy J. Waite, P.E., Michael Bruen, Bob Dewey, William Farkas, P.E., Tom Levin, and Christine Thompson, survey team members; and Janice Duncan and Lynda Marchman, administrative support.

Independent review and comment were provided by John M. Coil, S.E., John Coil Associates, Tustin, California; Mary C. Comerio, Professor of Architecture, University of California, Berkeley; Tak Fuji, Greater Los Angeles/Ventura Chapter Building Industry Association, Calabasas, California; John L. Gross, Ph.D., P.E., National Institute of Standards and Technology, U.S. Department of Commerce; Dr. Kaye M. Shedlock, Branch of Earthquake and Landslide Hazards, U.S. Geological Survey; and Edley G. Watson, Building and Safety Division, County of Los Angeles, California.

Thanks to Carl Deppe, William J. Foster, Anthony Giannini, Stephen Kiefer, G.P. “Preston” Meyer, and all those at the Department of Building and Safety, Los Angeles, California; Dee Zinke, Greater Los Angeles/Ventura Chapter Building Industry Association, Calabasas, California; Ken Ford, National Association of Home Builders, Washington, DC; and Phillip Hunter, Metromail Corporation, Atlanta, Georgia.

Special thanks and recognition to William Freeborne and the staff of the Innovative Technology Division, U.S. Department of Commerce for technical input and guidance.

# Foreword

As the population of the United States continues to expand in areas of high seismic activity, the increasing exposure to personal injury and property damage from earthquakes demands our exacting attention. The destruction caused by California's 1994 Northridge Earthquake provides a recent reminder of this concern. Yet, the destruction reaches far beyond physical damage, leaving lasting emotional and economic changes for people and communities during a long and difficult reconstruction process.

*Assessment of Damage to Residential Buildings Caused by the Northridge Earthquake* evaluates the performance of houses experiencing severe ground shaking during this earthquake. Extensive data collection, statistical analysis, and observations provide a realistic and scientific perspective to the damage that can help guide decisions related to housing in areas of high seismic risk. Comprehensive in detail, this report also identifies the major problems in home construction that can direct productive improvements in earthquake-resistant housing.

I hope that this report will be a useful resource in our quest to enhance the permanence of homes subject to earthquakes through a rational balance of important social issues—the preservation of life, property, and housing affordability.

Michael A. Stegman
Assistant Secretary for Policy
Development and Research

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# EXECUTIVE SUMMARY

This report presents the findings of a damage assessment survey of the Northridge earthquake. The primary purpose is to provide a statistically-based representation of the seismic performance of residential construction relative to local construction characteristics. In addition, case studies of more extreme failures provide insight into the causes of life-threatening performance problems.

The Northridge Earthquake occurred at 4:31 a.m. on January 17, 1994. Its epicenter was located in a densely populated area of Los Angeles county near the community of Northridge. Over 30 deaths were reported as a direct result of the tremor, and a total death toll of 58 was attributed to both direct and indirect causes. Current estimates of the severity of this earthquake place it at a magnitude of $M_L$= 6.4 on the Richter scale ($M_w$=6.7 and $M_S$=6.8).[1] Uncorrected peak horizontal ground accelerations were recorded at 0.9g near the epicenter and varied from 0.1g to 1.8g at specific near-field locations. In terms of the effective peak horizontal ground accelerations, the 475 year return period design estimate of 0.4 g was exceeded by a factor of 1.5 to 2 at several locations.[2] A large "pulse" of ground movement produced during the 15 and 20 second duration by this earthquake is among the worst recorded in U.S. history.[2] Large ground movements from the earthquake were felt as far away as Las Vegas.

## Sampling Methodology

Two groups of building types were surveyed: single-family detached (SFD) properties, and single-family attached and multifamily low-rise (MFLR/SFA) of two stories and under. The SFD survey was conducted as a random single-stage cluster sample. The home at the selected address was surveyed along with two homes on either side, or a total of five homes per site. For the MFLR/SFA survey, the selected building was considered a single structure and all accessible areas or dwelling units within the structure were assessed.

Construction characteristics and damage to 341 SFD homes and 30 MFLR/SFA buildings were recorded. In addition to the statistically-based survey, case studies of damage were performed on 54 SFD and 43 MFLR/SFA buildings. A damage assessment form was completed for each surveyed building.

## Single-Family Detached Homes

About 90 percent of the homes in the sample were built prior to the 1971 San Fernando Valley Earthquake. The 1971 $M_L$=6.5 quake, which resulted in 64 deaths, heightened concern for problematic site or architectural features which vary from the scope of prescriptive construction

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[1] John F. Hall, " Northridge Earthquake January 17, 1994: Preliminary Reconnaissance Report" (Oakland, CA.: Earthquake Engineering Research Institute, March 1994).

[2] Farzad Naeim, "Northridge Earthquake Ground Motions: Implications for Seismic Design of Tall Buildings", Third Conference on Tall Buildings in Seismic Regions (Los Angeles: Los Angeles Tall Buildings Structural Design Council, May 1994).

guidelines by earlier home. Currently, housing development is occurring on sloped sites surrounding the valley. Also, with high land prices, homes with custom architectural features are preferred. As a result, most new homes in the Los Angeles area are engineered to accommodate these new conditions.

All homes surveyed had wood exterior wall framing. SFD homes were typically one story and nearly two-thirds had an attached garage. Homes on crawlspace foundations outnumbered those on concrete slabs by almost two-to-one, despite a notable increase in the use of slab-on-grade foundations since the 1960s. Cripple-wall foundations were infrequent. Plywood was rarely used for exterior wall sheathing. A stucco exterior finish was typically applied over wire mesh and building paper or felt applied to the studs per the LA City “Type V” prescriptive requirements. A widespread use of wood roof rafters and plaster interior finish also reflected the age of the homes.

SFD homes suffered minimal structural damage to elements that are critical to the safety of occupants. Structural damage was most common in the foundation system. The small percentage of surveyed homes (approximately two percent) that experienced significant foundation damage were located in areas that endured localized ground effects or problems associated with hillside sites.

Interior and exterior finishes fared much worse than foundations and framing with nearly 50 percent of the homes experiencing at least some damage. However, the great majority of damage was limited to the lowest level of damage. Stucco was observed on nearly all home exteriors. Damage to stucco usually appeared as hairline cracks radiating from the corners of openings, particularly larger openings such as garage doors, or along the top of the foundation. Interior finish damage paralleled the occurence of exterior finish (stucco) damage. Resilient finishes, such as wood panel or lap board siding, fared well and often showed no evidence of damage even when stucco on other areas of the same building was modestly damaged.

### MFLR/SFA Dwellings

The sampling method used for the multifamily low-rise (MFLR) and single-family attached (SFA) survey resulted in a very diverse sample. Of the 30 residential sites visited, 13 were single-family attached (e.g., duplexes and townhomes) and 17 were multifamily (e.g., condominiums and garden apartments) structures.

Smaller SFA homes in the survey (primarily duplexes) were typically of the same construction as SFD homes. The larger SFA units were similar to MFLR construction.

Prior to the 1970s many MFLR buildings were built on “soft stories” comprised of open-garage parking underneath of multi-story dwelling units. The garage areas or foundations on these older buildings were typically constructed of steel pipe columns, wood-frame shear walls with stucco finish, or a combination of both. The wood-frame garage ceiling or first floor was supported by either steel or engineered wood (e.g., glulam) girders.

Following the 1971 San Fernando Valley Earthquake, multifamily construction began to transform with the pressures of more stringent building codes, policies, and engineering requirements. As a result, newer construction evolved with the use of plywood sheathing on wood-frame walls and stronger, more rigid foundation designs. Fully enclosed parking provided on the ground level (or slightly below) became the typical construction. Reinforced masonry perimeter walls and reinforced concrete columns supporting a reinforced concrete first floor slab also became popular forms of construction. In some cases, the foundation walls were also cast-in-place concrete.

Damage to SFA construction appeared to reflect a level of performance similar to that reported for the SFD homes. However, structural damage to MFLR construction was notably more dramatic and costly to lives, especially for certain construction types located in the San Fernando Valley. The more remarkable structural failures were associated with the older MFLR buildings situated on soft-story garage foundations. In agreement with observations and expectations, the performance of stucco finishes, particularly as lateral support to walls on these larger MFLR and SFA buildings, performed noticeably worse than on the “Type V” single-family detached homes.

# INTRODUCTION

This report presents the findings of a damage assessment survey of the San Fernando Valley housing stock following the Northridge Earthquake on January 17, 1994. The types of housing studied include single-family detached (SFD), single-family attached (SFA), and multifamily low-rise (MFLR) units up to four stories in height. The primary purpose is to provide a statistically-based representation of the performance of residential construction relative to local construction characteristics. In addition, case studies of more extreme failures were conducted to provide insight into the causes of life-threatening performance problems. The findings presented in this report will assist in the review of building codes relative to the local construction environment and in the development of effective hazard mitigation policy.

Historically, building performance has been reported anecdotally following natural disasters. Anecdotal reports inherently focus on the more serious failures. Although valuable information on specific types of failures can be obtained from such reports, the results are not necessarily representative of the overall performance of a large population of buildings. Modification of building codes and construction practices have historically been influenced by this incomplete view of overall building performance and occurence of damage.

To achieve a more balanced view of housing performance following the Northridge Earthquake, a strategy was employed which utilizes basic statistical sampling methods. This useful technique, commonly used in demographic studies, increases the objectivity of post-disaster building performance assessments. A similar approach was first used in a study of residential construction performance following two major hurricanes in 1992.[3]

In addition to this introduction, the report includes five other sections. A background section first provides the reader with a working knowledge of earthquakes as they relate to building construction, particularly homes and low-rise apartments. A brief description of the Northridge Earthquake is included. Next, the sampling method and assessment procedure are discussed. Results of the SFD survey are then presented, including a statistical assessment of the performance of the SFD housing stock, as well as case studies of more extreme damage. This is followed by a section on the characteristics and performance of MFLR and SFA homes. The closing section summarizes results of the study and offers recommendations for future consideration.

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[3] NAHB Research Center, *Assessment of Damage to Single-Family Homes Caused by Hurricanes Andrew and Iniki*, Prepared for the U.S. Department of Housing and Urban Development (Washington: GPO, 1993).

# BACKGROUND

## Earthquake Fundamentals

Earthquakes are generated by either tectonic activity, the movement of large rock plates which underlay the earth's surface, or volcanic activity. The most active seismic areas are associated with plate tectonics. Faults may be visible on the ground surface, but they are often hidden below layers of soil deposits. About 90 percent of the world's earthquakes occur at faults along the boundaries of the earth's major crustal plates.[4] As stresses buildup from the resistance to movement of adjacent plates, energy is accumulated. Movements originating below the earth's surface at the focus or hypocenter of an earthquake release this energy in the form of ground shaking.

The severity of an earthquake is commonly represented by a measurement known as the Richter Local Magnitude or $M_L$. The Richter Scale provides a relative comparison of the severity of ground shaking experienced in recorded earthquakes. Each unit increase in the Richter Scale (an $M_L$ increase of one) represents an approximately 30-fold increase in the earthquake's magnitude or energy. Estimates of $M_L$ are derived from peak ground acceleration readings of standard seismographs by application of generalized laws for the attenuation of ground shaking through the earth's crust. Thousands of moderately strong earthquakes ($M_L$=4.5 or greater) occur annually in the world. Newer methods of measuring earthquake severity, such as the Moment and Surface Wave Magnitudes ($M_w$ and $M_s$) are also used, but they describe somewhat different aspects of a given earthquake event.[5] Earthquake ground motions are typically reported as a fraction or decimal percent of the acceleration of gravity, g, where 1 g is equivalent to 9.81 $m/s^2$ or 32.2 $ft/s^2$.

Seismographs are employed to record earthquake ground motions in terms of a time versus ground acceleration plot recorded at the site of the instrument. A seismograph station must be capable of recording ground motions in both horizontal and vertical directions (triaxial) to fully document the ground motions experienced. From this information, the vertical and horizontal ground acceleration components, wave velocities, and deflections may be discerned by mathematically integrating the data. Each seismograph must be standardized and calibrated such that the raw data can be reliably converted to usable information. While some seismographs record digital data others use mechanical methods, such as light etching on photographic paper, to record ground motions. Uncorrected peak ground accelerations are usually available immediately following an earthquake because they are read directly from a seismograph output with the least amount of data processing. Seismograph instruments may be located on a "free-field" site with varying soil conditions, on rock outcrops, on topographic features, or on buildings—each giving a unique result for a given event. The distance to the hypocenter from the seismograph site is estimated by the difference in arrival

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[4] U.S. Geological Survey, *The Severity of an Earthquake* (Denver: GPO, 1991).

[5] David M. Boore and William B. Joyner (USGS), "Prediction of Ground Motion in North America", *Proceedings of Seminar on New Developments in Earthquake Ground Motion Estimation*, ATC 35-1 (Redwood City, CA: Applied Technology Council, 1994).

time of ground wave forms which have distinct differences in their rate of propagation through the ground.

When an earthquake occurs, energy is instantaneously radiated from the hypocenter creating cyclical waves through the ground in all directions. On the ground surface, these waves radiate outward from the epicenter (located on the ground surface directly above the hypocenter). Two basic types of ground surface waves, P-waves and S-waves, result from each earthquake. There is substantial variation within the cyclical nature and duration of these wave forms which makes each earthquake somewhat unique. Differences in ground conditions, topography, and fault mechanisms, among many other things, contribute to the large variability in ground shaking resulting from earthquakes. In “weak” soil conditions, ground fissuring, soil liquefaction, or ground settlement may occur. On hillsides, landslides may occur.

The P-waves or preliminary waves are the fastest to radiate from the epicenter. They travel through the ground as shock waves at very high speeds (near 18,000 mph) in a manner similar to the propagation of sound waves in the air. Because of the high velocity of these waves, the frequency is in the audible range to the human ear which explains the “rumbling” sounds associated with earthquakes. These waves do not produce the highest amplitudes of ground movement. They are in a frequency range above that which causes a detrimental reaction in buildings, and they attenuate or lessen in magnitude more rapidly than S-waves.

S-waves or shear waves travel at a slower rate than the P-waves (roughly 700 to 3,500 mph), but with greater amplitude of ground surface movement. They travel through the ground in a rolling manner similar to waves in water. Objects at the ground surface will experience vertical (up and down) and horizontal (back and forth) motions when these waves pass beneath. During a typical earthquake, there may be 15 to 75 cycles of horizontal and vertical ground movements produced by S-waves. S-waves also attenuate with distance from the epicenter. However, the effect of S-waves in a given locality may be amplified or dampened depending on local variations in ground properties, the surrounding topography, and the magnitude of shaking in underlying bedrock.

## Earthquake Loads

S-waves have the greatest impact on structures and, therefore, get most of the attention in design procedures to estimate seismic loads. There are several characteristics that govern the dynamic, inertial reaction of a building for a given ground motion. Although there are volumes of literature addressing this topic, this section summarizes only the primary issues surrounding building loads and refers the reader to other information for further details. The main building characteristics of concern include:

- building height,
- building configuration and style,
- structural geometry,
- method of connecting structural members,
- structural materials,
- non-structural materials, and
- interaction of the foundation system with the moving ground.

For a particular building, these characteristics define the building's weight distribution, its natural period or natural frequency of vibration, its potential to dampen or amplify vibrations, and its capacity to absorb the energy imparted from cyclical ground movements. By applying classical dynamic analysis theory, engineering research, and various academic assumptions, the current seismic design procedures use these factors to estimate a building's reaction to a simplified design ground acceleration parameter known as *effective peak acceleration*. Because the vertical ground acceleration components of earthquakes are comparatively low, the effective peak acceleration represents only horizontal accelerations. The dynamic building reaction is finally defined in terms of an equivalent static load by use of simple Newtonian mechanics (e.g., F = ma) and modifying factors to account for actual building response in comparison to theory. When structural engineering is required, this equivalent static force approach is the favored method of determining seismic loads and designing the necessary structural resistance. For important structures, original dynamic modeling using a selection of actual earthquake records may be applied directly to the structural analog of the proposed building.

The effective peak acceleration is derived from response spectra analyses of actual earthquake seismograph records grouped by similar soil conditions. A response spectra is created by analyzing the response of a simple elastic mass-spring-damper system when subject to a digitized seismograph record through dynamic computer modelling algorithms. From this analysis, the maximum response accelerations (peak spectral accelerations) of the mass are recorded for variations in the natural frequency of the modelled mass-spring-damper system. The response spectra is then plotted using only the peak spectral acceleration for each variation in the natural frequency of the elastically modelled system. From the response spectra plot, averaged peak spectral accelerations are estimated for ranges of natural frequencies considered applicable to buildings. As a final step, these values are divided by 2.5 to convert back to an approximation of actual peak ground accelerations. The outcome is a theory-based parameter, *effective peak acceleration*, with limited capabilities in describing the complex nature of earthquakes and their impact on structures.

Estimated effective peak accelerations shown on seismic risk maps are used in various design procedures to establish minimum seismic loads on buildings. These maps are not based simply on historic earthquake occurrences. They are subject to statistical processes, assumptions, and adjustment by expert opinion or local experience to approximate a desired return period or recurrence interval associated with an acceptable level risk.[6] In current practice, the design return period is 475 years which corresponds to a 10 percent chance of exceedance in a 50 year period.

Safety factors inherent to the design procedures and engineering practice further reduce risks of failure by effectively increasing the effective peak acceleration parameter through load combination factors, material safety factors, load duration factors, and others. In theory, the risk of structural failure may be further reduced by using a larger return period value of the effective peak acceleration. While this usually results in greater strength, structural stiffness may also be increased. However, strength increases may be offset because of the structure's decreased capacity to absorb and dissipate energy through flexure from severe ground shaking. The reader is referred to

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[6] Arthur Frankel, et al., "Ground Motion Mapping—Past, Present, and Future", *Proceedings of Seminar on New Developments in Earthquake Ground Motion Estimation,* ATC 35-1 (Redwood City, CA: Applied Technology Council, 1994).

publications by the National Earthquake Hazards Reduction Program (NEHRP)[7] and others listed in the bibliography for more detail regarding the development earthquake design procedures and the methods used to assess earthquake risks, loads, and structural capacity or resistance.

## Building Codes

Earthquake loads are generally accounted for by either performance or prescriptive requirements found in building codes. Engineering design procedures based on performance requirements (e.g., effective peak accelerations) are applied to critical structures, tall buildings, multifamily home construction, and special construction. However, these procedures are seldom used in single-family detached home construction. For most residential construction, prescriptive requirements provide for seismic resistance. In areas of greater seismic risk, local building authorities may either conservatively modify the minimum prescriptive and performance requirements of building codes or require engineering for seismic resistance of homes. Research, testing, and experience also influence performance and prescriptive requirements. Given the many uncertainties in accurately representing the risk of earthquakes and subsequently calculating building resistance, the experience of structural performance from actual earthquake events is invaluable.

The 1971 San Fernando Valley ($M_L$=6.5) Earthquake, which resulted in 64 deaths, heightened concern for problematic site or architectural features which vary from the scope of existing prescriptive construction guidelines by which many earlier homes had been built. During this time, new housing development was shifting to available sites on slope lands surrounding the valley. Also, homes with custom architectural features apparently became more popular. As a result, the LA City Building Department commonly requires seismically engineered home plans in lieu of the prescriptive design method which is reserved for very simple, rectangular homes (locally known as “ding-bats”) or additions on relatively flat sites.

Building codes in the Los Angeles area at the time of the Northridge Earthquake were based on the Uniform Building Code (UBC), 1991 Edition.[8] For all multifamily construction, the City of Los Angeles requires engineering according to the Uniform Building Code. Additional requirements for specific concerns are issued as policy memorandums, but the ultimate design responsibility remains with the engineer of record. Most single-family construction is also required to have seismically engineered plans according to the UBC seismic provisions.

In the past, a compendium of prescriptive specifications known as the “Type V” sheet[9] provided for the necessary strength for seismic and other service loads on wood-frame homes. The “Type V” sheet originated in the 1950s with the latest revisions occurring in 1986. Now, the “Type V” sheet

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[7] Building Seismic Safety Council, *NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings—Part 1: Provisions and Part 2: Commentary*, Prepared for the Federal Emergency Management Agency (Washington: GPO, 1991).

[8] International Conference of Building Officials, *Uniform Building Code* (Whittier, CA: ICBO, 1991).

[9] City of Los Angeles Department of Building and Safety, “Type V Sheet - Wood Frame Buildings, Typical One and Two Story Construction Details”, B-16, R. 1-86.

is only used for non-habitable buildings, such as detached garages. Figure 1 illustrates the "Type V" construction and some basic prescriptive requirements.

Many single-family homes in the Los Angeles area were built according to the "Type V" sheet during the 1950s and 1960s. This manner of construction was also common to older multifamily buildings. Within the "Type V" requirements are several basic options for providing the necessary seismic bracing (shear wall capacities) of the home. In practice, portland cement plaster (stucco) was commonly used to provide the required lateral resistance to seismic loads.

Following the 1994 Northridge Earthquake, Los Angeles City organized task forces to review the performance of various types of construction. Of particular concern to residential construction were the emergency enforcement measures (code modifications) instituted for wood-frame construction.[10] These code changes are summarized as follows:

- reduce the allowable shear values for stucco to 90 #/ft (half of the allowable capacity in Table 47-I of the 1991 UBC);
- reduce the maximum allowable shear values for gypsum sheathing board and gypsum wall board to 30 #/ft (20 to 40 percent of the allowable capacity in Table 47-I of the 1991 UBC);
- disallowance of stucco, gypsum sheathing, or gypsum wall board shear capacities to contribute to the seismic load resistance at the ground level of multi-story buildings;
- allow only 75 percent of the allowable plywood shear wall values of Table 25K-1 in the 1991 UBC;
- require 3x members at the bottom sill plate and between adjacent panel edges for all plywood shear walls with a design shear value of 300 #/ft or more;
- allow only 75 percent of the allowable load values of hold-down connectors;
- limit column deflection to 0.005xH and require a buckling length factor of K=2.1 for steel columns on open, soft-story designs;
- do not allow the principle of rotation to distribute shear forces in any design;
- require the lateral force resisting system to be clearly shown on the construction plans; and
- require sufficient elevations and detail references for all shear walls, frames, etc. to be clearly shown on the plans.

In addition to these changes, the maximum shear wall aspect ratios permitted in the 1991 UBC were greatly reduced, meaning that the minimum length of walls intended to provide lateral resistance to seismic loads must be increased considerably. It is understood that these changes are intended for all types of wood-frame construction, single-family detached homes included.

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[10] City of Los Angeles, "Emergency Enforcement Measures - Wood Frame Construction, Revised", Interdepartmental memorandum, May 20, 1994.

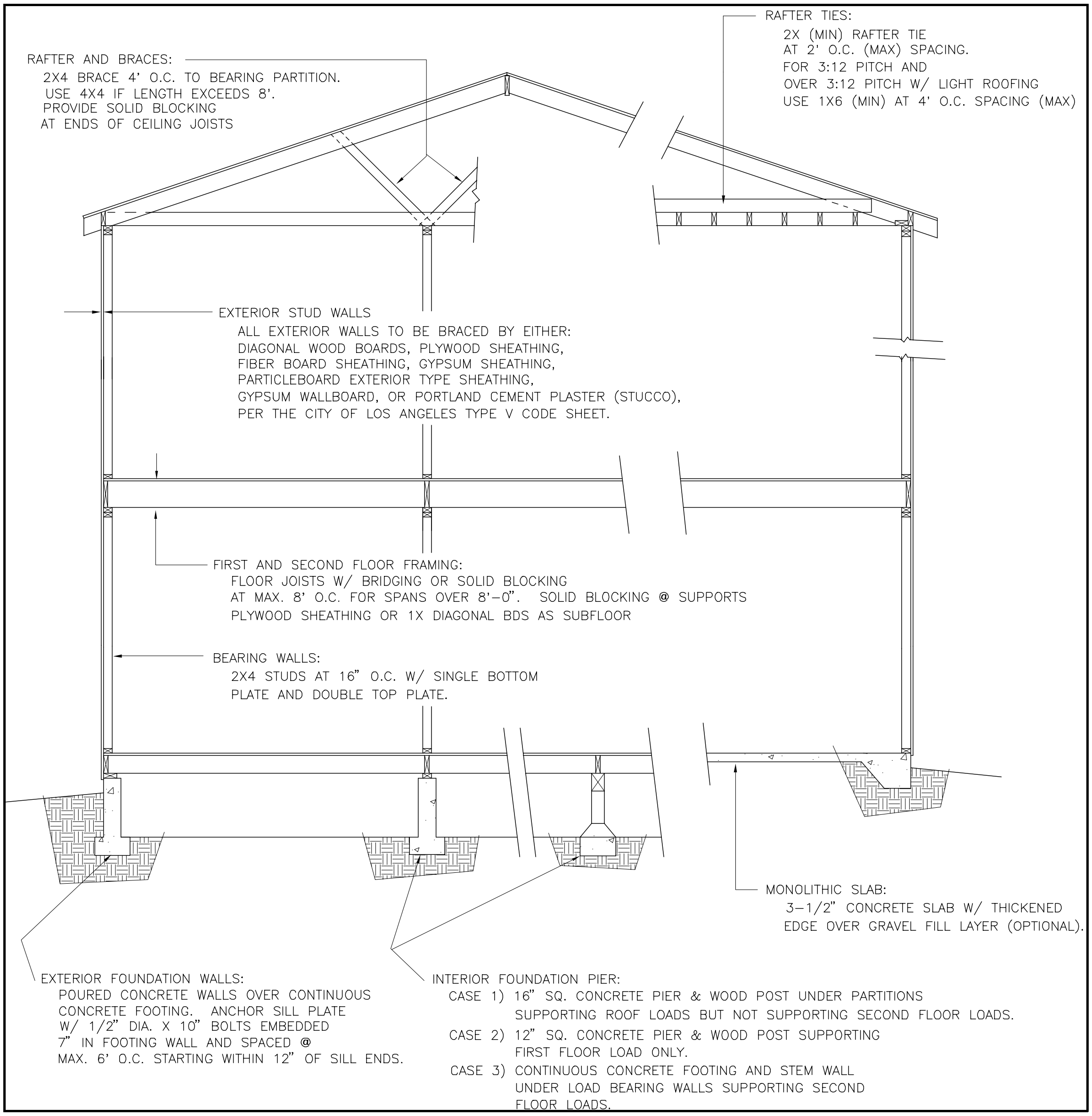

**Figure 1. Type V construction requirements typical of one-and-two story homes in the San Fernando Valley and Greater Los Angeles region.**

## Northridge Earthquake

The Northridge Earthquake occurred at 4:31 a.m. on January 17, 1994. Its epicenter was located in a densely populated area of Los Angeles county near the community of Northridge. Over 30 deaths were reported as a direct result of the tremor, and a total death toll of 58 was attributed to both direct and indirect causes.[11]

Current estimates of the severity of this earthquake place it at a magnitude of $M_L$= 6.4 on the Richter scale ($M_w$=6.7 and $M_S$=6.8).[12] The Northridge Earthquake is regarded as a moderately strong tremor by these magnitudes, but detailed analysis of specific characteristics from several seismograph readings shows this earthquake to be one of the worst in recorded history for the United States. In terms of the effective peak accelerations, the 475 year return period design estimate of 0.4 g was exceeded by a factor of 1.5 to 2 at several locations.[13]

There appears to be very little correlation between epicentral distance and the strong ground motion attributes for the records obtained in the north-west San Fernando Valley region.[13] Uncorrected peak horizontal ground accelerations were recorded at 0.9g near the epicenter and varied from 0.1g to 1.8g at specific near-field locations.[14] Also, uncorrected peak vertical accelerations between 0.4g and 0.5g were commonly observed. Large ground movements from the earthquake were felt as far away as Las Vegas. A map with the recorded peak horizontal ground accelerations is shown in Figure 2. These data are estimated from strong motion records of seismographs distributed in the San Fernando Valley and surrounding regions and is uncorrected for sources of “noise” in the readings.[15] For much of the San Fernando Valley, the ground motion, or pulse in this case, was oriented in a North-South direction.

Lasting about 15 to 20 seconds, the Northridge Earthquake created particularly severe loads for short period structures, such as low-rise buildings less than 4 stories in height.[13] The potential is manifested in the short duration pulse of energy imparted to buildings at one point during the duration of near-field ground motions. Because of this strong pulse, the impact was concentrated on the lowest story of many structures. In particular, soft-story construction (typically an open garage with little racking resistance underneath dwelling units) found in many older MFLR buildings were severely loaded by this earthquake.

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[11] National Institute of Standards and Technology, *1994 Northridge Earthquake—Performance of Structures, Lifelines, and Fire Protection Systems* (Washington: GPO, 1994).

[12] Hall.

[13] Naeim.

[14] R.L. Porcella, et al., “Accelerograms recorded at USGS National Strong-Motion Network Stations During $M_s$ = 6.6 Northridge, California Earth of January 17, 1994,” U.S. Geological Survey, Open File Report 94-141, February 1994.

[15] M.D. Trifunac, et al., *A Note on Distribution of Uncorrected Peak Ground Accelerations During the Northridge, California, Earthquake of 17 January, 1994* (Los Angeles: University of Southern California, 1994).

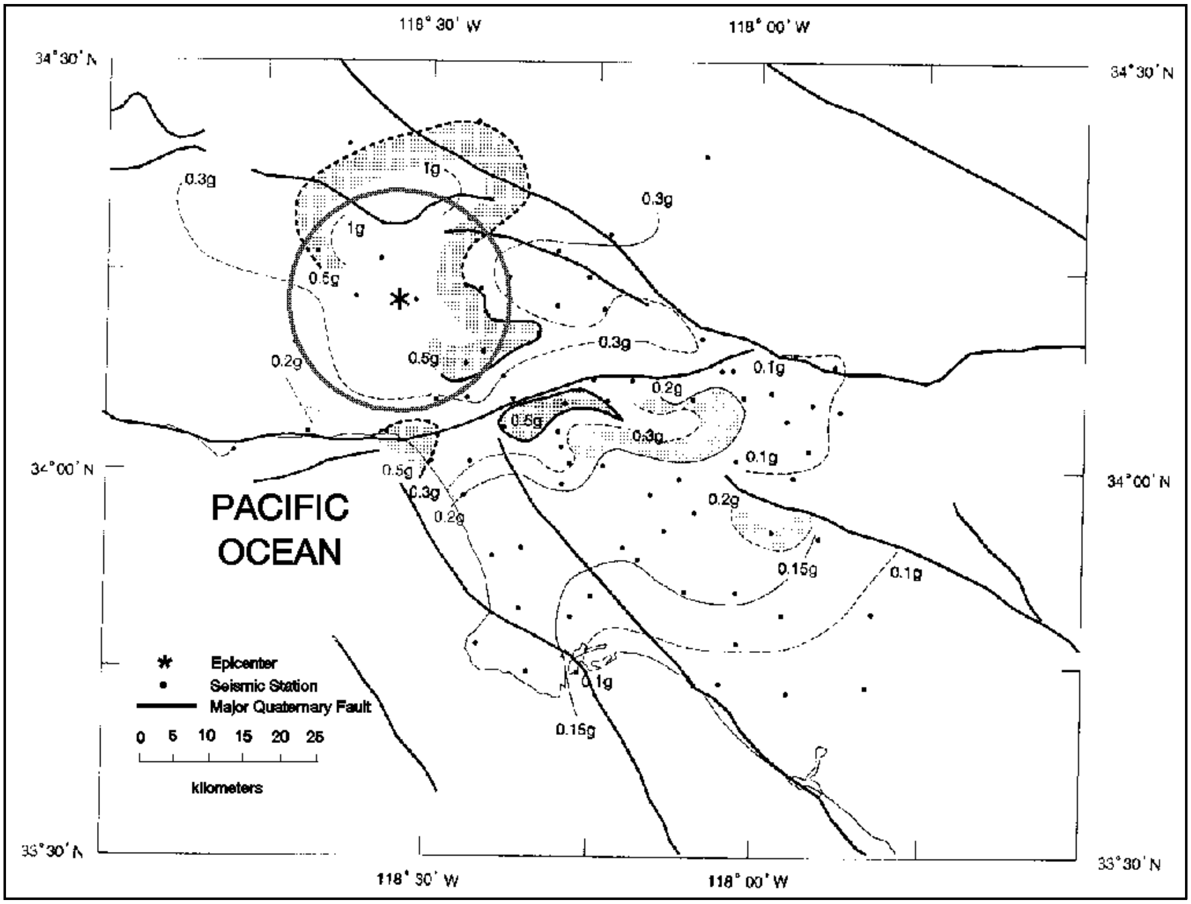

**Figure 2. Map of peak horizontal ground accelerations from the Northridge Earthquake. (after Trifunac, et al., University of Southern California)**

## Building Safety Inspections

As a major part of emergency response activities following the Northridge Earthquake, buildings were inspected by the Office of Emergency Services (OES) administered by the Los Angeles City Building Department. While other building jurisdictions performed similar inspections, the largest area was covered in the LA Building Department. In this process, buildings were rapidly inspected and tagged according to their hazard to occupants. “Red” tags were affixed to structures deemed hazardous to life. “Yellow” tags were assigned to buildings that posed a threat to life, but not so much that an occupant could not re-enter to remove possessions. “Green” tags were issued to buildings that did not pose a life-safety hazard to the occupants. For most residential structures, these inspections were initiated by calls from the occupants or property owner.

The outcome of these inspections as of February 21, 1994 is summarized in Table 1 and Figure 3. It should be noted that many of the “red” and “yellow” tagged SFD homes were subsequently downgraded to account for initial over-cautious tagging or removed hazards such as leaning or cracked chimneys. These data indicate a low incidence of serious structural damage, especially when one considers that most of these inspections were initiated by a concern for damage. In effect, Table 1 is biased toward over-estimation of actual damage (or hazard) occurence levels for the affected building population. While not an issue in the emergency inspections, non-structural damage was prevalent.

**Table 1**
**L.A. DEPARTMENT OF BUILDING & SAFETY**
**BUILDING INSPECTION RESULTS**

| Inspection Tagging | Single-Family Detached | Single-Family Attached | Low-Rise Multifamily |
|---|---|---|---|
| | Total | Total | Total |
| Green | 36,414 | 613 | 3,736 |
| Yellow | 4,604 | 112 | 766 |
| Red | 837 | 22 | 287 |
| Totals | 41,855 | 747 | 4,789 |

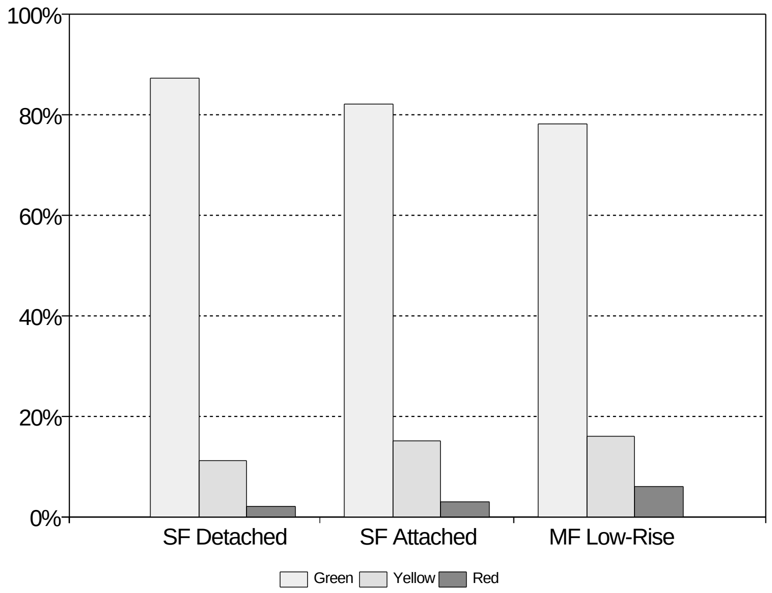

**Figure 3. Results of building inspections performed by L.A. Department of Building and Safety.**

# SURVEY METHOD

## Sampling Methodology

Prior to this survey, a preliminary site visit provided background information on the extent and type of damage experienced.[16] With information from the preliminary investigation, a damage zone for statistical sampling was established with a 10-mile radius around the epicenter, as shown in Figure 4. Postal regions defined by five-digit ZIP codes which fell within the damage zone or intersected its border were used as the basis for a random selection of homes from property tax records.

Two groups of building types were selected: single-family detached (SFD) properties, and single-family attached and multifamily low-rise (MFLR/SFA) of two stories and under. Along with the street address, the tax records included information on the age of the property, square footage, and name of the owner, among other data. According to current records, there are about 300,000 residential units of all types within the selected ZIP codes. The SFD survey was conducted as a random single-stage cluster sample. Seventy-five sites were selected by street address from the tax record database. The home at the selected address was surveyed along with two homes on either side, or a total of five homes per site. For the MFLR/SFA survey, the selected building was considered a single structure and all accessible areas or dwelling units within the structure were assessed.

Three damage assessment teams from the NAHB Research Center were each accompanied by a Los Angeles City building inspector for the duration of the survey. The entire survey was conducted over a 6 day period. At the completion of the field survey work, construction characteristics and damage to 341 SFD homes and 30 MFLR/SFA buildings were recorded. In addition to the statistically-based survey, case studies of damage were performed on 54 SFD and 43 MFLR/SFA buildings. Specific cases of excessive damage were identified by the Los Angeles City Building Department through their rapid screening inspection database. From this database and by word of mouth, “red- and yellow-tagged” or “severely damaged” homes were inspected to identify the cause(s) of damage.

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[16] Edward M. Laatsch, P.E., *January 17, 1994 San Fernando Valley Earthquake: Residential Damage Assessment—Draft Report,* Prepared for the U.S. Department of Housing and Urban Development, Manufactured Housing & Construction Division, February 2, 1994.

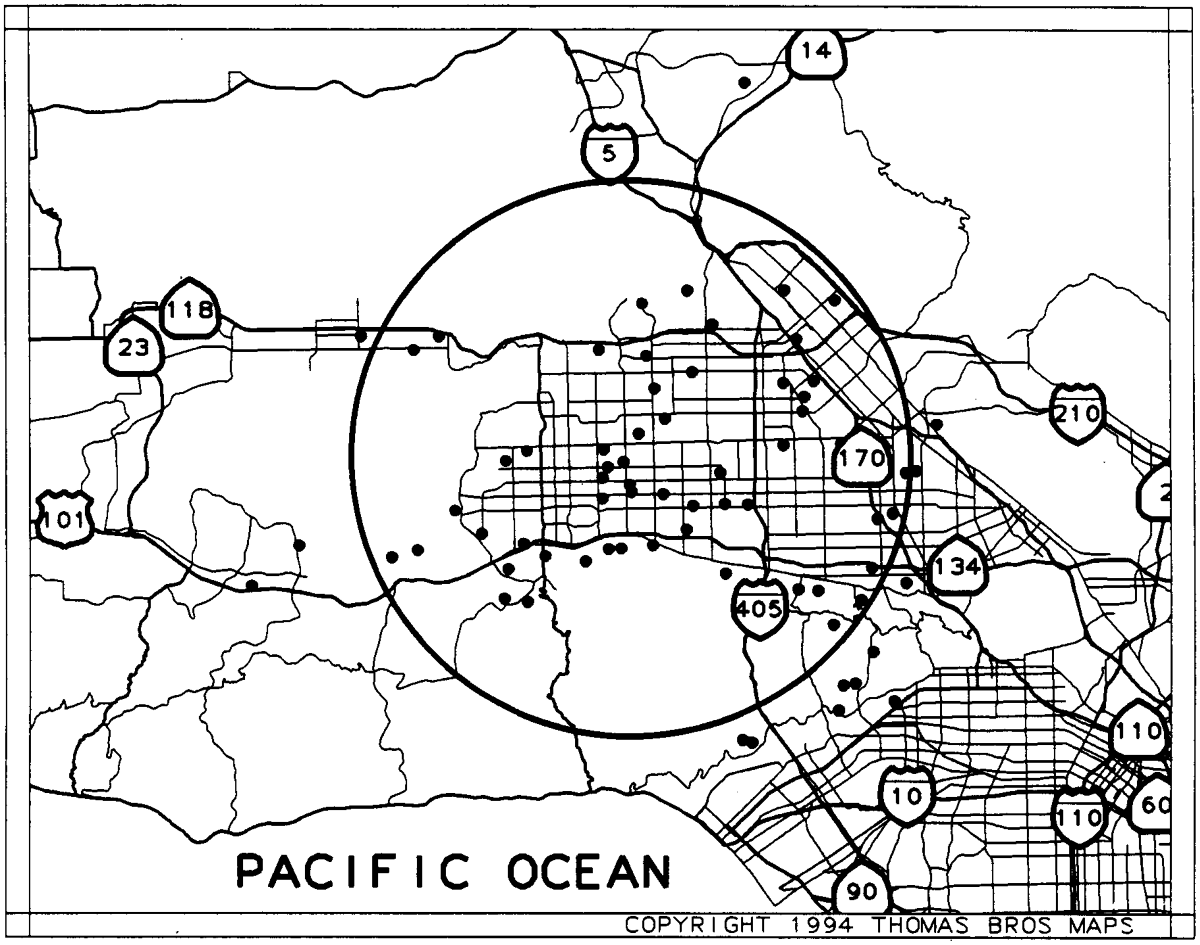


**Figure 4. Damage zone defined by a 10-mile radius around the epicenter and 5-digit ZIP codes. The dots represent the locations of the SFD survey samples.**

## Performance Grading Standardization

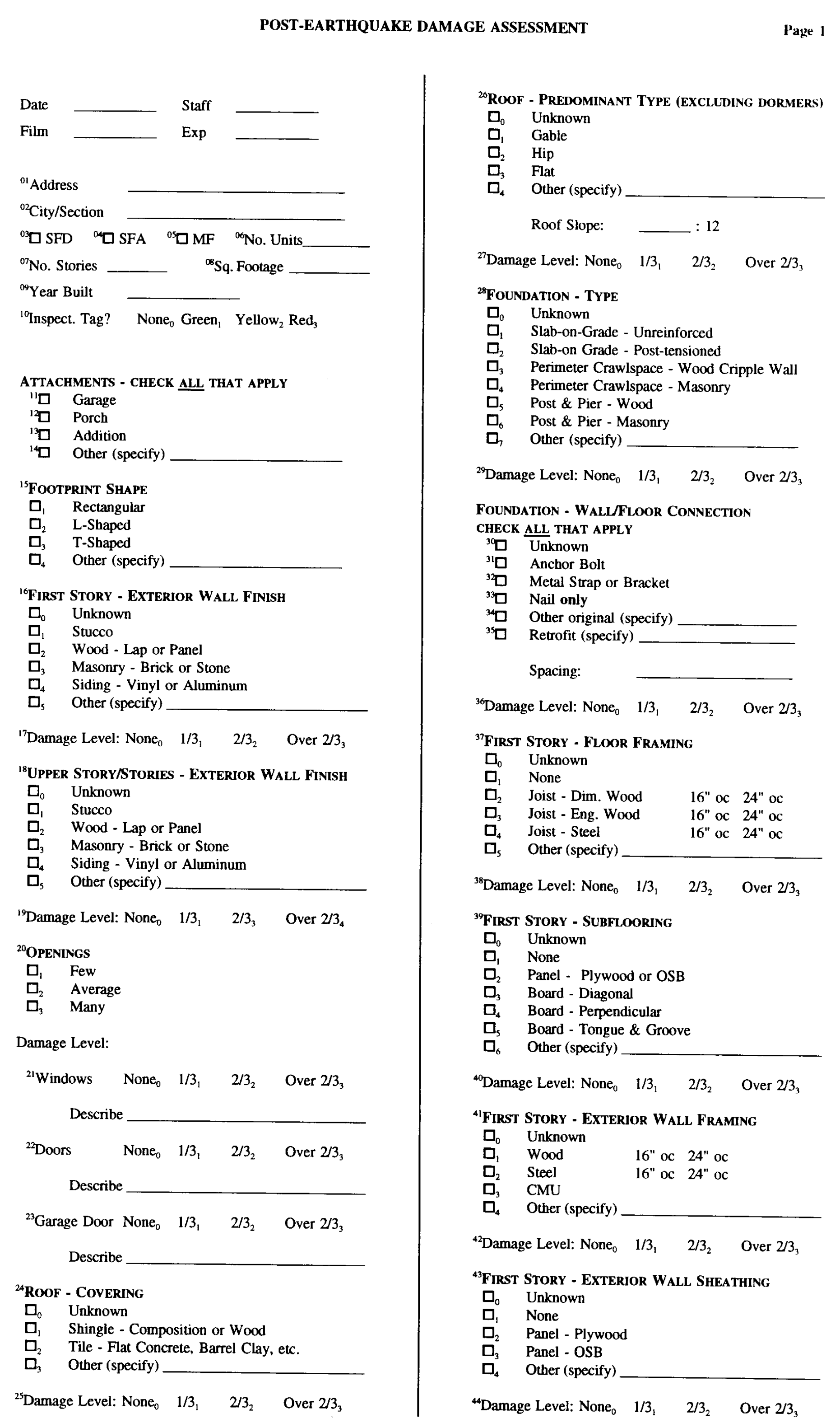
A damage assessment form, shown in Figures 5 and 6, was completed for each surveyed building. The completed form provides a record of the construction characteristics and performance of each assessed structure. In the comment section of the form, miscellaneous observations were recorded along with notes explaining non-typical conditions or unusual damage. Damage to chimneys was also recorded in the comment section and unfortunately can only be used to provide anecdotal observations. Photographs were taken of each assessed property. For each category listed on the survey form, earthquake damage was graded according to four basic levels of severity, as follows:

- NONE - no visible damage;
- LOW - components are stressed, but in functional condition;
- MODERATE - evidence of severe stress, permanent deflection, or near failure in any structural component; and
- HIGH - partial or complete failure of any structural component.

The detailed grading criteria applied by the assessment teams are described in Table 2.

Figures 7 and 8 illustrate application of the grading criteria to the *Foundation - wall/floor connection* and *First story - exterior wall finish* categories on the survey form.

In order to standardize the assignment of damage ratings by different teams, all teams graded several selected buildings and compared notes before commencing the survey. This exercise, conducted on the first day, helped the teams to develop a uniform approach to grading the severity of damage for each category on the survey form. Ten SFD homes and one MFLR building were used for this purpose. During the course of the survey, communication was maintained between teams to further insure against inconsistencies in grading.



**POST-EARTHQUAKE DAMAGE ASSESSMENT** Page 1

Date ______ Staff ______
Film ______ Exp ______

$^{01}$Address ______________
$^{02}$City/Section ______________
$^{03}$☐ SFD $^{04}$☐ SFA $^{05}$☐ MF $^{06}$No. Units______
$^{07}$No. Stories ______ $^{08}$Sq. Footage ______
$^{09}$Year Built ______
$^{10}$Inspect. Tag? None$_0$ Green$_1$ Yellow$_2$ Red$_3$

**ATTACHMENTS - CHECK ALL THAT APPLY**
$^{11}$☐ Garage
$^{12}$☐ Porch
$^{13}$☐ Addition
$^{14}$☐ Other (specify) ______________

**$^{15}$FOOTPRINT SHAPE**
☐$_1$ Rectangular
☐$_2$ L-Shaped
☐$_3$ T-Shaped
☐$_4$ Other (specify) ______________

**$^{16}$FIRST STORY - EXTERIOR WALL FINISH**
☐$_0$ Unknown
☐$_1$ Stucco
☐$_2$ Wood - Lap or Panel
☐$_3$ Masonry - Brick or Stone
☐$_4$ Siding - Vinyl or Aluminum
☐$_5$ Other (specify) ______________

$^{17}$Damage Level: None$_0$ 1/3$_1$ 2/3$_2$ Over 2/3$_3$

**$^{18}$UPPER STORY/STORIES - EXTERIOR WALL FINISH**
☐$_0$ Unknown
☐$_1$ Stucco
☐$_2$ Wood - Lap or Panel
☐$_3$ Masonry - Brick or Stone
☐$_4$ Siding - Vinyl or Aluminum
☐$_5$ Other (specify) ______________

$^{19}$Damage Level: None$_0$ 1/3$_1$ 2/3$_3$ Over 2/3$_4$

**$^{20}$OPENINGS**
☐$_1$ Few
☐$_2$ Average
☐$_3$ Many

Damage Level:

$^{21}$Windows None$_0$ 1/3$_1$ 2/3$_2$ Over 2/3$_3$
Describe ______________

$^{22}$Doors None$_0$ 1/3$_1$ 2/3$_2$ Over 2/3$_3$
Describe ______________

$^{23}$Garage Door None$_0$ 1/3$_1$ 2/3$_2$ Over 2/3$_3$
Describe ______________

**$^{24}$ROOF - COVERING**
☐$_0$ Unknown
☐$_1$ Shingle - Composition or Wood
☐$_2$ Tile - Flat Concrete, Barrel Clay, etc.
☐$_3$ Other (specify) ______________

$^{25}$Damage Level: None$_0$ 1/3$_1$ 2/3$_2$ Over 2/3$_3$

**$^{26}$ROOF - PREDOMINANT TYPE (EXCLUDING DORMERS)**
☐$_0$ Unknown
☐$_1$ Gable
☐$_2$ Hip
☐$_3$ Flat
☐$_4$ Other (specify) ______________

Roof Slope: ______ : 12

$^{27}$Damage Level: None$_0$ 1/3$_1$ 2/3$_2$ Over 2/3$_3$

**$^{28}$FOUNDATION - TYPE**
☐$_0$ Unknown
☐$_1$ Slab-on-Grade - Unreinforced
☐$_2$ Slab-on Grade - Post-tensioned
☐$_3$ Perimeter Crawlspace - Wood Cripple Wall
☐$_4$ Perimeter Crawlspace - Masonry
☐$_5$ Post & Pier - Wood
☐$_6$ Post & Pier - Masonry
☐$_7$ Other (specify) ______________

$^{29}$Damage Level: None$_0$ 1/3$_1$ 2/3$_2$ Over 2/3$_3$

**FOUNDATION - WALL/FLOOR CONNECTION**
**CHECK ALL THAT APPLY**
$^{30}$☐ Unknown
$^{31}$☐ Anchor Bolt
$^{32}$☐ Metal Strap or Bracket
$^{33}$☐ Nail only
$^{34}$☐ Other original (specify) ______________
$^{35}$☐ Retrofit (specify) ______________

Spacing: ______________

$^{36}$Damage Level: None$_0$ 1/3$_1$ 2/3$_2$ Over 2/3$_3$

**$^{37}$FIRST STORY - FLOOR FRAMING**
☐$_0$ Unknown
☐$_1$ None
☐$_2$ Joist - Dim. Wood 16" oc 24" oc
☐$_3$ Joist - Eng. Wood 16" oc 24" oc
☐$_4$ Joist - Steel 16" oc 24" oc
☐$_5$ Other (specify) ______________

$^{38}$Damage Level: None$_0$ 1/3$_1$ 2/3$_2$ Over 2/3$_3$

**$^{39}$FIRST STORY - SUBFLOORING**
☐$_0$ Unknown
☐$_1$ None
☐$_2$ Panel - Plywood or OSB
☐$_3$ Board - Diagonal
☐$_4$ Board - Perpendicular
☐$_5$ Board - Tongue & Groove
☐$_6$ Other (specify) ______________

$^{40}$Damage Level: None$_0$ 1/3$_1$ 2/3$_2$ Over 2/3$_3$

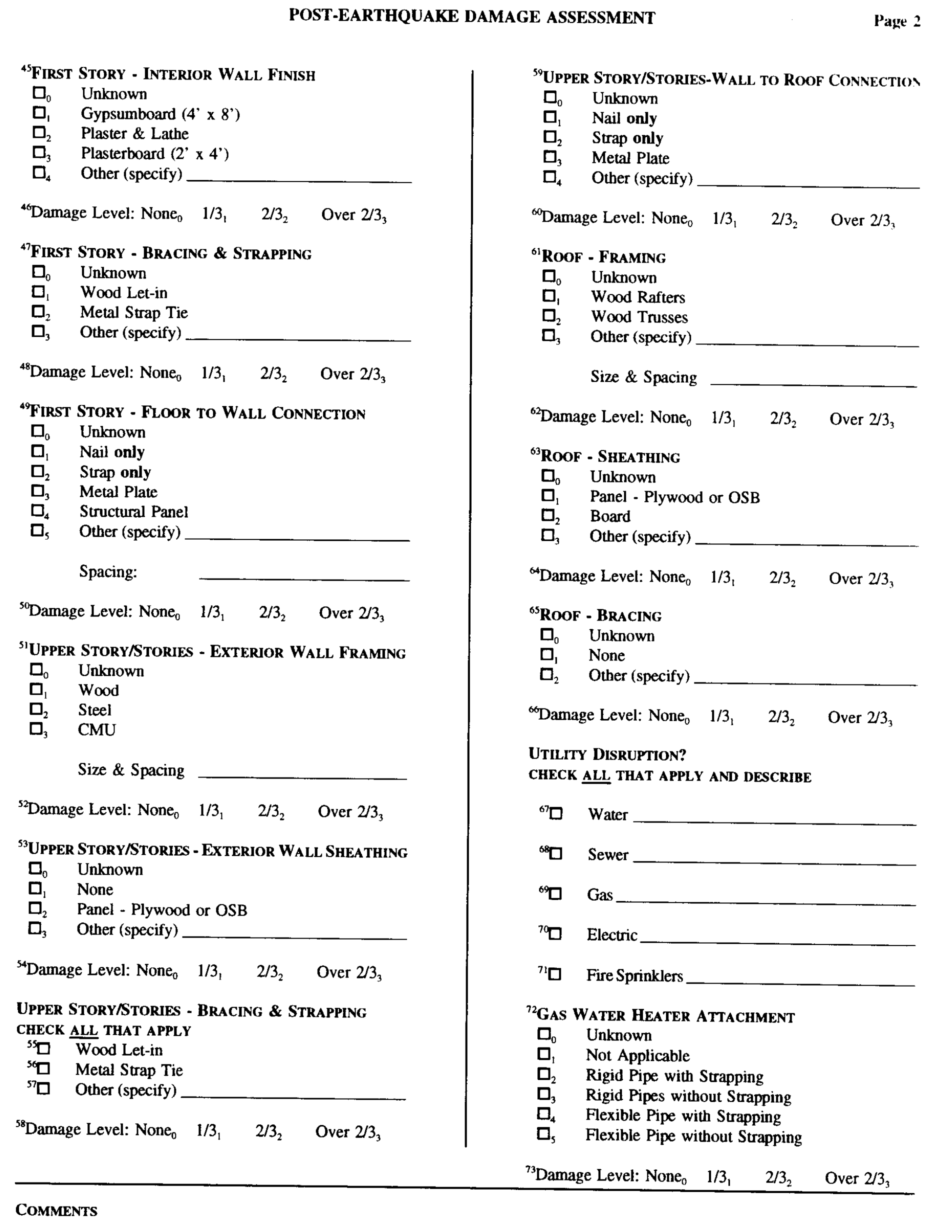
**$^{41}$FIRST STORY - EXTERIOR WALL FRAMING**
☐$_0$ Unknown
☐$_1$ Wood 16" oc 24" oc
☐$_2$ Steel 16" oc 24" oc
☐$_3$ CMU
☐$_4$ Other (specify) ______________

$^{42}$Damage Level: None$_0$ 1/3$_1$ 2/3$_2$ Over 2/3$_3$

**$^{43}$FIRST STORY - EXTERIOR WALL SHEATHING**
☐$_0$ Unknown
☐$_1$ None
☐$_2$ Panel - Plywood
☐$_3$ Panel - OSB
☐$_4$ Other (specify) ______________

$^{44}$Damage Level: None$_0$ 1/3$_1$ 2/3$_2$ Over 2/3$_3$

**Figure 5. Earthquake damage assessment survey form—Page 1.**



**POST-EARTHQUAKE DAMAGE ASSESSMENT** Page 2

$^{45}$**FIRST STORY - INTERIOR WALL FINISH**
☐$_0$ Unknown
☐$_1$ Gypsumboard (4' x 8')
☐$_2$ Plaster & Lathe
☐$_3$ Plasterboard (2' x 4')
☐$_4$ Other (specify) ____________________

$^{46}$Damage Level: None$_0$ 1/3$_1$ 2/3$_2$ Over 2/3$_3$

$^{47}$**FIRST STORY - BRACING & STRAPPING**
☐$_0$ Unknown
☐$_1$ Wood Let-in
☐$_2$ Metal Strap Tie
☐$_3$ Other (specify) ____________________

$^{48}$Damage Level: None$_0$ 1/3$_1$ 2/3$_2$ Over 2/3$_3$

$^{49}$**FIRST STORY - FLOOR TO WALL CONNECTION**
☐$_0$ Unknown
☐$_1$ Nail only
☐$_2$ Strap only
☐$_3$ Metal Plate
☐$_4$ Structural Panel
☐$_5$ Other (specify) ____________________

Spacing: ____________________

$^{50}$Damage Level: None$_0$ 1/3$_1$ 2/3$_2$ Over 2/3$_3$

$^{51}$**UPPER STORY/STORIES - EXTERIOR WALL FRAMING**
☐$_0$ Unknown
☐$_1$ Wood
☐$_2$ Steel
☐$_3$ CMU

Size & Spacing ____________________

$^{52}$Damage Level: None$_0$ 1/3$_1$ 2/3$_2$ Over 2/3$_3$

$^{53}$**UPPER STORY/STORIES - EXTERIOR WALL SHEATHING**
☐$_0$ Unknown
☐$_1$ None
☐$_2$ Panel - Plywood or OSB
☐$_3$ Other (specify) ____________________

$^{54}$Damage Level: None$_0$ 1/3$_1$ 2/3$_2$ Over 2/3$_3$

**UPPER STORY/STORIES - BRACING & STRAPPING**
**CHECK ALL THAT APPLY**
$^{55}$☐ Wood Let-in
$^{56}$☐ Metal Strap Tie
$^{57}$☐ Other (specify) ____________________

$^{58}$Damage Level: None$_0$ 1/3$_1$ 2/3$_2$ Over 2/3$_3$

$^{59}$**UPPER STORY/STORIES-WALL TO ROOF CONNECTIO**
☐$_0$ Unknown
☐$_1$ Nail only
☐$_2$ Strap only
☐$_3$ Metal Plate
☐$_4$ Other (specify) ____________________

$^{60}$Damage Level: None$_0$ 1/3$_1$ 2/3$_2$ Over 2/3$_3$

$^{61}$**ROOF - FRAMING**
☐$_0$ Unknown
☐$_1$ Wood Rafters
☐$_2$ Wood Trusses
☐$_3$ Other (specify) ____________________

Size & Spacing ____________________

$^{62}$Damage Level: None$_0$ 1/3$_1$ 2/3$_2$ Over 2/3$_3$

$^{63}$**ROOF - SHEATHING**
☐$_0$ Unknown
☐$_1$ Panel - Plywood or OSB
☐$_2$ Board
☐$_3$ Other (specify) ____________________

$^{64}$Damage Level: None$_0$ 1/3$_1$ 2/3$_2$ Over 2/3$_3$

$^{65}$**ROOF - BRACING**
☐$_0$ Unknown
☐$_1$ None
☐$_2$ Other (specify) ____________________

$^{66}$Damage Level: None$_0$ 1/3$_1$ 2/3$_2$ Over 2/3$_3$

**UTILITY DISRUPTION?**
**CHECK ALL THAT APPLY AND DESCRIBE**

$^{67}$☐ Water ____________________
$^{68}$☐ Sewer ____________________
$^{69}$☐ Gas ____________________
$^{70}$☐ Electric ____________________
$^{71}$☐ Fire Sprinklers ____________________

$^{72}$**GAS WATER HEATER ATTACHMENT**
☐$_0$ Unknown
☐$_1$ Not Applicable
☐$_2$ Rigid Pipe with Strapping
☐$_3$ Rigid Pipes without Strapping
☐$_4$ Flexible Pipe with Strapping
☐$_5$ Flexible Pipe without Strapping

$^{73}$Damage Level: None$_0$ 1/3$_1$ 2/3$_2$ Over 2/3$_3$

**COMMENTS**

Figure 6. Earthquake damage assessment survey form—Page 2.

## Table 2
## PERFORMANCE GRADING CRITERIA FOR KEY ELEMENTS OF A HOME

| BUILDING ELEMENT | PERFORMANCE GRADING CRITERIA | | |
|---|---|---|---|
| | LOW | MODERATE | HIGH |
| FOUNDATION STRUCTURE | Minor movement in the foundation structure which results in cosmetic damage, such as hairline cracking of finishes No visible settlement or permanent deflection of structural components. | Moderate movement in the foundation structure which results in wider cracks in stucco finishes along the foundation. The building is not displaced from the foundation. Evidence of some permanent movement may exist from sliding at the foundation connections. Settlement with minor cracking may have occurred at an isolated location (ie. one corner) of the foundation. | Extensive movement and damage to the foundation which may result in settlement, cracking of the foundation, collapse of the foundation, deformation of connections, or wholesale sliding of the building relative to the foundation. The damage may be life threatening, particularly on hillsides homes. |
| WALL STRUCTURE | Minor evidence of wholesale wall lateral movements without visible permanent deflection. Hairline cracks in stucco finish at openings in the wall. | Doors and windows may be difficult to operate. Some minor separation of framing members at connections is evidenced along the sill or top plates of wood framing. Stucco finishes exhibit localized diagonal cracks indicative of overstressing of in-plane shear capacity. Cracks in stucco radiate from openings in the wall. Evidence of permanent deflection/racking is visible in wall elements with large openings. | Wholesale racking of walls is evident. Framing members may be disjointed at connections. Partial to complete collapse of any wall section may have occurred. Stucco finishes are severely stressed with diagonal cracking and may be disconnected from the underlying framing. |
| ROOF STRUCTURE | Roof is intact and no visible signs of settlement has occurred. Localized damage from chimney movement may have stressed surrounding roof framing and sheathing connections. | Ridgeline shows evidence of sagging and rafters and bracing show evidence of movement or stressing of connections. Walls show minor bowing outward from settling of the roof. | Partial to complete collapse of any section of the roof has occurred. |
| INTERIOR FINISH | Hairline cracks exist at first story wall openings and isolated cracking at joints in gypsum or plasterboard sheathing. | Cracking at sheathing joints and wall openings is widespread and exists on interior walls and ceilings. Some plaster has spalled along cracks at major openings. | Major cracking and spalling at cracks. Connection of gypsum sheathing panels to framing is stressed. Gypsum board, or other finish system may be disconnected from the wall framing. |
| EXTERIOR FINISH | Hairline cracks exist at the top of the foundation and/or at openings in the first story walls. | Hairline cracks in stucco radiate from several large and small openings. First story cracks and those along the foundation may have widened from several cycles of shaking. Hairline cracks are evident at openings in upper stories. | Major cracking and spalling at cracks at more than the first story. Stucco, or other exterior finish, may be disconnected from the framing. Diagonal cracking is evident between openings. |

Figure 7. Photograph showing an example of "HIGH" damage to the foundation-wall/floor connection on the crawlspace foundation in a SFD home.

Figure 8. Photograph of a MFLR building with "MODERATE" damage to the First Story-Exterior Wall Finish (stucco) of a MFLR building.

# RESULTS: SINGLE-FAMILY DETACHED HOMES

## Description of SFD Homes

The survey teams visited 75 sites in the hope of surveying 375 SFD homes—five homes per site. These visits resulted in 341 usable survey forms. The balance included homes that were inaccessible (e.g., in a secure, gated community) or sites where fewer than five homes were within a reasonable distance of the selected address.

Using information provided by the property tax record database and inspectors with the Department of Building and Safety, it was determined that about 90 percent of the homes in the sample were built prior to the 1971 San Fernando Valley Earthquake when simple prescriptive requirements were normal to SFD home construction. About 60 percent of the surveyed homes were built during the 1950s and 1960s. Sampled homes ranged in age from the 1920s to the present.

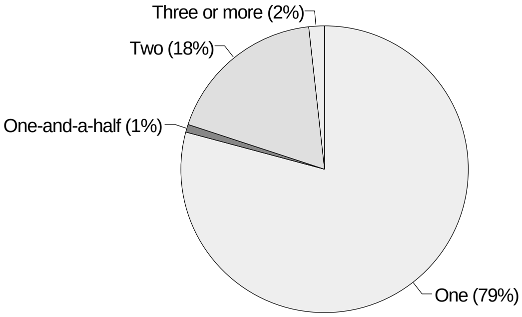


**Figure 9. Survey results: number of stories in single-family detached homes.**

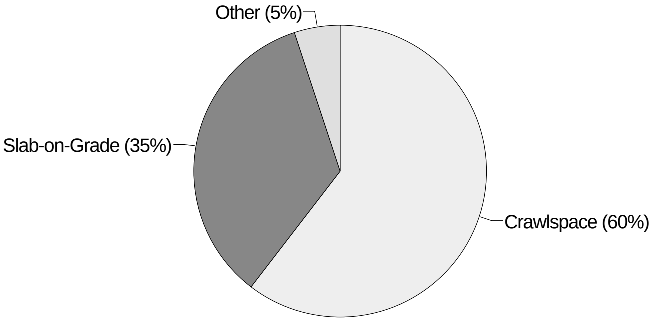


**Figure 10. Survey results: type of foundation in single-family detached homes.**

The basic construction characteristics of the housing stock in the assessment area is summarized in Table 3 with a 95 percent confidence interval of 2 to 5 percentage points on either side of the stated estimate. The major characteristics are shown in Figures 9 through 11.

SFD homes were typically one story and nearly two-thirds had an attached garage. Styles of SFD homes ranged from expensive custom homes (Figure 12) to more affordable and older homes of typical “Type V” construction (Figure 13). As expected with the predominance of “Type V” construction, all homes surveyed had wood exterior wall framing. Homes on crawlspace foundations outnumbered those on concrete slabs by almost two-to-one, despite a notable increase in the use of slab-on-grade foundations since the 1960s. Most of the crawlspace foundations used full-height concrete or masonry stem walls and not cripple walls. Plywood was rarely used for exterior wall sheathing as common to newer, engineered homes. A stucco exterior finish was typically applied over wire mesh and building paper or felt applied to the studs per the "Type V" prescriptive requirements. A widespread use of wood roof rafters and plaster interior finish also indicates a predominance of older homes.

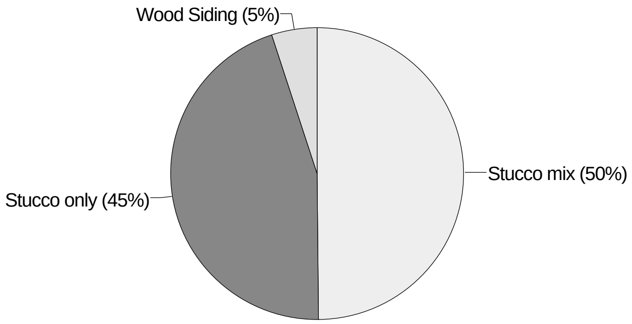


Figure 11. Survey results: type of exterior finish on single-family detached homes.

Figure 12. One of several custom built homes randomly selected for damage assessment in the SFD survey.

Figure 13. One of many affordable homes of "Type V" (wood-frame and stucco) construction selected for study in the SFD random survey.

## Table 3
## CHARACTERISTICS OF THE SINGLE-FAMILY DETACHED HOME SAMPLE

| **Sample: 341 homes at 75 sites** | | |
|---|---|---|
| Year Built | 1970 or before | 88% |
| | 1971 or later | 12% |
| Stories | One | 79% |
| | Two | 18% |
| | One-and-a-half | 1% |
| | Three or more | 2% |
| Shape | Rectangular | 41% |
| | Irregular | 59% |
| Attachments<br>(May be more than one type per home) | Garage | 64% |
| | Porch | 20% |
| | Addition | 11% |
| | Other | 3% |
| Exterior Finish | Stucco mix | 50% |
| | Stucco only | 45% |
| | Wood Siding | 5% |
| Interior Finish | Plaster | 60% |
| | Gypsum Board | 26% |
| | Other | 1% |
| | Unknown | 13% |
| Exterior Framing | Wood | 99% |
| | Other | 1% |
| Wall Sheathing | None | 80% |
| | Plywood | 7% |
| | Unknown | 13% |
| Roof Framing | Wood Rafter | 87% |
| | Wood Truss | 5% |
| | Other | 5% |
| | Unknown | 3% |
| Roof Sheathing | Board | 69% |
| | Panel - Ply or OSB | 16% |
| | Other | 3% |
| | Unknown | 12% |
| Foundation | Crawlspace—stem wall | 68% |
| | Crawlspace—cripple wall | 3% |
| | Slab-on-Grade | 34% |
| | Other | 5% |

## Performance of SFD Homes

The performance of SFD homes, as judged by the methods used in this survey, is shown in Table 4. The table is broken into the observed damage in the sample of home and estimates of damage for the entire population of homes within the survey area. The estimated damage is also shown in Figure 14. According to property tax records, there were 183,514 SFD properties in the survey area. As is inherent in all survey work, some error is present in applying these performance ratings as estimates for the entire housing stock of the study area. For example, it is known by the case study observations (discussed later) that homes with “HIGH” wall and roof damage did exist in the study zone, but were undetected by the random draw of homes for the survey. For this reason, 95 percent confidence intervals are shown for each estimate. The method used to calculate the confidence intervals is described in the Appendix.

**Table 4**
**DESCRIPTION OF DAMAGE**
**TO SINGLE-FAMILY DETACHED HOMES**

| **Observed Damage** | Sample Size | No Damage | Low Damage | Moderate Damage | High Damage |
|---|---|---|---|---|---|
| Foundation | 327 | 295 | 26 | 3 | 3 |
| Foundation-to-Walls | 324 | 293 | 24 | 5 | 2 |
| Walls | 317 | 311 | 6 | 0 | 0 |
| Roof | 328 | 326 | 2 | 0 | 0 |
| Exterior Finish | 306 | 155 | 141 | 9 | 1 |
| Interior Finish | 265 | 132 | 122 | 11 | 0 |
| | | | | | |
| **Estimated Damage within Survey Area** | | **No Damage** | **Low Damage** | **Moderate Damage** | **High Damage** |
| Foundation | | 87.9% < **90.2%** < 92.5% | 5.9% < **8.0%** < 10.0% | 0.3% < **0.9%** < 2.7% | 0.3% < **0.9%** < 2.7% |
| Foundation-to-Walls | | 88.1% < **90.4%** < 92.7% | 5.4% < **7.4%** < 9.4% | 0.5% < **1.5%** < 3.6% | 0.2% < **0.6%** < 2.2% |
| Walls | | 94.0% < **98.1%** < 99.0% | 0.9% < **1.9%** < 4.1% | 0.0% < **0.0%** < 0.9% | 0.0% < **0.0%** < 0.9% |
| Roof | | 97.2% < **99.4%** < 99.6% | 0.2% < **0.6%** < 2.2% | 0.0% < **0.0%** < 0.9% | 0.0% < **0.0%** < 0.9% |
| Exterior Finish | | 46.7% < **50.7%** < 54.7% | 42.1% < **46.1%** < 50.1% | 1.6% < **2.9%** < 5.5% | 0.1% < **0.3%** < 1.8% |
| Interior Finish | | 45.5% < **49.8%** < 54.1% | 41.8% < **46.0%** < 50.3% | 2.4% < **4.2%** < 7.3% | 0.0% < **0.0%** < 1.1% |
| | | | | | |
| Foundation | | 161,300 < **165,600** < 169,800 | 10,700 < **14,600** < 18,400 | 600 < **1,700** < 4,900 | 600 < **1,700** < 4,900 |
| Foundation-to-Walls | | 161,800 < **166,000** < 170,200 | 9,900 < **13,600** < 17,300 | 900 < **2,800** < 6,500 | 400 < **1,100** < 4,100 |
| Walls | | 172,600 < **180,000** < 181,700 | 1,600 < **3,500** < 7,500 | 0 < **0** < 1,700 | 0 < **0** < 1,700 |
| Roof | | 178,400 < **182,400** < 182,700 | 300 < **1,100** < 4,000 | 0 < **0** < 1,700 | 0 < **0** < 1,700 |
| Exterior Finish | | 85,600 < **93,000** < 100,300 | 77,200 < **84,600** < 91,900 | 2,900 < **5,400** < 10,100 | 100 < **600** < 3,300 |
| Interior Finish | | 83,500 < **91,400** < 99,300 | 76,600 < **84,500** < 92,400 | 4,300 < **7,600** < 13,400 | 0 < **0** < 2,100 |

## Discussion of SFD Performance

***Foundation and Framing Observations.*** Damage to structural elements—foundation, wall framing, and roof framing—was limited to a small proportion of surveyed homes. In general, as shown in Table 4, SFD homes suffered minimal damage to elements that are critical to the safety of occupants.

Of the structural elements, damage was most common in the foundation system. The small percentage of surveyed homes that experienced MODERATE to HIGH foundation damage were located in areas that endured localized ground effects or problems associated with hillside sites. The ground effects included localized fissures or ground settlement which cracked foundations. For hillside sites, partial slope failures contributed to the foundation damage. Examples of these conditions are addressed in a later section devoted to case studies.

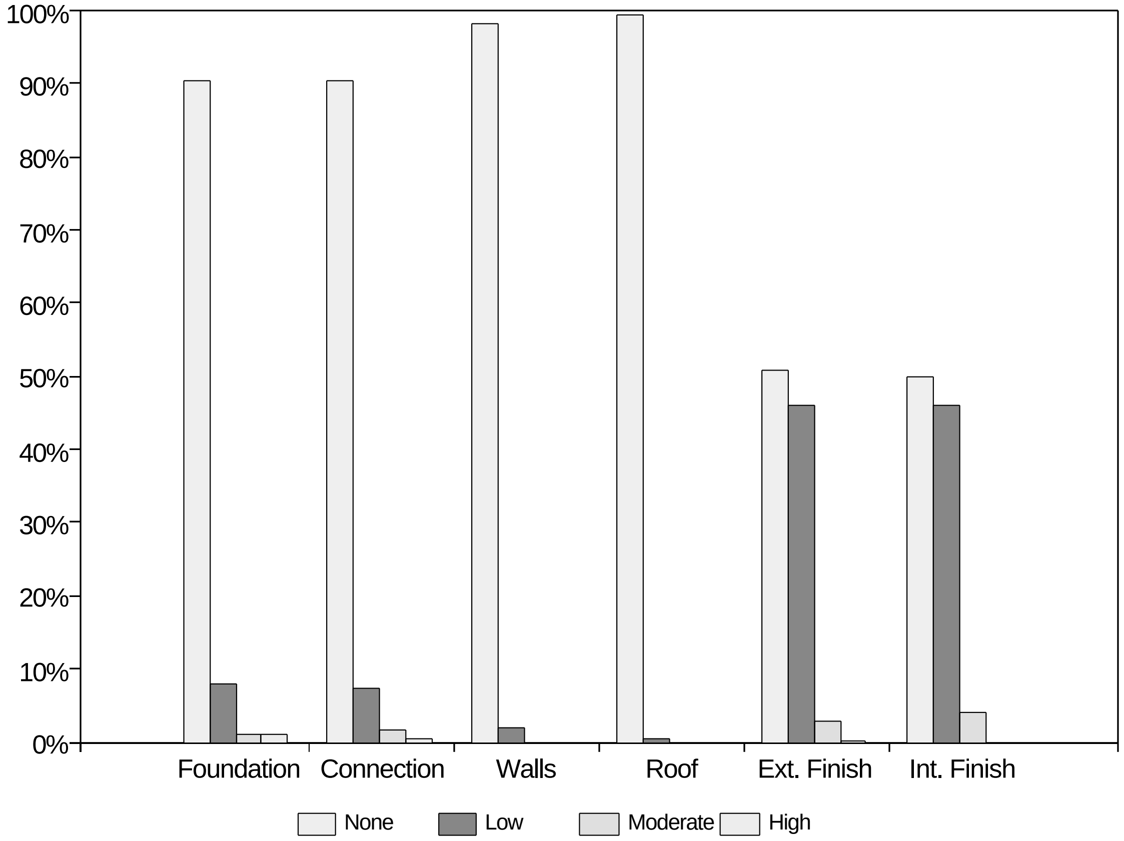


**Figure 14. Survey results: Damage to single-family detached homes observed by area of building.**

***Interior and Exterior Finishes Observations.*** Interior and exterior finishes suffered more widespread damage than foundation and framing, with only about half the buildings escaping unscathed. However, the great majority of damage was limited to the lowest rating categories. Stucco was observed on nearly all home exteriors. Damage to stucco usually appeared as hairline cracks radiating from the corners of openings, particularly larger openings such as garage doors, or along the top of the foundation. Interior finish damage paralleled the occurence of exterior finish (stucco) damage. Resilient finishes—such as wood panel or lap board siding—fared well and often showed no evidence of damage even when stucco on other areas of the same building was modestly damaged.

***Statistical Inferences on the Performance Data.*** Because damage to foundations and framing elements was observed so infrequently, statistical analysis to discern significant differences in building earthquake resistance is limited. Statistical analysis is further hampered by the homogeneity of the housing stock in the San Fernando Valley, where surveyed houses portrayed similar characteristics ("Type V" wood-frame construction) and experienced little damage overall.

The Chi-square test was used—at a 95 percent level of confidence—to judge statistical significance of various conditions on the outcome of a home's performance. Chi-square, commonly known as a non-parametric test, provides a simple statistical test based on the difference between observed and expected frequency distributions. It is often used because it is easy to understand and calculate, and makes few assumptions on the underlying population.[17]

The inferences initially designated for study by the Chi-square test included observed performance versus:

- peak ground acceleration estimates,
- age of the home,
- roof type
- number of stories, and
- foundation type.

Chi-square analyses requires a large number of observations in each category to produce valid results. Thus, the analysis was limited to the exterior damage rating as the performance indicator since it represented the greatest extent of damage. Also, the LOW, MODERATE, and HIGH damage ratings were grouped such that a damage/no-damage test was applied.

All inferences—with the exception of foundation type—were inconclusive. Using only data from one-story homes, comparison of crawlspace versus slab-on-grade foundation construction shows a significant difference in the level of damage to the stucco used on one-story homes. It is likely that the stucco damage rating was influenced largely by the horizontal cracking commonly seen along the top of the foundation (Figure 15). Single-story homes with slab foundations exhibited damage to exterior finishes in about 30 percent of the cases, while homes on crawlspace foundations with masonry or concrete stem walls approached a 60 percent rate of occurrence.

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[17] Thomas H. Wonnacott and Ronald J. Wonnacott, *Introductory Statistics for Business and Economics* (New York: J. Wiley and Sons, 1990).

**Figure 15. Stucco damage along the top of a crawlspace foundation on a SFD home.**

There are differences between slabs and crawlspaces in the sample aside from the obvious fact that slab homes rest on the ground and crawlspace homes are largely above it. The majority of crawlspace homes in the survey area were built before 1960 while nearly three-quarters of slab homes were built after 1960. Stucco performance alone as an indicator of differences in foundation performance is not sufficiently rigorous to conclude that one foundation type is necessarily better than another. There may be factors influencing stucco performance other than merely foundation type, such as:

- lower resiliency of older stucco;
- variations in stucco formulation over time;
- effects of differences in the severity of ground shaking across the survey area;
- foundation/soil interaction effects;
- changes in application methods, thickness, and backing materials; and
- differences in the construction of other building elements that may affect stucco performance.

For slab-on-grade homes, the continuity between the wall system and foundation is maintained by a single joint defined by the connection of the sill plate directly to the slab (Figure 16). This connection only needs to transfer the lateral loads imparted by the inertial reaction of the walls, roof, and any upper stories. For crawlspace homes, the connection of the walls to the foundation must also pass through the floor system (Figure 16). This construction requires two joints—one at the sill plate and one at the wall plate—separated by the height of the floor joists. Because this connection bears the inertial reaction of the first floor and the rest of the above ground structure, the seismic load is greater than for similar homes with slab-on-grade foundations.

In effect, greater flexibility in the foundation connections associated with crawlspace construction by "Type V" prescriptive requirements result in greater deflections during severe ground shaking. Since stucco is brittle, it is sensitive to increases in flexibility of the framing to which it is adhered. As an advantage, this inherent flexibility in the crawlspace construction helps dissipate the transfer of seismic energy or loads to the upper stories of the home which would otherwise create a greater life safety risk for homes on relatively flat sites.

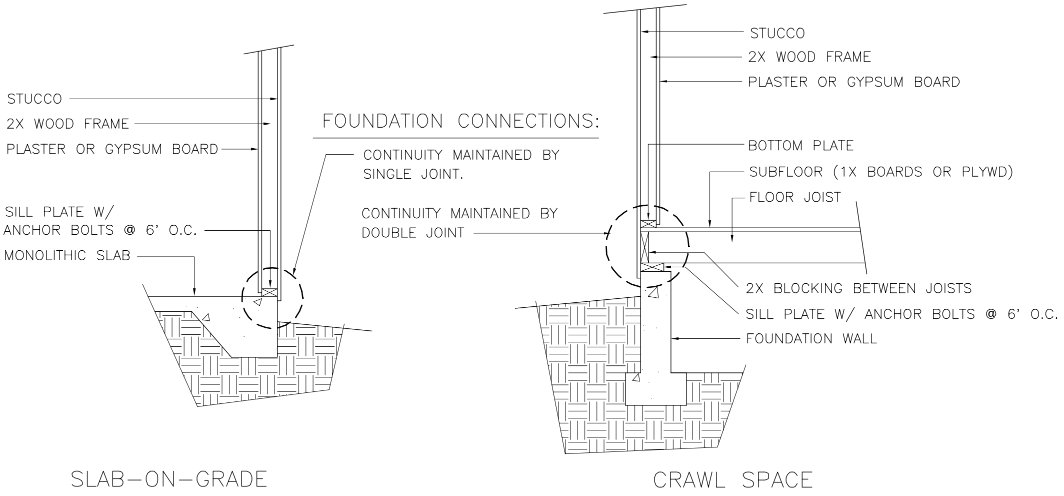

**Figure 16 . Detail of the foundation connections for crawlspace and slab-on-grade construction built to the outmoded LA City Type V prescriptive requirements.**

## Case Studies of SFD Homes

This section presents findings from case studies of damage to 54 SFD homes that experienced severe damage during the Northridge earthquake. Since structural damage was uncommon among the affected housing population, these case studies were conducted on a selected sample representative of less than 0.02 percent of the housing population in the study area and surrounding communities. The most notable sources of structural damage to these case study homes were related to ground conditions (e.g., fissures and settlement) and hillside construction conditions (e.g., weak foundation connections or partial slope failures). Damage to wall finishes, building contents, mechanical equipment, masonry chimneys, and masonry privacy fences was much more common.

The following case studies address both structural and non-structural damage using photographic documentation and site observations. When appropriate, the case study damage is referenced in terms of the statistical survey results to allow comparison to the housing population's performance reported earlier. The following topics are addressed:

- Ground settlement,
- Ground fissuring,
- Hillside construction problems,
- Foundation cripple wall collapse,
- Racking of walls,
- Roof framing damage,
- Roof tile damage,
- Masonry chimney failures,
- Damage to masonry privacy walls,
- Contents damage,
- Damage to mechanical equipment,
- Exterior finish damage,
- Interior finish damage,
- Damage to building attachments, and
- Fire damage.

## CASE STUDY

## TOPIC: Ground Settlement

**Figure 17. An example of one home in Simi Valley which experienced settlement because of soil liquifaction. (Foundation damage rating: HIGH)**

## COMMENTARY:

Damage to homes from ground settlement or liquifaction was very isolated and limited in extent in the San Fernando Valley. As shown in the photograph above, this home settled several inches as evidenced by the door threshold being lower than the sidewalk. In Simi Valley, damage from ground fissures was also observed. Other phenomena—such as sand boils—also indicate that ground conditions were the primary cause of serious damage experienced in this community. Roads, sidewalks, underground utilities, and other infrastructure were damaged by these types of ground problems. In a few cases for homes surveyed in the San Fernando Valley, isolated settlement occurred at a corner of a home. Lateral ground spreading was also found at localized sites in the San Fernando Valley where two homes in the statistical survey were assessed a MODERATE damage rating to their foundations.

## CASE STUDY

### TOPIC: Ground Fissuring

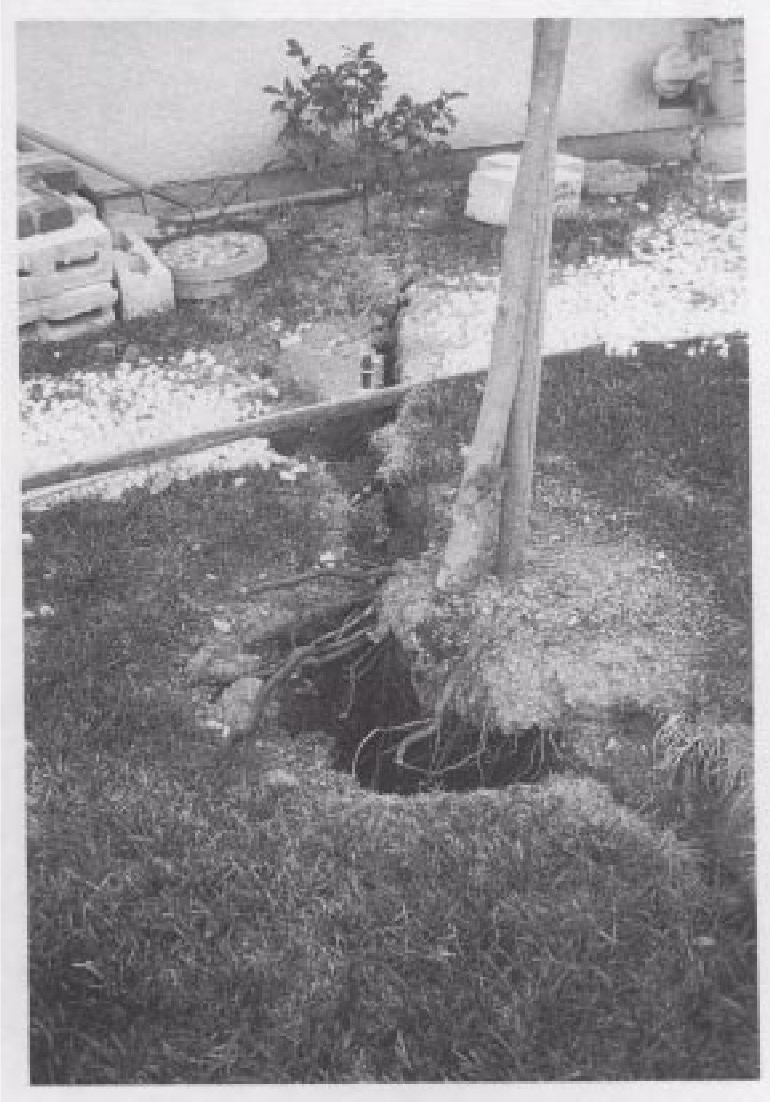

**Figure 18. An example of a ground fissure intersecting the foundation of a home located in the Tujunga Canyon area.**

### COMMENTARY:

As in Simi Valley, isolated incidences of ground fissuring were found in the Tujunga Canyon area. The fissure passed directly underneath a home which was also part of the statistical damage survey. Needless to say, this home was given a “HIGH” damage rating to its foundation. The floor slab was severely cracked with offsets in floor height approaching four to five inches along a major crack.

## CASE STUDY

### TOPIC: Hillside Construction Problems

**Figure 19. One example of the serious nature of foundation damage on hillside homes with a stepped foundation wall (Foundation/wall connection damage rating: HIGH)**

**Figure 20. Splintered and leaning, the 6x6 wood columns were marginally successful in supporting this home which overhangs a hill-side. (Foundation damage rating: HIGH)**

## CASE STUDY

### TOPIC: Hillside Construction Problems (continued)

**Figure 21. Example of a critical failure at the connection of the floor joists to the foundation wall on the same home as in Figure 20. (Foundation/wall connection rating: HIGH)**

### COMMENTARY:

While only 2 percent of the surveyed homes throughout the San Fernando Valley area experienced any level of structural damage to the foundation, this became a more serious concern for homes on sloped sites. In Figure 19, stepping the footing to negotiate the sloped site created discontinuities at the foundation which weakened lateral resistance. Also susceptible to collapse were hillside homes that were supported on columns on the down slope side and attached to a concrete foundation wall on the uphill side (Figures 20 and 21). Collapse of this home was narrowly avoided as evidenced by the splintered and leaning wood column (Figure 20) and torn-out bolts connecting floor joists to the foundation wall (Figure 21). In a few cases, these types of hillside construction collapsed and crashed down the slope. Three deaths were attributed to this type of failure.

## CASE STUDY

### TOPIC: Foundation Cripple Wall Collapse

**Figure 22. An example of a foundation collapse of the section of a home supported on a cripple wall caused by the 1994 Northridge Earthquake.**

### COMMENTARY:

It is well-known that improperly braced foundation cripple walls are highly susceptible to racking as shown in Figure 22 above. While the walls of this home were reinforced following damage from the 1971 (Figure 23) earthquake, the need to reinforce the cripple wall was apparently overlooked (Figure 22). Also, discontinuity in foundation type under this home may have contributed to the damage.

**Figure 23. Photograph of the home shown in Figure 22 following the 1971 San Fernando Valley Earthquake (from "Earthquakes-Safety and Survival", prepared by the Department of Building and Safety, City of LA, Feb. 9, 1971).**

## CASE STUDY

### TOPIC: Racking of Walls

**Figure 24. An example of wall racking resulting in damage to a garage door opening. (Wall damage rating: HIGH)**

### COMMENTARY:

Racking of the walls was infrequent and not a source of major life-safety concerns for SFD homes. In fact, the effects of permanent wall racking were realized in much less than 2 percent of the housing population affected by the worst ground shaking. As shown by the garage door opening in the photograph above, walls which contained large openings (relative to the length of wall), were more susceptible to permanent racking. Location of openings, such as near corners of the wall, also increased susceptibility of damage. In the example above, heavy roofing caused a greater inertial load on the garage door opening. In a few cases, permanent racking was not visible, but was evidenced by windows or doors which no longer operated smoothly and needed adjustment.

## CASE STUDY

### TOPIC: Roof Framing Damage

**Figure 25. An example of severe roof damage on an overloaded gable-roof with heavy tile roofing. (Roof damage rating: HIGH)**

### COMMENTARY:

The photograph above shows an extremely rare case of a collapsed roof. Roof structural damage was almost nonexistent in the SFD housing population, with the exception of localized roof damage caused by masonry chimneys. Perhaps the large vertical component of ground acceleration contributed to this roof's failure. More likely, it was the lack of properly sized and spaced rafter ties for the added dead load of a tile roof covering, as required by the LA City "Type V" prescriptive requirements. When found, roof structural damages were most often precipitated by alterations or renovations to the homes which modified, removed, or overloaded the rafter ties.

## CASE STUDY

### TOPIC: Roof Tile Damage

**Figure 26. An example of dislodged roof tiles caused by ground shaking and poor attachment.**

### COMMENTARY:

Damage to roof tiles was infrequent and dispersed throughout the San Fernando Valley. The photograph above reflects the worst observed damage to roof tiles. Ground shaking and poor attachment of tiles on this roof caused them to loosen and slide down the roof on top of each other in a telescoping fashion.

## CASE STUDY

### TOPIC: Masonry Chimney Failures

**Figure 27. An example of damage to masonry chimneys and the surrounding roof framing.**

### COMMENTARY:

Masonry chimney damage was fairly common and widespread. The type of damage to masonry chimneys was varied. Some were leaning with no cracking, while others were collapsed. In many cases the movement of the chimney caused localized damage to interior finishes, exterior finishes, and the roof structure. In several cases, damage was related to improper grouting or lapping of steel reinforcement. The hazard of a leaning or cracked chimney was a major factor in the number of red- and yellow-tagged homes. Recent policy changes by Los Angeles City building authorities require engineering for all masonry chimney new construction or repairs. Prefabricated wood chimneys with steel flue pipe performed very well and do not require engineering under current Los Angeles City policies.

## CASE STUDY

## TOPIC: Damage to Masonry Privacy Walls

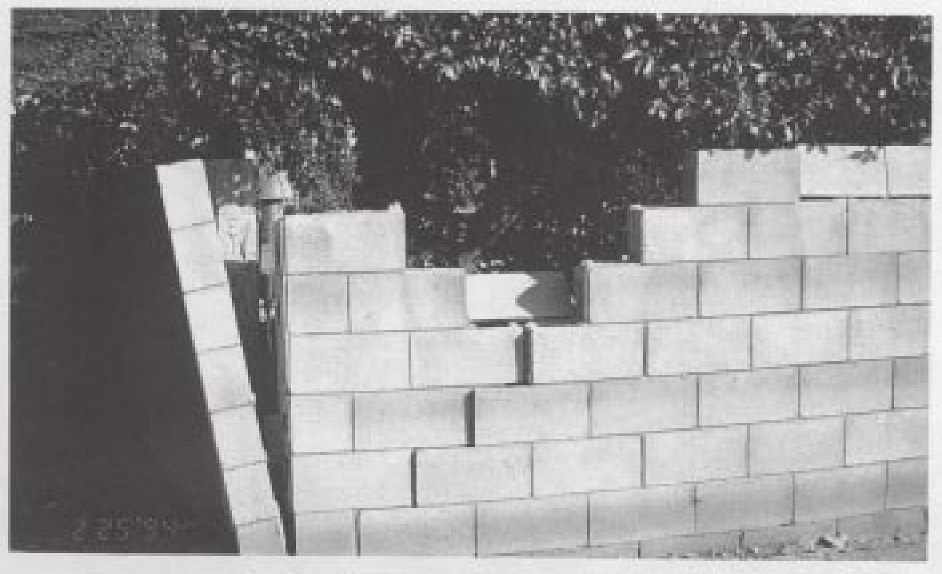

**Figure 28. An example of common damage to masonry privacy walls or fences.**

## COMMENTARY:

Damage to masonry privacy walls was widespread and common. In the picture shown above, the masonry units were unreinforced and the corners were not interlocked by alternating courses of block.

## CASE STUDY

## TOPIC: Contents Damage

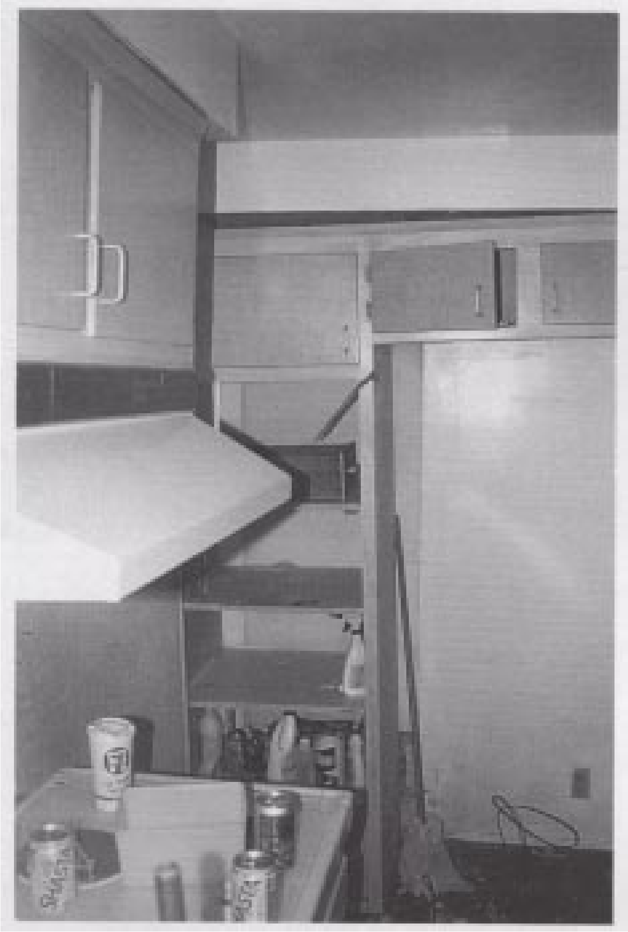

**Figure 29. An example of damage to shelves and cabinets in the kitchen of one home.**

## COMMENTARY:

Damage to contents of homes was widespread. In extreme cases, cabinets became detached from walls or were racked by the weight of heavy appliances. At a minimum, china, appliances, and other valuables were broken.

## CASE STUDY

## TOPIC: Damage to Mechanical Equipment

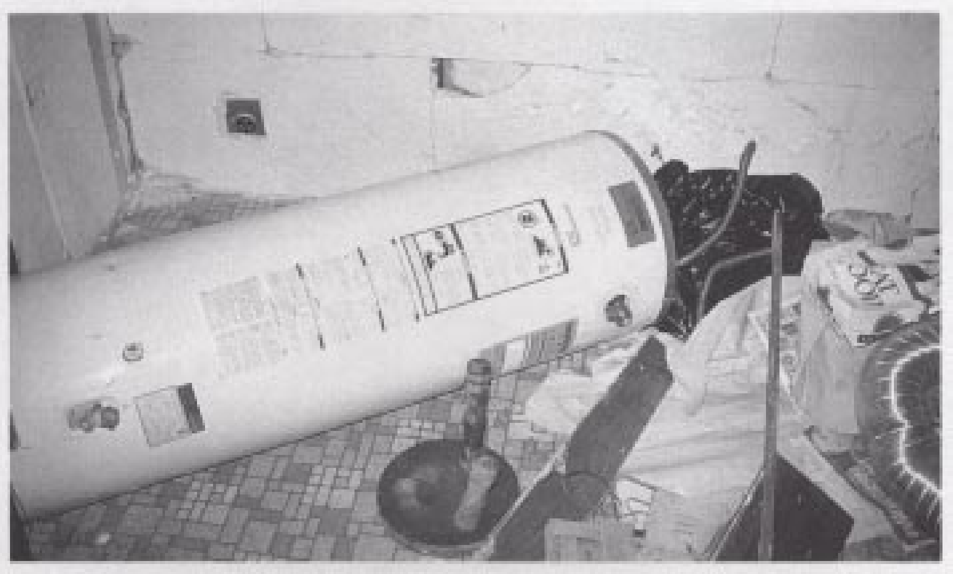

**Figure 30. An example of frequent damage to water heaters.**

## COMMENTARY:

Water heaters were frequently toppled by the ground shaking. In the photograph above, flexible water piping was used with a light gauge steel strap to harness the tank to the wall through a single nail. Water heaters were also installed with rigid steel pipe and no strapping. While both installation methods were prone to failure, the rigid piping appeared to steady the tanks with better success. Other mechanical equipment—such as AC units attached to the roof with steel bracketing—seemed to fare better.

## CASE STUDY

### TOPIC: Exterior Finish Damage

Figure 31. An example of severe stucco damage.

### COMMENTARY:

Damage to exterior stucco finishes was widespread. However, the ‘HIGH’ level of stucco damage represented in the photograph above was experienced in less than 2 percent of the homes. In fact, half of the homes experienced no damage to exterior finishes, and nearly half had only hairline cracks along the foundation or radiating from corners of large openings. The stucco damage in this example was influenced by racking of narrow shear walls at either end of a garage door opening.

## CASE STUDY

### TOPIC: Interior Finish Damage

**Figure 32. An example of severe (“HIGH”) interior finish damage (gypsum board) at partition wall intersections and openings in the walls.**

### COMMENTARY:

Interior finishes suffered widespread damage analogous to stucco on the exterior. However, the level of damage shown in the photograph above was experienced by less than 5 percent of the housing population. When present, cracks or spalling of interior finishes (gypsum board and plaster) were usually located at openings, wall intersections, or joints in the finish system.

## CASE STUDY

## TOPIC: Damage to Building Attachments

Figure 33.  An infrequent collapse of a porch attached to a home.

## COMMENTARY:

Damage to building attachments—such as porches—was infrequent. But when problems occurred (as shown above) it was usually because the connection to the building was insufficient and the porch was dependent on the connection for lateral support as well as normal bearing loads.

## CASE STUDY

### TOPIC: Fire Damage

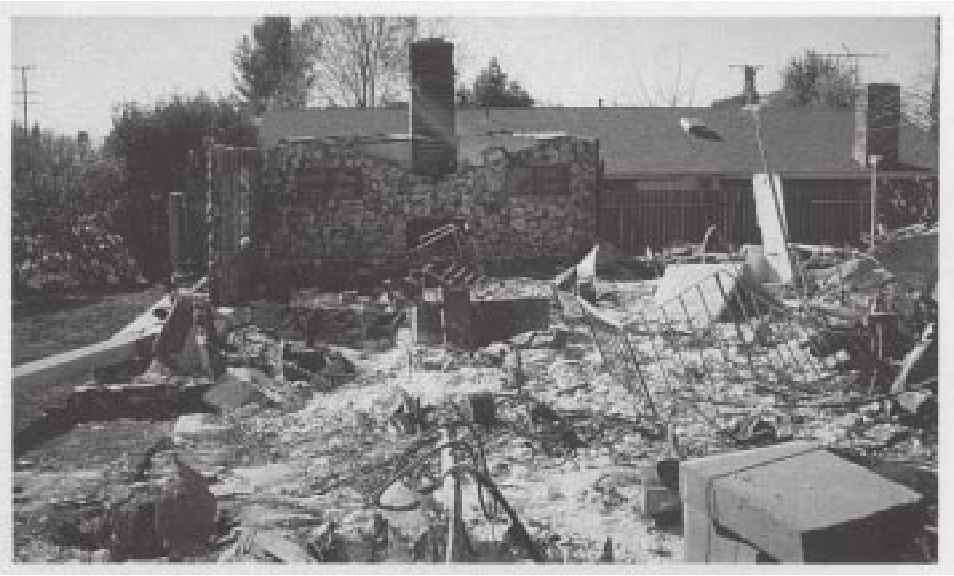

**Figure 34. An example of the rare occurrence of fire damage resulting from ignited gas leaks caused by the earthquake.**

### COMMENTARY:

The ground shaking at the home pictured above was not particularly severe—as evidenced by the standing masonry chimneys. However, in this case, a very rare occurrence of fire from an ignited gas leak consumed the home.

# RESULTS: MULTIFAMILY LOW-RISE AND SINGLE-FAMILY ATTACHED HOMES

## Description of MFLR/SFA Dwellings

The sampling methods used for multifamily low-rise (MFLR) and single-family attached (SFA) homes resulted in a very diverse sample. Multifamily buildings of 20 or more units were commingled with duplexes. Of the 30 residential sites visited, 13 were single-family attached (e.g., duplexes and townhomes) and 17 were multifamily (e.g., condominiums and garden apartments) structures. The distribution of the 30 MFLR and SFA samples in the survey area are shown in Figure 35. An additional 43 MFLR sites were visited for case studies.

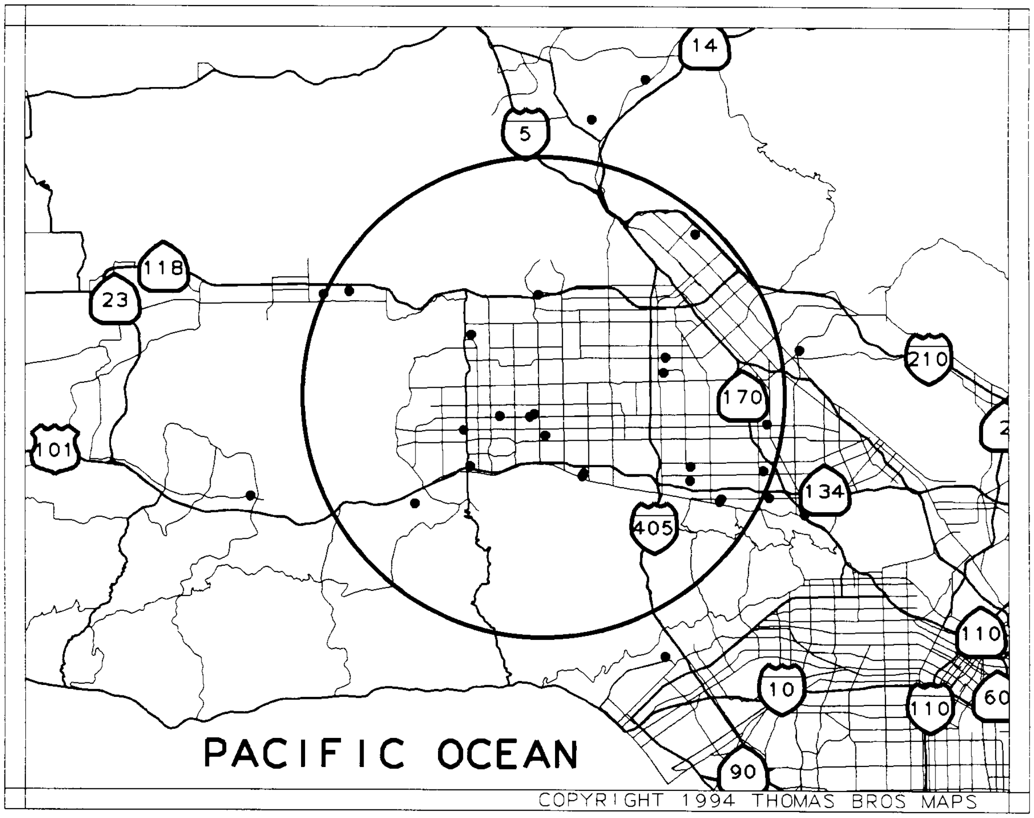

**Figure 35. Distribution of the MFLR and SFA samples (shown as dots) in the survey area.**

The basic styles of MFLR/SFA construction are shown in Figures 36 through 39. The construction of SFA duplexes (Figure 36) is very similar to that used for SFD construction discussed earlier. Larger SFA construction (Figure 37) was very similar to MFLR construction because of the arrangement of parking areas underneath the living area. This type of parking arrangement is the practical result of LA City policy which requires “off-street” parking for each dwelling unit. The garage areas for the SFA construction must be separated by walls according to the property line of each living unit located directly above the garage. The MFLR garages did not require partitioning according to individual living units as required for SFA construction. In effect this allowed greater variation in the openness and spacing of shear walls at the garage level of MFLR buildings.

The age of the construction was the primary determinant in the methods and materials used in MFLR/SFA buildings. Prior to the 1970s many MFLR buildings were built on a soft story comprised of open-garage parking underneath of multistory dwelling units. The garage areas or foundations on these older buildings were typically constructed of steel pipe columns, wood-frame shear walls with stucco finish, or a combination of both. The wood-frame garage ceiling or first floor was supported by either steel or engineered wood (e.g., glulam) girders. In some cases, parts of the building were supported on the garage area and also on crawlspace or slab-on-grade foundations. The upper stories of these buildings are constructed using conventional wood-frame practices with let-in bracing and stucco finishes on the exterior (similar to the “Type V” sheet requirements used for SFD construction). The interiors were commonly finished with plaster. The interior and exterior finishes provided an integral contribution to the lateral resistance of these buildings.

Following the 1971 San Fernando Valley Earthquake, MFLR/SFA construction began to transform with the pressures of more stringent building code enforcement and engineering requirements. As a result, newer construction evolved with the use of plywood sheathing on wood-frame walls and stronger, more rigid foundation designs. Fully enclosed parking provided on the ground level (or slightly below) became the norm. Reinforced masonry perimeter walls and reinforced concrete columns supporting a reinforced concrete first floor slab became popular forms of construction. In some cases, the foundation walls were also cast-in-place concrete. While the preferred exterior finish remains stucco, plywood sheathing is used to provide the lateral support to the wood-frame walls. The preferred interior finish material is gypsum sheathing and gypsum board that often functions as interior partition walls and as a shear resisting element.

Figure 36. Photograph of a SFA duplex building.

Figure 37. An example of a MFLR structure with soft-story garage construction underneath the dwelling units.

Figure 38. Example of MFLR condominium structure.

Figure 39. An example of a modern MFLR garden apartment arrangement.

## Performance of MFLR/SFA Dwellings

Two major problems existed with the MFLR/SFA sample of buildings. First, most of the multifamily buildings surveyed were made up of individually-owned condominium units which were represented in the tax database as separate entries (i.e., individual, taxable properties). By contrast, multifamily rental buildings were classified as single properties regardless of the number of individual units contained. In effect, this classification method flooded the database with individually-owned multifamily units—creating a strong bias for the selection of condos. Second, while intending to sample only MFLR buildings with two or less habitable stories, the actual sample included three- and four-story buildings because tax records identified individually-owned units by their story height and not the overall height of the building. Also, very different styles of construction (e.g., duplex vs. townhome) in the SFA sample would have been better analyzed in separate surveys. These complexities in obtaining a representative sample create a undeterminable bias in the data collected for the MFLR and SFA dwellings.

For the reasons stated above, the distribution of damage for the MFLR/SFA survey—as shown in Table 5—is presented without confidence intervals and shows observed damage in terms of the sampled buildings. The data are only representative of the homes in the sample and should not be used to form objective conclusions on the condition of MFLR/SFA construction in the affected area. The low occurence of structural damage reflected in Table 4 is not inconsistent with the Los Angeles Department of Building and Safety's inspections reported earlier. The Department's database showed that only 3 percent (22 total) of the inspected SFA buildings and 6 percent (287 total) of the inspected MFLR buildings were assigned red tags.

**Table 5**
**DESCRIPTION OF OBSERVED DAMAGE TO**
**SINGLE-FAMILY ATTACHED AND MULTIFAMILY STRUCTURES**

|  | **Damage to Units by Rating Category (By Number of Surveyed Units)** | | | |
|---|---|---|---|---|
|  | None | Low | Moderate | High |
| Foundation System | 21 | 7 | 2 | 0 |
| Wall Framing | 23 | 7 | 0 | 0 |
| Roof Framing | 30 | 0 | 0 | 0 |
| Exterior Finishes | 2 | 22 | 6 | 0 |
| Interior Finishes | 4 | 22 | 4 | 0 |

## Discussion of MFLR/SFA Performance

***SFA Performance Observations.*** Damage to wood-frame, upper stories on SFA construction appeared to reflect a level of performance similar to that reported for the SFD homes. Most SFA homes had little cracking of stucco in the upper stories. The similarity to SFD homes was most pronounced for the duplex style of construction. The wood-frame and stucco foundation/garage walls on SFA homes were subject to racking to a lesser extent than found in similar MFLR construction. The additional lateral support provided by property separation walls was a feature that appeared to limit the extent of structural damage to SFA homes.

***MFLR Performance Observations.*** Structural damage to MFLR construction was notably dramatic and costly to lives—especially for certain construction types located in the San Fernando Valley. Structural failures were often associated with the older MFLR buildings situated on soft-story garage foundations. The performance of stucco finishes—particularly as lateral support elements of first story walls on these larger MFLR and SFA buildings—performed notably worse than on the "Type V" single-family detached or attached homes.

The following section on case studies provides a review of the critical problems which resulted in damage to the SFA and MFLR structures. The primary focus is on MFLR construction which represents the bulk of structural damage. As in the SFD assessment, damage to building contents, mechanical equipment, and wall finishes was widespread and fairly common among MFLR/SFA buildings within the study zone in the San Fernando Valley.

## Case Studies of MFLR/SFA Dwellings

This section presents findings from case studies of damage to a total of 60 MFLR and 13 SFA buildings. The most notable source of structural damage to these case study homes was related to soft-story garage foundation construction. As noted earlier, the Northridge Earthquake ground motions were particularly severe for this class of construction (see the background section describing the Northridge Earthquake). Also important was the level of performance of stucco, plaster, and gypsum board finishes that were intended to provide lateral bracing to wood-frame walls. Problems in newer, engineered wood-frame construction indicate structural detailing and connection problems which may have been exacerbated by larger lateral loads imparted to upper stories by the more rigid foundation construction upon which they were fastened.

The case studies address both structural and non-structural damage using photographic documentation supplemented by commentary from field observations. The following topics are addressed:

- Soft story collapse
- Soft story shear walls
- Reinforced concrete and masonry garage foundations
- Mixed foundations
- Old wood-frame construction
- New wood-frame construction
- Building irregularities

## CASE STUDY

### TOPIC: Soft-Story Collapse

Figure 40. The Northridge Meadows collapse where 16 lives were lost in dwelling units located on the crushed soft story of this MFLR building.

Figure 41. Another section of the Northridge Meadows MFLR building where the soft story is severely racked, but not collapsed.

## CASE STUDY

### TOPIC: Soft-Story Collapse (continued)

**Figure 42.** A soft-story collapse of MFLR buildings on Victory Boulevard Dwelling units were not located at the garage or soft-story level in this case.

**Figure 43.** A view beneath the Victory Boulevard MFLR building collapse showing the bent steel pipe column and a crushed vehicle.

## CASE STUDY

### TOPIC: Soft-Story Collapse (continued)

### COMMENTARY:

The previous photographs show two of the most notable collapses of older MFLR dwellings built on soft stories. The single largest contributor to the loss of life during the earthquake is attributed to one building—the Northridge Meadows apartments. The soft story of this building included a combination of parking areas and living space. While complete collapse of soft- story construction was infrequent, many structures with soft-story garages were severely racked and close to collapse. These racked buildings were a notable contribution to the number of “red-tagged” MFLR structures. The major factors affecting the level of damage to soft-story construction were:

- the number, spacing, and length of wood-frame/stucco shear walls in the garage,
- the weight/size of the structure,
- the balancing of lateral stiffness along the structure,
- the orientation of the building and its shear walls with respect to the most remarkable horizontal ground motion or pulse, and
- level of ground shaking at the site.

The term “soft story” is not intended to designate a particular type of material such as wood-frame/stucco walls. It is intended to describe a story of a building in which the structural system is proportionately weaker than adjacent stories. Since the lowest levels of a building support the most weight of the structure, lateral loads from the inertial reaction of upper stories during an earthquake are greatest on the lowest story of a building. Lateral resistance or bracing by shear walls must be proportionately increased on lower stories or a soft-story condition is potentially created. The increased lateral support can be achieved by increasing the linear footage of shear walls or by switching to alternate materials or structural systems. The performance of shear walls used in garage or parking areas is a crucial element in the lateral support system of many MFLR/SFA buildings and often resulted in a soft-story reaction for the older buildings.

## CASE STUDY

### TOPIC: Soft-Story Shear Walls

**Figure 44. An example of severe deflection of a steel column and stucco shear wall of soft-story MFLR construction.**

**Figure 45. Failure and diagonal cracking of a wood-frame and stucco shear wall used in this soft-story MFLR construction.**

## CASE STUDY

## TOPIC: Soft-Story Shear Walls (continued)

**Figure 46. Racking of wood-frame and stucco walls along the garage openings of a SFA building.**

## CASE STUDY

### TOPIC: Soft-Story Shear Walls (continued)

### COMMENTARY:

When a building is subject to a seismic event, energy is absorbed by the structure by three basic ways:

- damping energy (non-destructive frictional losses in the movement of the building),
- kinetic and recoverable strain energy (energy converted to "elastic" motion and bending of the building and its structural components),
- hysteretic energy (energy consumed by permanent damage or breaking down of materials).

As an earthquake increases in magnitude, a greater amount of energy is likely to be absorbed as hysteretic energy. For properly detailed structures, hysteretic energy absorption is an important way of dissipating a tremendous amount of energy from particularly large earthquakes. Depending on the materials, structural methods, and level of ground shaking, the three forms of energy absorption will make differing contributions to the survival of the structure. The important structural properties to consider are stiffness, strength, and ductility. Ductility allows for major hysteretic energy absorption through deformation of structural components and "break-down" of materials without failure or collapse of the building. While extremely important to the survival of a building and its occupants, a ductile response to a severe earthquake may result in severe damage to architectural finishes and components.

A large amount of hysteretic energy absorption occurred in the soft-story or garage levels of the older MFLR and SFA buildings, particularly in the stucco finishes on wood-frame shear walls and in steel columns. This condition is shown in the preceding photographs of damaged shear walls. This hysteretic or "ductile" response resulted in severe damage to finishes on the lower stories of MFLR buildings.

As demonstrated in the three photographs, the orientation of the garage shear walls with respect to the stronger direction of ground movement resulted in different reactions. In the first two pictures, the strongest ground movement occurred parallel to the shear walls dividing the parking areas. In the last photograph, the severe ground motion was directly along the garage openings (perpendicular to the shear walls) causing the dividing walls to rotate about their base or weak axis. This was the case for the Northridge Meadows apartments that collapsed.

## CASE STUDY

## TOPIC: Reinforced Concrete and Masonry Garage Foundations

**Figure 47.** A new (1988 vintage) MFLR building on Sherman Way with a rare collapse of a reinforced concrete and masonry garage foundation.

**Figure 48.** A view inside the collapsed garage showing a small, telescoped concrete column crushed by the weight of a thick concrete slab and added inertial load from potentially high vertical ground acceleration.

## CASE STUDY

### TOPIC: Reinforced Concrete and Masonry Garage Foundations (continued)

### COMMENTARY:

Damage to newer MFLR garage foundations was apparently rare, and a collapse was even less likely. These foundations are built using reinforced concrete slabs supported by reinforced concrete columns and reinforced masonry perimeter walls. Reinforced concrete perimeter walls were also observed. While this type of foundation generally provides great strength, its inherent stiffness more readily transmits ground movement to the upper stories, which were typically wood framed.

The previous photographs show the only case of a collapse associated with this type of foundation construction found in the case study investigations. It is believed that this collapse is related to a combination of unique factors including:

- a high vertical ground acceleration component produced by the Northridge Earthquake,
- an unusually thick and stiff concrete slab creating heavy vertical loads, and
- relatively small diameter, widely spaced interior concrete columns.

These factors combined to overload and crush the concrete columns. The heavy slab, unable to support itself, fractured along its centerline, collapsed, and tilted the wood-frame upper stories into each other. A more detailed analysis may reveal other circumstances that contributed to this failure.

## CASE STUDY

### TOPIC: Mixed Foundations

**Figure 49. Separation and collapse of a soft-story garage area (right side) once connected to the unmoved portion supported by a slab-on-grade foundation (left side).**

**Figure 50. Collapse of a cripple-wall foundation connected to a collapsed soft-story garage on Mammoth Avenue.**

## CASE STUDY

### TOPIC: Mixed Foundations (continued)

### COMMENTARY:

Several instances of severe damage were found in buildings supported on mixed foundation types. Older MFLR buildings partially supported on different foundation types were particularly susceptible to damage. In the previous photographs, the buildings were supported by soft-story garage levels in combination with slab-on-grade or crawlspace (cripple-wall type) foundations in other parts. In the one case, the cripple wall and soft-story level both collapsed. In the other case, the portion of the building supported on a slab-on-grade stood fast while the soft-story section collapsed, separating the building at the dividing line of foundation types. Cases of more moderate damage were found in the survey which may have been related to similar mixing of foundation types.

Multiple foundation types effectively create an irregularity in the building configuration which may result in increased loads at certain locations, depending on the orientation of the building and magnitude of ground shaking. Irregularities may cause rotation and nonuniform movements of building parts.

## CASE STUDY

### TOPIC: Old Wood-Frame Construction

Figure 51. A damaged stucco and wood-frame wall under repair showing 3x framing and a 1x let-in brace disconnected from the sill plate.

Figure 52. Sliding of floor framing on a crawlspace foundation (concrete stem-wall type) supporting an older MFLR building.

## CASE STUDY

## TOPIC: Old Wood-Frame Construction (continued)

**Figure 53. A damaged stucco and wood-frame narrow shear wall located on the first story of an old garden-apartment complex.**

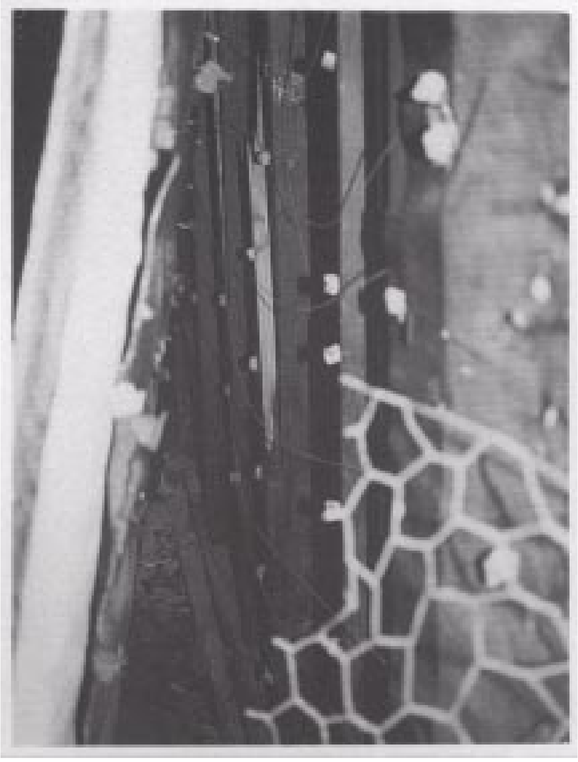

**Figure 54. Pulling back the stucco to view longitudinal splitting of studs and stucco adhering to nail heads only inside the shear wall of Figure 53.**

## CASE STUDY

### TOPIC: Old Wood-Frame Construction (continued)

**Figure 55.** Severe shear cracks in stucco finishes between window openings and along the top of the garage foundation.

**Figure 56.** Wholesale loss of stone veneer.

## CASE STUDY

### TOPIC: Old Wood-Frame Construction (continued)

### COMMENTARY:

“Old wood-frame” describes the style of construction used prior to major building code changes in the mid-1970s. As shown in the previous photographs, it is a simple combination of repetitive wood members overlaid with steel reinforcing mesh and portland cement plaster (stucco). Severe damage to this type of construction on MFLR buildings was not widespread, but seemed to be located in specific pockets. This observation may be the result of directed or localized ground shaking phenomena as well as the land development characteristics of the San Fernando Valley. When studying buildings at these heavily damaged locations, very different levels of damage could be found among adjacent buildings. Some of the factors which help explain the differences in damage include:

- architectural features and structural discontinuities which prevented a unified or “whole building” response,
- orientation of the strong and weak axis of the building with respect to the stronger direction of lateral ground movement,
- differences in foundation type (particularly as it affects stiffness),
- building height and configuration, and
- distribution and size of lateral force resisting elements.

Failure of narrow (short in length) stucco shear walls was a substantial source of weakness. But at the same time, they absorbed a great deal of energy through hysteresis and resisted wholesale collapse. Stucco wall sections with several window openings also suffered large amounts of cracking when oriented such that the strongest ground motions paralleled the wall.

## CASE STUDY

### TOPIC:  New Wood-Frame Construction

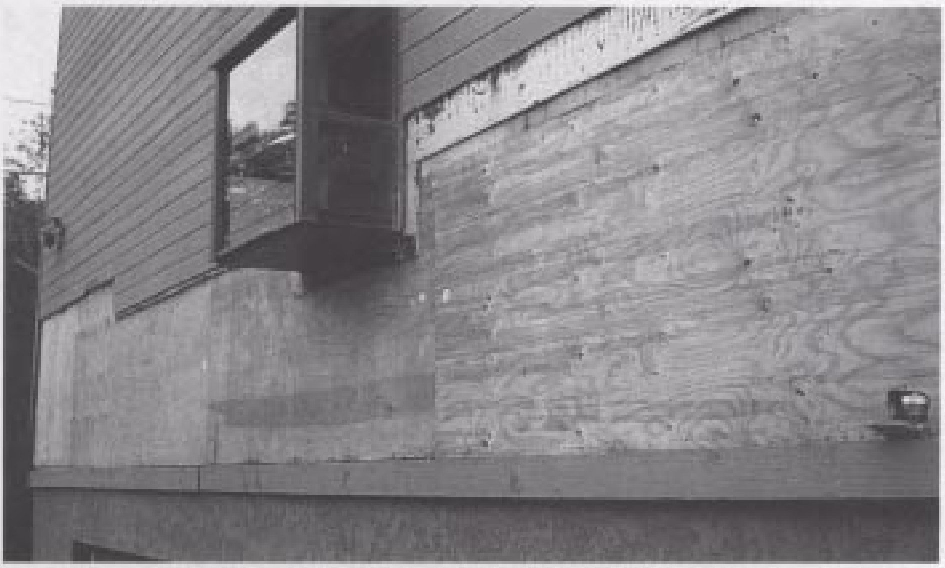

**Figure 57.  Newer MFLR construction showing the use of plywood sheathing on wood framing.**

**Figure 58. Exposed heavy-timber framing and steel bracket on the first floor showing evidence of a discontinuous connection between the top plate and a header beam.**

## CASE STUDY

### TOPIC: New Wood-Frame Construction (continued)

Figure 59. Fractured sill plate and sliding of a new MFLR building on top of an undamaged, reinforced concrete garage foundation.

Figure 60. A view inside the building shown in Figure 59 that reveals a missing hold-down bracket, a sheared sill bolt, and a splintered sill plate.

## CASE STUDY

### TOPIC: New Wood-Frame Construction (continued)

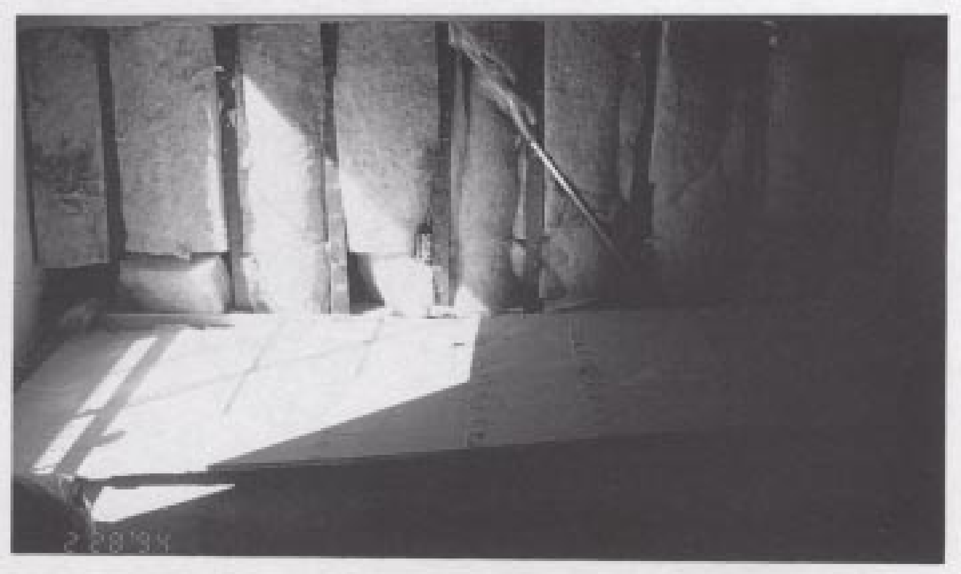

**Figure 61. Failed gypsum wall board nailed at 3" on center to provide lateral support to first story of the building on Mammoth Avenue shown in the three previous photographs.**

### COMMENTARY:

As previously stated, newer construction—built to more stringent building codes and engineering practices—has essentially eliminated the soft-story condition at the garage level. Consequently, newer garage foundations have greater stiffness which results in larger lateral loads imparted to the upper stories or living areas of the MRLF and SFA buildings. In accordance, these walls are also built to more stringent requirements than seen in buildings built prior to the mid-1970s.

Most wood-frame walls built to newer construction requirements (after the mid-1970s) performed well. The exceptions were located in apparently isolated regions of higher damage, perhaps associated with geologic conditions and the complex distribution of ground motions created by the earthquake. In one newer MFLR building, a particularly poor performance was associated with construction, design, and inspection oversights (shown in several of the preceding photographs).

## CASE STUDY

### TOPIC: Building Irregularities

**Figure 62. An older soft-story foundation supported by stucco shear walls on one end and steel pipe columns on the other end (near side) creating an imbalance in lateral stiffness.**

### COMMENTARY:

Building irregularities were observed in many forms. Some examples of irregularities and their effects are as follows:

- nonuniform weight distribution which creates overloading of certain components by torsional building reaction to horizontal inertial loads,
- imbalanced lateral stiffness which distributes greater loads to stiffer elements and may result in torsional effects or isolated overloading, and
- buildings with irregular shapes or plan configurations which react differentially for a given direction of ground motion.

While the shape of the MFLR building shown above is uniform (rectangular), the distribution of stucco shear walls and steel pipe column supports created an imbalance in the lateral stiffness. The damage is manifested in overstressed connections to the ceiling girder causing it to rotate and in deformed steel columns.

# CONCLUSIONS AND RECOMMENDATIONS

Results of this study supports the following conclusions:

- Although new homes are commonly engineered in the Greater Los Angeles region, the majority of existing single-family homes in the San Fernando Valley area were built to prescriptive methods known locally as "Type V". This manner of construction is also common to older multifamily buildings.

- Structural damage to SFD homes was infrequent, and performance was generally very good.

- Structural damage was primarily located in the foundation systems where less than 2 percent of the SFD homes suffered moderate to high levels of damage to their foundations.

- Most occurrences of moderate to high foundation damage were associated with localized site conditions including liquifaction, fissuring, and hillside slope failures.

- Damage to wall and roof framing in SFD homes was limited to low damage on about 2 percent of the walls and less than 1 percent of roofs.

- Case studies of extreme damage to SFD homes reveal that severe structural damage to foundations, walls, and roofs, existed, but at extremely low levels of occurrence.

- Finishes experienced the most widespread damage, with 50 percent of all SFD buildings suffering at least minor damage. However, only 4 percent or less could be classified as moderate to high damage. Most finish damage was related to stucco and drywall/plaster cracks at the foundation or at openings in walls.

- Statistical inferences conducted using a Chi-square test were generally inconclusive. One exception was a significant difference in damage levels to exterior finishes on SFD single-story homes with crawlspaces versus slab-on-grade foundations. Homes on slab foundations suffered some degree of damage to exterior finishes in about 30 percent of the sample, while crawlspace homes approached a 60 percent damage rate.

Although not captured in the random statistical survey results, it was observed in the field that:

- Case studies of MFLR and SFA homes indicate that soft-story garage construction is particularly susceptible to severe damage. In a few cases, severe racking led to total collapse of the soft story. When properly detailed and constructed, newer buildings with stronger foundations and plywood wall sheathing seemed to perform well.

- As with SFD homes, cracking of stucco and interior finishes on SFA and MFLR dwellings was widespread, particularly at openings in walls.

- Damage to masonry chimneys and fireplaces was common but not consistent. In many cases, movement of masonry chimneys caused localized damage to other parts of the building. Prefabricated wood chimneys with metal flues did not appear to be similarly affected.

- Damage to masonry privacy walls appeared to be widespread. Many of these were unreinforced walls.

- Damage to contents appeared widespread in all types of homes.

The following recommendations are offered based on results of this study:

- Based on the varying performance of different types of construction, "across the board" code changes should be avoided. For example, it may be necessary to increase the racking resistance of larger attached buildings, but results indicate that SFD homes built to the older, less stringent prescriptive ("Type V") requirements performed well.

- Performance requirements or prescriptive requirements in building codes should consider solutions addressing the unique seismic risks associated with construction on sloped sites (hillsides) in active seismic regions.

- Prescriptive building code structural requirements should be expanded to include cost-effective solutions addressing the added seismic risks associated with the architectural features common to newer homes (e.g., cathedral ceilings and large wall openings).

- Inspections and retrofit should be considered for older soft-story construction, especially where living spaces are located in the soft story.

- Future studies should attempt to assess the amount of damage to contents and nonstructural elements relative to overall building structural damage.

- The methodology and data sheets used in this study and the previous HUD-sponsored study of Hurricane Andrew and Iniki should be examined to identify improvements in the sampling and analysis methods.

- Research should be conducted into alternative garage foundation construction methods for MFLR buildings which will absorb greater amounts of energy in a non-destructive manner. For example, heavy, treated timber construction may be a viable alternative which would be compatible with wood-framed upper stories and also reduce lateral loads on the upper stories.

- Results of this report should be widely disseminated to policymakers and building authorities of communities located in the active seismic regions of the U.S.

- Statistically-valid damage estimates presented in this report should be used to help determine costs and benefits related to building code modifications, policy decisions, and other actions that affect the seismic hazard to homes.

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# APPENDIX

## CALCULATION OF CONFIDENCE INTERVALS FOR DAMAGE ESTIMATES

For a normal distribution, a 95 percent confidence interval around on estimated proportion $p$ is approximated by the equation

$$p \pm 1.96 \sqrt{\frac{p(1-p)}{n}}, \qquad \textbf{(1)}$$

where $n$ is the sample size. However, when $p$ is small (i.e., the number of observed occurrences are few), the distribution of the sample is no longer normal and the approximation is no longer valid. As a rule of thumb, this condition develops when $np(1\text{-}p) < 9$.[18]

A confidence interval for a small proportion—of which $p$ is a part—can be calculated by the equation

$$\sum \left( \frac{n!}{x!(n-x)!} \right) p^{x} (1-p)^{n-x}, \qquad \textbf{(2)}$$

for $x = 0, 1, 2, \ldots, n$, where $x$ is the number of observed occurrences. This cumulative mass function of a binomial variable gives the probability of obtaining $x$ or fewer observations in a sample size of $n$.

If there are no observations ($x = 0$) of the survey condition—for example, moderate damage to exterior walls of SFD units was not seen—Equation 2 reduces, and the 95 percent confidence interval around the estimated proportion is bounded below by 0 and above by solving

$$\mathbf{(1\text{-}\boldsymbol{p})^{\boldsymbol{n}} = 0.05}$$

for $p$. If there is one observation ($x = 1$), the 95 percent confidence interval around the estimated proportion has a lower bound of

$$\boldsymbol{np}\mathbf{(1\text{-}\boldsymbol{p})^{\boldsymbol{n}\text{-}1} = 0.975}$$

and an upper bound of

$$\boldsymbol{np}\mathbf{(1\text{-}\boldsymbol{p})^{\boldsymbol{n}\text{-}1} = 0.025,}$$

both solved for $p$.

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[18] Sidney Siegel, *Nonparametric Statistics for the Behavioral Sciences* (New York: McGraw-Hill, 1956).

By setting Equation 2 equal to 0.975 for the lower bound and equal to 0.025 for the upper bound and solving for $p$, a confidence interval can be stated for any $x$. Note, however, that this calculation becomes increasingly cumbersome as $x$ increases, and is easily approximated by Equation 1—given $np(1-p) < 9$.