

Earthquake Damage Assessment and Repair Guidelines for Residential Wood-Frame Buildings

Volume 1 | GENERAL GUIDELINES

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Earthquake Damage Assessment and Repair Guidelines for Residential Wood-Frame Buildings, Volume 1 – General Guidelines

Prepared by

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Notice

Cover photographs: Houses damaged in the 2014 South Napa earthquake (photo credit: CEA).

Preface

In 2018, the California Earthquake Authority (CEA) funded a project with the Applied Technology Council (ATC) to develop guidelines for the assessment and repair of residential wood-frame buildings damaged by earthquakes. This building class represents the most common type of dwelling in California and other regions of the United States. Although wood-frame construction has generally provided good performance in past earthquakes, wide-spread damage to these types of buildings is nonetheless expected in large, future earthquakes centered near urban areas. Additionally, past earthquakes in California have demonstrated the need for more efficiency, consistency, and reliability in the earthquake damage assessment process for residential wood-frame buildings by engineers, insurance claim adjusters, and contractors.

This ATC-143 Project built upon previous work funded by the CEA and others and conducted through the Consortium of Universities for Research in Earthquake Engineering (CUREE) that led to the publication of two documents for the assessment and repair of earthquake-damaged residential wood-frame buildings. The first document, CUREE EDA-06, *Engineering Guidelines for the Assessment and Repair of Earthquake Damage in Residential Woodframe Buildings*, *Version 2005-4* (CUREE, 2005), was published in 2005, is geared towards geotechnical engineers, and includes guidance for making repair and mitigation recommendations for earthquake-induced permanent ground deformation. The second document, CUREE EDA-02, *General Guidelines for the Assessment and Repair of Earthquake Damage in Residential Woodframe Buildings* (CUREE, 2010), was originally published in 2007, was updated in 2010, and is geared towards insurance claim adjusters, contractors, and homeowners. ATC is indebted to all of the individuals involved in this CUREE work, in particular Dan Dyce, John Osteraas, Robert Reitherman, Jonathan Stewart, and Jon Wren, whose leadership and authorship were essential for the development of the original documents.

The ATC-143 Project updated and expanded both documents. In particular, the project expanded the *Engineering Guidelines* by developing guidance for repair of structurally significant earthquake damage to structural elements and to structural bracing of certain nonstructural components, making the document multi-disciplinary in scope and relevant to both structural and geotechnical engineers. As part of this effort, the original geotechnical material was reviewed, reorganized, and in some cases expanded to include recent advances in the practice and to make its presentation consistent with the format and approach of the updated document. The updated *Engineering Guidelines* are published as CEA-EDA-02, *Earthquake Damage Assessment and Repair Guidelines for Residential Wood-Frame Buildings*, *Volume 2 – Engineering Guidelines* (CEA, 2020). The project also took a fresh look at the *General Guidelines* to incorporate feedback from users and lessons learned from recent earthquakes and to ensure alignment with the updated *Engineering Guidelines*. The *General Guidelines* repair tables were expanded to cover additional building elements and were updated to be consistent with damage thresholds presented in the *Engineering Guidelines*. The design of the *General Guidelines* checklists was revised to make them more user friendly and streamlined, and their content was updated for consistency with changes to other sections of the document. The updated documents are now more integrated and are presented as a two-volume series, *Earthquake Damage Assessment and Repair Guidelines for Residential Wood-Frame Buildings*.

ATC is indebted to the Project Technical Director Morgan Griffith and the Associate Technical Director John Osteraas for their leadership and technical expertise, and to the members of the Project Technical Committee, consisting of David Bonowitz, Kelly Cobeen, David Cocke, and Dan Dyce, for their authorship, review, and technical expertise. ATC would like to thank the members of the Project Review Panel, consisting of Robert Reitherman (Chair), Lyle Carden (ATC Board Contact), Warner Chang, Tara Hutchinson, Bret Lizundia, Lisa Lohmann, David Ojala, and Frank Rollo, who provided advice, review, and assistance at key stages of the work. Lisa Lohmann's input on the *General Guidelines* checklists was particularly valuable. ATC also would like to thank Working Group Members Sean Ahdi, Christine Beyzaei, and Jon Wren for their work on the geotechnical material in the *Engineering Guidelines*; Taylor Funk and Kari Klaboe for, among other things, their test runs of draft versions of the structural damage assessment and repair procedures in the *Engineering Guidelines*; and Evelyn Mikailian for her help in reviewing and identifying photos.

ATC also gratefully acknowledges funding provided by the CEA and the guidance and support provided by Janiele Maffei (CEA Chief Mitigation Officer), Mitch Ziemer (CEA Insurance and Claim Director), and Erin Rogers (CEA Project Coordinator). Carol Singer provided graphic design services, Ayse Hortacsu (ATC) provided project management services, and Carrie J. Perna (ATC) provided report production services.

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Table of Contents

Preface .... **iii**

List of Figures .... **xi**

List of Tables .... **xxiii**

1. Introduction **1-1**
- 1.1 Organization and Content 1-2
- 1.2 Post-Earthquake Assessment 1-3
  - 1.2.1 Urban Search and Rescue Assessment 1-3
  - 1.2.2 Safety Assessment 1-4
  - 1.2.3 Damage Assessment 1-5
  - 1.2.4 Attic and Crawlspace Inspections 1-8
  - 1.2.5 Technical Consultant Assistance 1-8
  - 1.2.6 Destructive Investigation 1-9
- 1.3 Earthquake Damage Repair Standards 1-9
  - 1.3.1 Like Kind and Quality Repair 1-10
  - 1.3.2 Code-Triggered Upgrades 1-10
  - 1.3.3 Voluntary Upgrades 1-10
- 1.4 Earthquake Basics 1-11
  - 1.4.1 Earthquake Damage 1-13

2. Earthquake Ground Motions and Damage Potential **2-1**
- 2.1 Introduction 2-1
- 2.2 Measuring Earthquakes 2-1
  - 2.2.1 Earthquake Magnitude 2-1
  - 2.2.2 Intensity of Ground Shaking 2-3
  - 2.2.3 Modified Mercalli Intensity Scale 2-4
  - 2.2.4 Instrumental Intensity 2-5
  - 2.2.5 Community Internet Intensity 2-7
  - 2.2.6 Instrumental Records 2-7
  - 2.2.7 Ground Surface Strains 2-8
- 2.3 Vulnerabilities and Damage Potential in Houses 2-8
  - 2.3.1 Inadequate Anchorage of Superstructure at Foundation 2-8
  - 2.3.2 Unbraced Cripple Wall 2-10
  - 2.3.3 Hillside House 2-11
  - 2.3.4 Narrow Wall Pier 2-14
  - 2.3.5 Living Space Over Garage 2-15
  - 2.3.6 Framing Discontinuity 2-16
  - 2.3.7 Masonry Chimney 2-17
  - 2.3.8 Appurtenances 2-19

3. Geotechnical Aspects 3-1
3.1 Quick Guide 3-1
3.1.1 Where to Look 3-1
3.1.2 What to Look For 3-1
3.1.3 Repair Guidelines 3-2
3.2 Overview 3-2
3.3 Limitations 3-3
3.4 Description of Geotechnical Aspects 3-3
3.5 Long-Term Sources of Earth Movement 3-5
3.5.1 Settlement 3-5
3.5.2 Expansive Soil Movement 3-5
3.5.3 Slope Deformation (Creep) 3-8
3.5.4 Slope Instability (Landslide) 3-9
3.5.5 Retaining Wall Deformation or Instability 3-9
3.6 Earthquake-Induced Permanent Ground Deformation 3-10
3.6.1 Surface Fault Rupture 3-10
3.6.2 Liquefaction 3-13
3.6.3 Seismic Compression (Soil Densification) 3-15
3.6.4 Earthquake-Induced Slope Instability (Landslide) 3-17
3.6.5 Ridge-Top Shattering 3-21
3.6.6 Retaining Wall Deformation or Instability 3-21
3.7 Assessment Guidelines and Methodologies 3-23
3.7.1 Site Inspection 3-23
3.8 Repair Methodologies 3-25

4. Foundations and Slabs-on-Grade 4-1
4.1 Quick Guide 4-1
4.1.1 Where to Look 4-1
4.1.2 What to Look For 4-1
4.1.3 Repair Guidelines 4-1
4.2 Overview 4-2
4.3 Limitations 4-3
4.4 Description of Typical Construction 4-3
4.5 Non-Earthquake Sources of Damage 4-8
4.6 Earthquake-Induced Damage 4-14
4.7 Assessment Guidelines and Methodologies 4-19
4.7.1 Technical Consultant Assessment 4-20
4.7.2 Establishing the Cause of Cracks 4-21
4.8 Repair Methodologies 4-32
4.8.1 No Structural Repair Warranted 4-34
4.8.2 Seal Cracks or Gap 4-34
4.8.3 Apply Leveling Compound 4-35
4.8.4 Epoxy Injection 4-35
4.8.5 Removal and Replacement 4-35
4.8.6 Cosmetic Considerations 4-35
4.8.7 Technical Consultant Repair Recommendations 4-36
4.8.8 Releveling 4-37
4.8.9 Permits and Code-Triggered Upgrades 4-37

5. Walls **5-1**
5.1 Quick Guide 5-1
5.1.1 Where to Look: Exterior Walls 5-1
5.1.2 What to Look For: Exterior Walls 5-1
5.1.3 Where to Look: Interior Walls 5-2
5.1.4 What to Look For: Interior Walls 5-2
5.1.5 Repair Guidelines 5-2
5.2 Overview 5-2
5.3 Limitations 5-3
5.4 Description of Typical Construction 5-3
5.5 Non-Earthquake Sources of Damage 5-6
5.5.1 Stucco 5-7
5.5.2 Plaster 5-11
5.5.3 Drywall 5-12
5.5.4 Ceramic and Stone Tile 5-12
5.5.5 Doors and Windows 5-13
5.5.6 Wood Trim 5-13
5.6 Earthquake-Induced Damage 5-13
5.6.1 Stucco 5-15
5.6.2 Drywall 5-19
5.6.3 Gypsum Lath and Plaster 5-20
5.6.4 Ceramic and Stone Tile 5-21
5.6.5 Doors and Windows 5-21
5.7 Assessment Guidelines and Methodology 5-22
5.7.1 Exterior 5-22
5.7.2 Interior 5-24
5.7.3 Technical Consultant Assessment 5-26
5.7.4 Establishing the Cause of Cracks 5-27
5.8 Repair Methodologies 5-29
5.8.1 Crack Repair 5-31
5.8.2 Construction Joints 5-32
5.8.3 Technical Consultant Repair Recommendations 5-32
5.8.4 Permits and Code-Triggered Upgrades 5-33

6. Floors, Ceilings, and Roofs **6-1**
6.1 Quick Guide 6-1
6.1.1 Where to Look: Roof 6-1
6.1.2 What to Look For: Roof 6-1
6.1.3 Where to Look: Ceilings 6-1
6.1.4 What to Look For: Ceilings 6-1
6.1.5 Where to Look: Interior Floors 6-2
6.1.6 What to Look For: Interior Floors 6-2
6.1.7 Where to Look: Exterior Floors 6-2
6.1.8 What to Look For: Exterior Floors 6-2
6.1.9 Repair Guidelines 6-3
6.2 Overview 6-3
6.3 Limitations 6-3
6.4 Description of Typical Construction 6-3
6.4.1 Typical Roof Construction 6-5
6.4.2 Typical Ceiling Construction 6-5
6.6.3 Typical Floor Construction 6-6

6.5 Non-Earthquake Sources of Damage 6-6
6.5.1 Non-Earthquake Roof Damage 6-6
6.5.2 Non-Earthquake Ceiling Damage 6-9
6.5.3 Non-Earthquake Floor Damage 6-11
6.6 Earthquake-Induced Damage 6-15
6.6.1 Earthquake-Induced Roof Damage 6-17
6.6.2 Earthquake-Induced Ceiling Damage 6-21
6.6.3 Earthquake-Induced Floor Damage 6-23
6.7 Assessment Guidelines and Methodology 6-25
6.7.1 Exterior 6-26
6.7.2 Interior 6-27
6.7.3 Roof 6-27
6.7.4 Attic 6-27
6.7.5 Crawlspace 6-28
6.7.6 Technical Consultant Assessment 6-28
6.8 Repair Methodologies 6-29
6.8.1 Roofs 6-30
6.8.2 Ceilings 6-30
6.8.3 Floors 6-31
6.8.4 Permits and Code-Triggered Upgrades 6-31

7. Fireplaces and Chimneys 7-1
7.1 Quick Guide 7-1
7.1.1 Where to Look: Exterior Chimney 7-1
7.1.2 What to Look For: Exterior Chimney 7-1
7.1.3 Where to Look: Fireplace 7-1
7.1.4 What to Look For: Fireplace 7-1
7.1.5 Where to Look: Interior Chimney 7-2
7.1.6 What to Look For: Interior Chimney 7-2
7.1.7 Repair Guidelines 7-2
7.2 Overview 7-2
7.3 Limitations 7-3
7.4 Description of Typical Construction 7-3
7.5 Non-Earthquake Sources of Damage 7-11
7.5.1 Firebox 7-11
7.5.2 Chimney 7-11
7.5.3 Interior Facings 7-14
7.6 Earthquake-Induced Damage 7-15
7.6.1 Fireplace 7-15
7.6.2 Chimney 7-15
7.6.3 Interior Facings 7-23
7.7 Assessment Guidelines and Methodology 7-25
7.7.1 Ground Level 7-25
7.7.2 Interior 7-26
7.7.3 Roof 7-26
7.7.4 Attic 7-28
7.7.5 Consultant Assessment 7-28
7.8 Repair Methodologies 7-28
7.8.1 Permits and Code-Triggered Upgrades 7-30

8. Mechanical, Electrical, and Plumbing Systems 8-1
8.1 Quick Guide 8-1
8.1.1 Where to Look 8-1
8.1.2 What to Look For 8-1
8.1.3 Repair Guidelines 8-2
8.2 Overview 8-2
8.3 Limitations 8-5
8.4 Description of Typical MEP Systems 8-5
8.4.1 Plumbing 8-5
8.4.2 Mechanical 8-6
8.4.3 Electrical 8-8
8.5 Non-Earthquake Sources of MEP System Damage 8-8
8.5.1 Plumbing 8-8
8.5.2 Mechanical 8-9
8.5.3 Electrical 8-9
8.6 Earthquake-Induced MEP System Damage 8-10
8.6.1 Plumbing 8-10
8.6.2 Mechanical 8-13
8.6.3 Electrical 8-13
8.7 Assessment Guidelines and Methodology 8-14
8.7.1 Plumbing 8-14
8.7.2 Mechanical 8-15
8.7.3 Electrical 8-15
8.8 Repair Methodologies 8-15
8.8.1 Plumbing 8-15
8.8.2 Mechanical 8-16
8.8.3 Electrical 8-16
8.8.4 Permits and Code-Triggered Upgrades 8-16

9. Working with Technical Consultants 9-1
9.1 Introduction 9-1
9.2 Circumstances Requiring Technical Consultant Services 9-1
9.2.1 Safety Assessment 9-1
9.2.2 Damage State 9-2
9.2.3 Structural Configuration 9-3
9.2.4 Hazardous Construction Materials 9-3
9.3 Selecting Technical Consultants 9-4
9.3.1 When are the Stamp and Signature of an Engineer Required? 9-5
9.3.2 Qualifications for Technical Consultants Performing Post-Earthquake Damage Assessment 9-6
9.3.3 Locating Potentially Qualified Engineers 9-6
9.3.4 Contracting for Technical Consultant Services 9-6
9.4 Other Consultants and Subcontractors 9-8
9.5 Technical Report Guidelines 9-9

Appendix A: Building Occupant Questionnaire **A-1**

Appendix B: Useful Earthquake Damage Inspection Tools **B-1**

Appendix C: General Earthquake Damage Inspection Checklist **C-1**

Appendix D: Crawlspace Earthquake Damage Inspection Checklist **D-1**

Appendix E: Attic Earthquake Damage Inspection Checklist **E-1**

Appendix F: Attic and Crawlspace Inspection Safety **F-1**

Appendix G: Recommendations for Crack Repair by Epoxy Injection in Residential Concrete ... **G-1**
G.1 General Recommendations G-1
G.2 Crack Width Criteria G-2
G.3 Footings or Stemwalls G-2
G.4 Slabs-on-Grade G-3
G.5 Quality Assurance and Quality Control G-3

Glossary and Acronyms **H-1**
H.1 Glossary H-1
H.2 Acronyms H-23

References **I-1**

Project Participants **J-1**

List of Figures

Figure 1-1 Post-earthquake damage assessment process envisioned by the *General Guidelines* 1-7

Figure 1-2 Illustration of a strike-slip fault 1-12

Figure 1-3 Illustration of a blind thrust fault 1-12

Figure 1-4 Effect of acceleration and deceleration (i.e., braking) on vertical objects, where the red arrows indicate the direction of force 1-14

Figure 1-5 Illustration of racking distortion in walls caused by earthquake ground motions, shown as red arrows. The amount of racking shown in this figure is greatly exaggerated for clarity 1-15

Figure 1-6 Out-of-plumb deformation patterns in a full-scale shake-table test of a two-story wood-frame building. Horizontal deflections indicated are in inches 1-15

Figure 1-7 Elements of a typical wood-frame house 1-17

Figure 1-8 Schematic of the role of horizontal diaphragms (e.g., floors or roofs) and shear walls in resisting earthquake forces, where the red arrows indicate the direction of forces 1-18

Figure 2-1 Illustration of total energy release as a function of earthquake magnitude 2-2

Figure 2-2 ShakeMap showing the instrumental intensities for the 2014 South Napa, California earthquake 2-6

Figure 2-3 Community Internet Intensity Map for the 2014 South Napa, California earthquake 2-7

Figure 2-4 Earthquake-caused sliding of superstructure at foundation. The wall has shifted to the right several inches relative to the foundation, stucco wall finishes have cracked and spalled along the sill plate, and the sill plate is fractured near the right end of the wall 2-9

Figure 2-5 Earthquake-caused sliding of superstructure at floor slab. The wall has shifted less than 1 inch to the left, as evidenced in the left photo by the tapered gap between the left side of the door and doorjamb and in the right photo by the gap between the carpet and doorjamb 2-9

Figure 2-6 Damage to cripple wall finishes caused by the 2014 South Napa, California earthquake 2-10

Figure 2-7 Cripple wall collapse caused by the 1994 Northridge, California earthquake resulting in widespread related damage in upper-story framing and relative movement between the main house and the covered porch 2-11

Figure 2-8 Damaged framing enclosing the underfloor area of a hillside house caused by the 2003 San Simeon, California earthquake. The damage includes detachment of the stucco relative to the wall framing and both in-plane and out-of-plane lean of the wood-frame walls 2-12

Figure 2-9 Damage at uphill end of a hillside house caused by the 2003 San Simeon, California earthquake. The floor framing detached and pulled away from the uphill foundation, causing the floor to sag........ 2-13

Figure 2-10 Large in-plane drift of narrow wall piers at garage door opening caused by the 1971 San Fernando, California earthquake........ 2-14

Figure 2-11 Damage related to living space over garage caused by the 2014 South Napa, California earthquake. In-plane racking of the front wall line of the garage caused cracking and possible framing damage in the narrow wall segments on either side of the garage door 2-15

Figure 2-12 Left: Adjoining wings of a house create a framing discontinuity. Right: Separation of wood siding at intersection of adjoining wings caused by the 2014 South Napa, California earthquake. The separation was not structurally significant because there was no continuous framing or structural connection between the wings........ 2-16

Figure 2-13 Earthquake-induced fractured chimney near the roof line. The brace between the chimney and roof, visible behind the chimney, was not adequate to prevent the damage........ 2-17

Figure 2-14 Separation of chimney from house caused by the 2014 La Habra, California earthquake. The separation was relatively minor, and the chimney remained attached to the house........ 2-18

Figure 2-15 Earthquake-caused detachment of the carport from the house wall, resulting in collapse 2-19

Figure 3-1 Schematic cross-section of a cut-fill building pad........ 3-4

Figure 3-2 Schematic of typical long-term, non-earthquake distress caused by expansive soil to the exterior of a residential building with a perimeter concrete foundation 3-6

Figure 3-3 Schematic of typical long-term, non-earthquake distress caused by expansive soil to the interior of a residential building with a perimeter concrete foundation........ 3-7

Figure 3-4 Long-term, non-earthquake desiccation cracking of expansive soil within a crawlspace........ 3-8

Figure 3-5 Schematic of damage to residence resulting from long-term, non-earthquake soil creep........ 3-9

Figure 3-6 Surface fault rupture from the 1971 San Fernando, California earthquake and associated damage to pavement and buildings 3-10

Figure 3-7 House damaged by surface fault rupture from the 1971 San Fernando, California earthquake........ 3-11

Figure 3-8 Waterline break along fault rupture from the 1972 Managua, Nicaragua earthquake 3-11

Figure 3-9 Surface faulting midway between El Centro and Holtville from the 1940 El Centro, California earthquake 3-12

Figure 3-10 Sidewalk displaced by distributed faulting from the 1972 Managua, Nicaragua earthquake 3-12

Figure 3-11 Sand boils at Kawaihae Harbor from the 2006 Kiholo Bay, Hawaii sequence of earthquakes 3-13

Figure 3-12 Sand boil due to liquefaction of old, poorly compacted, water-saturated fill during the 1989 Loma Prieta, California earthquake 3-14

Figure 3-13 Tennis court damage with ejection of wet sand from soil liquefaction (site is adjacent to a river) during the 1989 Loma Prieta, California earthquake 3-14

Figure 3-14 Schematic showing possible earthquake damage to a fill slope 3-15

Figure 3-15 Building damaged by movements in hillside fill during the 1994 Northridge, California earthquake 3-16

Figure 3-16 Evidence of lateral ground movement in the direction of the arrow, near back of building shown in Figure 3-15 3-16

Figure 3-17 Minor settlement caused by densification of loose sandy fill in San Francisco during the 1989 Loma Prieta, California earthquake; the building is pile-supported 3-17

Figure 3-18 House displaced by large blocks of soil uplifted at toe of L Street landslide, Anchorage district, during the 1964 Alaska earthquake 3-18

Figure 3-19 Rockfall from the 1970 Peru earthquake 3-18

Figure 3-20 Rockfall from the 2016 Kaikoura, New Zealand earthquake 3-19

Figure 3-21 Top: rockfall from the 2003 San Simeon, California earthquake; bottom: similar rockfall occurred downslope and impacted the pictured house—impact marks on slope and house indicated by arrows 3-20

Figure 3-22 Examples of different types of retaining walls utilized in residential construction 3-21

Figure 3-23 Retaining wall damage during the 2003 San Simeon, California earthquake caused backfill to spill from a new crack in the retaining wall 3-22

Figure 3-24 Collapse of unmortared and unreinforced stone retaining wall in Honokaa, Hawaii, during the 2006 Kiholo Bay, Hawaii sequence of earthquakes 3-22

Figure 3-25 Schematic illustration of evidence of possible earthquake-induced ground failure 3-23

Figure 3-26 Asphalt pavement rupture as a result of a deep rotational slope failure in fill during the 2014 Iquique, Chile earthquake 3-26

Figure 3-27 Street and house damaged by several inches of landslide displacement during the 1971 San Fernando, California earthquake; displacement is readily visible as street crack in photograph 3-26

Figure 3-28 Pavement patching and damage to adjacent sidewalk in San Fernando following the 1971 San Fernando, California earthquake 3-27

Figure 3-29 Offset sidewalk from the 1971 San Fernando, California earthquake 3-27

Figure 3-30 Damaged street, gutter, and curb from the 1971 San Fernando, California earthquake 3-28

Figure 3-31 Buckling of driveway due to liquefaction during the 1989 Loma Prieta, California earthquake 3-29

Figure 3-32 Projection of liquefaction-induced ground cracking through a building in the city of Chimbote during the 1970 Peru earthquake 3-29

Figure 3-33 Driveway cracking following the 1971 San Fernando, California earthquake 3-30

Figure 3-34 Driveway cracking and differential settlement following the 1989 Loma Prieta, California earthquake 3-31

Figure 3-35 Two-inch separation at the construction joint between the garage slab and driveway slab following the 1957 Daly City, California earthquake 3-31

Figure 3-36 Concrete porch and steps offset from original position by earthquake-induced permanent ground deformation, as evidenced by exposed foundation concrete 3-32

Figure 3-37 Dropping of entry walkway supported on poorly compacted backfill during the 1994 Northridge, California earthquake 3-32

Figure 3-38 Different vintages of grout between a sidewalk and residence near a top of slope indicating a history of lateral movement as a result of slope creep rather than earthquake damage 3-33

Figure 3-39 Grout within driveway slab-on-grade crack indicating long-term problem with expansive soil beneath driveway rather than earthquake damage 3-33

Figure 3-40 Utility pipe ruptured by lateral spreading from the 1994 Northridge, California earthquake 3-34

Figure 3-41 Pipe failures and resulting pavement distress and settlement from the 1971 San Fernando, California earthquake 3-34

Figure 3-42 Schematic cross-section of typical in-ground swimming pool 3-35

Figure 3-43 Damage to house foundation from lateral spreading in Wakami, Japan, during the 1983 Nihonkai-Chubu, Japan earthquake 3-35

Figure 3-44 Damage to foundation slab and wall of house by small settlement and ground cracking evident in the lawn (arrow) during the 1994 Northridge, California earthquake 3-36

Figure 3-45 Foundation and ground cracking following the 2003 San Simeon, California earthquake; bottom shows the out-of-plane offset present across the foundation crack shown in top photograph 3-37

Figure 3-46 Foundation and ground cracking following the 2003 San Simeon, California earthquake 3-38

Figure 3-47 One-story masonry house damaged due to differential settlement caused by liquefaction in the town of Caucete during the 1977 Caucete, San Juan, Argentina earthquake. Damage to the interior slab is shown in Figure 3-48 3-38

Figure 3-48 Damaged concrete slab-on-grade floor of the house shown in Figure 3-47; sandy mud ejected by liquefaction covers part of the floor 3-39

Figure 3-49 Damage to a residence from lateral spreading following the 2003 San Simeon, California earthquake 3-39

Figure 3-50 Damage to a slab-on-grade from liquefaction during the 1971 San Fernando, California earthquake 3-40

Figure 3-51 Releveling of foundation indicates prior settlement and possibly on-going deformation mode rather than earthquake damage 3-40

Figure 4-1 Continuous footing at perimeter of a slab-on-grade—single-pour system 4-4

Figure 4-2 Continuous footing at perimeter of a slab-on-grade—two-pour system with cold joint between slab and footing 4-5

Figure 4-3 Continuous footing supporting wood-frame cripple wall 4-5

Figure 4-4 Stemwall supporting first-floor wood framing 4-6

Figure 4-5 Isolated footings supporting wood posts of first-floor wood framing 4-6

Figure 4-6 Drilled pier-and-grade beam foundation supporting first-floor wood framing 4-7

Figure 4-7 Concrete shrinkage crack emanating from reentrant corner at a step in a perimeter stemwall 4-9

Figure 4-8 Shrinkage crack in a concrete stemwall emanating from an anchor bolt 4-9

Figure 4-9 Shrinkage crack in a concrete stemwall emanating from a beam pocket 4-10

Figure 4-10 Slab-on-grade with independent perimeter footing and horizontal construction joint—two-pour system 4-11

Figure 4-11 Slab-on-grade with independent perimeter footing and vertical construction joint—two-pour system 4-12

Figure 4-12 Core extracted from concrete stemwall showing cracking caused by swelling pressure generated by corroding reinforcing steel 4-13

Figure 4-13 Uplift and cracking of concrete sidewalk caused by tree roots 4-13

Figure 4-14 Cracking due to vehicle loads on a concrete driveway over soft soil 4-14

Figure 4-15 Earthquake-induced relative movement at slab-footing interface in two-pour slab-on-grade construction due to sand covering the footing during construction 4-16

Figure 4-16 Earthquake-induced differential movement and spalling at cold joint between stemwall and slab in two-pour construction 4-16

Figure 4-17 Earthquake-induced cracking of ceramic tile spanning the cold joint between the floor slab and the stemwall in a two-pour system 4-17

Figure 4-18 Earthquake-induced opening of cold joint between floor slab and perimeter footing 4-17

Figure 4-19 Earthquake-induced cracking of ceramic tile on a slab-on-grade 4-18

Figure 4-20 Illustration of out-of-plane offset in a concrete slab-on-grade. Concrete slab on one side of the crack is higher than on the other side 4-20

Figure 4-21 Fresh crack in concrete exhibiting sharp edges, crack faces free of contamination and gap clear of debris 4-22

Figure 4-22 Older crack in concrete exhibiting worn and rounded edges 4-23

Figure 4-23 Fresh crack in concrete exhibiting lighter color on crack face relative to weathered surface 4-23

Figure 4-24 Older crack in concrete exhibiting worn and rounded edges contaminated with paint 4-24

Figure 4-25 Older crack in concrete floor slab contaminated with carpet pad adhesive 4-24

Figure 4-26 Parquet flooring adhesive filling crack in concrete slab 4-25

Figure 4-27 Dabs of drywall joint compound within shrinkage crack in concrete slab-on-grade floor 4-25

Figure 4-28 Older crack in foundation stemwall exhibiting prior patching and painting 4-26

Figure 4-29 Mortar within garage slab-on-grade crack indicates previous patching of crack 4-26

Figure 4-30 Crack in concrete slab-on-grade floor that exhibits two prior generations of patching, as well as opening since last patching 4-27

Figure 4-31 White leveling compound spread across existing crack at time of carpet installation 4-27

Figure 4-32 Debris (sawdust) from original construction indicates foundation crack is not recent 4-28

Figure 4-33 Dirt and efflorescence indicates age of foundation wall crack is not recent 4-28

Figure 4-34 Debris and vegetation in older crack 4-29

Figure 4-35 Grout completely filling slab-on-grade crack indicates that slab crack was present at the time of the tile installation and has not experienced movement since tile installation....4-29

Figure 4-36 Setting mortar that had flowed into an existing slab crack that remained bonded to the backside of a ceramic tile when the tile was removed, indicating that the concrete slab was cracked when the tile was installed....4-30

Figure 4-37 Termination of crack in older concrete (upper left) where it abuts newer concrete (lower right) indicates that crack existed prior to the installation of the newer concrete....4-30

Figure 4-38 Pattern of efflorescence around crack in stemwall indicates that crack is not of recent origin....4-31

Figure 4-39 Linear shrinkage crack in concrete floor slab at location of a concealed control joint created by a “zip strip”....4-31

Figure 5-1 Typical wall construction for older single-story houses in California—sheathing materials may vary....5-4

Figure 5-2 Typical wall construction for more modern two-story houses in California—sheathing materials may vary....5-5

Figure 5-3 Mock-up of typical three-coat stucco showing building paper, wire lath, scratch coat, brown coat, and finish or color coat....5-5

Figure 5-4 Illustration of common effects of differential settlement....5-7

Figure 5-5 Diagonal non-earthquake shrinkage cracks extending from the corners of a wall opening in stucco....5-8

Figure 5-6 Semi-random, semi-orthogonal grid work of non-earthquake shrinkage cracks in stucco—the cracks are highlighted by patching material applied in the course of repainting the building....5-8

Figure 5-7 Roughly linear vertical non-earthquake shrinkage cracks corresponding to the locations of underlying studs; crack locations have been highlighted with parallel lines of blue chalk....5-9

Figure 5-8 Magnified non-earthquake crazing cracking in stucco—circle is 5/8-inch across; bumps are grains of sand in stucco texture....5-9

Figure 5-9 Stucco terminated at weep screed on mudsill of recent addition at the right side of the image juxtaposed with stucco extended down onto the original foundation at the left side of the image....5-11

Figure 5-10 Typical crack pattern in wall finishes due to minor earthquake shaking....5-14

Figure 5-11 Severity of earthquake-induced cracking of wall finishes of multi-story buildings generally decreases at upper stories....5-14

Figure 5-12 Severe cracking and spalling of stucco wall test specimen after earthquake load testing 5-15

Figure 5-13 Earthquake-induced "X" cracking between windows in stucco panels with a thin brick veneer 5-16

Figure 5-14 Relationship between seismic drift (racking) of wall and cracking of stucco finish of laboratory test specimen. Here, the "drift" is measured as the ratio of the lateral movement divided by the wall height 5-16

Figure 5-15 Earthquake-induced delamination of stucco from wood framing and associated damage to aluminum door frame 5-17

Figure 5-16 Earthquake-induced crack in stucco at sill line where stucco was extended down over the foundation 5-18

Figure 5-17 Earthquake-induced cracking and buckling of stucco at the sill line where stucco was extended onto the perimeter concrete stemwall 5-18

Figure 5-18 Earthquake-induced cracking of drywall as a result of strong shaking 5-19

Figure 5-19 Earthquake-induced cracking and delamination of gypsum lath and plaster 5-20

Figure 5-20 Earthquake-induced cracking of ceramic tile 5-21

Figure 5-21 Earthquake-induced stucco cracking and buckling at a cripple wall 5-23

Figure 5-22 Earthquake-induced racking and delamination of stucco as viewed from the interior of a wall within a garage. Arrows point to nails that have pulled through 5-23

Figure 5-23 Earthquake-induced displacement of an interior partition due to inadequate attachment to floor slab 5-26

Figure 5-24 Photo of "T"-shaped cracks in stucco. Dark lines added for emphasis 5-28

Figure 6-1 Elements of a typical wood-frame house 6-4

Figure 6-2 Schematic of the role of horizontal diaphragms (e.g., floors or roofs) as structural elements resisting earthquake forces, where the red arrows indicate the direction of forces 6-4

Figure 6-3 Heavy tile roof sagging between wall supports, indicated by arrows 6-7

Figure 6-4 Poor fit-up of roof framing at rafter-to-ridge board junction 6-8

Figure 6-5 Nail withdrawal from plywood roof sheathing due to long-term moisture cycling 6-8

Figure 6-6 Deteriorated mastic at repair of built-up roof 6-9

Figure 6-7 Nail pop visible in ceiling 6-10

Figure 6-8 Gap between post and pier foundation in crawlspace 6-11

Figure 6-9	Tilted support posts in crawlspace	6-12
Figure 6-10	Cracked mudsill and missed nails	6-12
Figure 6-11	Gaps in flooring due to elongation of floor diaphragm caused by non-earthquake-induced slope movement	6-13
Figure 6-12	As-built misalignment between girder and footing accommodated with offset post	6-13
Figure 6-13	Shrinkage cracks in lightweight concrete fill	6-15
Figure 6-14	Re-entrant corners of plan irregularities are often locations of damage in horizontal diaphragms during strong shaking	6-16
Figure 6-15	Stemwall anchorage failure and earthquake-induced separation across discontinuous floor and roof diaphragms of a split-level house	6-16
Figure 6-16	Clay roof tile and mortar joints shifted by earthquake shaking	6-17
Figure 6-17	Buckled chimney flashing due to earthquake shaking	6-18
Figure 6-18	Earthquake damage from impact of falling masonry chimney	6-19
Figure 6-19	Masonry chimney and fireplace that have tilted away from the house. The chimney tore loose the wood framing to which steel tie straps from the chimney were attached	6-19
Figure 6-20	Diagonal ridge brace buckled due to earthquake; this brace is in line with the brace shown in Figure 6-21	6-20
Figure 6-21	Diagonal ridge brace cracked during earthquake; this brace is in line with the brace shown in Figure 6-20	6-21
Figure 6-22	Earthquake damage to ceiling corner bead at stairwell	6-22
Figure 6-23	Earthquake damage to tape joints at vertical load path irregularity	6-22
Figure 6-24	Earthquake damage to ceiling finish	6-23
Figure 6-25	Sagging floor due to earthquake-induced shifting and loss of support	6-23
Figure 6-26	Sliding of joists on mudsill due to earthquake	6-24
Figure 6-27	Earthquake-induced gap between floor and wall supported on retaining wall on uphill side of house on sloped lot	6-25
Figure 7-1	Damage to masonry chimney at shoulder	7-4
Figure 7-2	Schematic diagram of masonry fireplace and chimney structure	7-6
Figure 7-3	Undamaged masonry chimney above the roof	7-7
Figure 7-4	Chimney visible in attic with undamaged steel tie strap between chimney and framing	7-7

Figure 7-5 Schematic diagram of a factory-built fireplace 7-8

Figure 7-6 Undamaged factory-built fireplace and metal flue in wood-frame chase during construction 7-8

Figure 7-7 Schematic diagram of a factory-built fireplace and chimney assembly 7-9

Figure 7-8 Undamaged stucco-clad, wood-frame chimney chase 7-10

Figure 7-9 Undamaged firebox of factory-built fireplace with brick patterned refractory panels 7-10

Figure 7-10 Typical thermal cracking of firebrick and mortar lining firebox of a masonry fireplace 7-11

Figure 7-11 Normal crack between masonry fireplace and chimney and exterior stucco wall 7-12

Figure 7-12 Gap between chimney and house, where mortar filler was used to fill the previous gap. Since the repair, the gap has widened, evidenced by paint in the gap and the cobweb spanning the gap 7-13

Figure 7-13 Tapered gap between chimney and house that has resulted from long-term differential settlement of fireplace foundation. Mortar filler was used to fill the previous gap 7-13

Figure 7-14 Random isolated cracking of brick and mortar joints commonly found on masonry fireplaces and chimneys 7-14

Figure 7-15 Mortar joint between firebox and masonry facing where hairline cracks are frequently found 7-14

Figure 7-16 Earthquake-induced failure of masonry fireplace at firebox level 7-15

Figure 7-17 Earthquake-induced damage to masonry chimney above roofline 7-16

Figure 7-18 Earthquake-induced failure of masonry chimney at roofline 7-16

Figure 7-19 Earthquake-induced damage to masonry chimney in attic 7-17

Figure 7-20 Earthquake-induced failure of masonry chimney at gable 7-17

Figure 7-21 Earthquake-induced damage to masonry chimney at mid-story 7-18

Figure 7-22 Earthquake-induced damage to masonry chimney at shoulder 7-18

Figure 7-23 Earthquake-induced damage to masonry fireplace at foundation level 7-19

Figure 7-24 Earthquake-induced masonry chimney and fireplace that have tilted away from the house. The chimney tore loose the wood framing to which steel tie straps from the chimney were attached 7-19

Figure 7-25 Earthquake-induced tapered separation between masonry chimney and exterior wall. There is also damage to the top of the chimney due to deterioration of mortar 7-20

Figure 7-26 Relative cyclic movement between chimney and building caused by earthquake, indicated by elongated hole in metal flashing and gap between caulking and flashing 7-21

Figure 7-27 Tearing of flashing between chimney and roof caused by relative movement between chimney and building during earthquake 7-21

Figure 7-28 Rooftop debris from collapse of masonry chimney during earthquake 7-22

Figure 7-29 Collapsed unreinforced stone chimney caused by earthquake 7-23

Figure 7-30 Masonry mantle that separated slightly from the wall finish during earthquake 7-24

Figure 7-31 Collapsed masonry facing caused by earthquake 7-24

Figure 7-32 Illustration of rocking procedure for checking chimney for earthquake-induced cracking 7-27

Figure 8-1 Undamaged rooftop HVAC unit 8-3

Figure 8-2 Earthquake-casued damage to rooftop HVAC unit 8-3

Figure 8-3 Earthquake-caused displacement of unsecured water heater 8-4

Figure 8-4 Manual gas shut-off valve, where photos on the right show the valve closed 8-6

Figure 8-5 Gas meters with seismic shut-off valves 8-7

Figure 8-6 Toppled “swamp cooler” due to earthquake 8-8

Figure 8-7 Earthquake-caused displacement of unsecured water heater vent 8-11

Figure 8-8 Undamaged water heater with flexible piping and strapping 8-11

Figure 8-9 Undamaged flexible piping between unsecured water heater and house piping 8-12

Figure 8-10 Undamaged water heater with hard piping 8-12

Figure 8-11 Earthquake-caused racking and delamination of exterior stucco resulting in damage to electrical outlet 8-13

Figure 8-12 Close-up of earthquake damage to electrical outlet box 8-14

List of Tables

Table 2-1 Abridged Modified Mercalli Intensity Scale 2-5

Table 4-1 Repair Methods Not Requiring Technical Consultant Assistance for Nominal Earthquake Damage to Foundations and Slabs-On-Grade 4-32

Table 5-1 Repair Methods Not Requiring Technical Consultant Assistance for Nominal Earthquake Damage to Wood-frame Wall Surface Materials 5-29

Table 6-1 Repair Methods Not Requiring Technical Consultant Assistance for Nominal Earthquake Damage to Wood-frame Ceiling Surface Materials 6-29

Table 7-1 Repair Methods Not Requiring Technical Consultant Assistance for Nominal Earthquake Damage to Chimneys 7-29

CHAPTER 1

Introduction

This document is the first of two volumes comprising the series *Earthquake Damage Assessment and Repair Guidelines for Residential Wood-Frame Buildings*. The documents describe the process of identifying, evaluating, and repairing common earthquake damage in typical residential wood-frame buildings and are intended to increase the efficiency, consistency, and reliability of the earthquake damage assessment and repair process. They provide guidance on issues related to:

- common earthquake vulnerabilities and damage potential in houses,
- identification and documentation of earthquake damage,
- evaluation of earthquake damage, and
- development of a conceptual scope of repair for earthquake damage.

The focus of these documents is typical one- and two-family wood-frame dwellings, generally referred to herein as "houses." While manufactured homes (mobile homes) and larger multi-unit residential buildings are outside the scope of the documents, the general principles and methodology may still be applicable for these buildings. Some of the details and references are California-centric, but the general principles and methodology are applicable throughout the United States. It is not intended that use of these documents is limited to any particular building configuration or location; rather, the intent is to inform users that certain building characteristics were contemplated in the organization of the documents and the development of their content.

This document, referred to herein as the *General Guidelines*, is primarily intended for use by building contractors, insurance claim representatives (adjusters), homeowners, and others familiar with construction and repair. The *General Guidelines* are intended to help users: (1) select appropriate repairs for damage that can be reliably identified and appropriately implemented by qualified tradespersons without the assistance of technical consultants; and (2) identify those conditions for which the assistance of a technical consultant may be necessary for the accurate assessment and repair of damage.

The companion document to the *General Guidelines* is an in-depth technical report, CEA-EDA-02, *Earthquake Damage Assessment and Repair Guidelines for Residential Wood-Frame Buildings*, *Volume 2 – Engineering Guidelines* (CEA, 2020), referred to herein as the *Engineering Guidelines*. The intended audience of the *Engineering Guidelines* is technical consultants, such as engineers and architects, who are involved in post-earthquake damage assessment of wood-frame buildings.

1.1 Organization and Content

This document consists of nine chapters and a series of appendices:

Chapter 1 presents general aspects of damage assessment, including a description of the stages of an assessment, and provides an overview of earthquakes and the various types of damage they cause.

Chapter 2 describes various quantitative and qualitative measures of earthquake ground shaking, and the general types of damage associated with various levels of ground shaking. Common earthquake vulnerabilities in houses and their potential for damage are presented. Sources of maps of ground shaking data are identified.

Chapter 3 describes common types of soils, typical non-earthquake related conditions, typical types of earthquake-related ground failure, and common repair techniques. Guidelines are provided for conducting an inspection and the circumstances indicating the need for technical assistance.

Chapter 4 describes common types of foundations, typical non-earthquake related conditions, typical types of earthquake-related damage, and common repair techniques. Guidelines are provided for conducting an inspection, appropriate repair of common types of nonstructural earthquake damage, and the circumstances indicating the need for technical consultant assistance.

Chapter 5 describes common types of wall construction, including finishes as well as concealed framing, typical non-earthquake related conditions, typical types of earthquake-related damage, and common repair techniques. Guidelines are provided for conducting an inspection, appropriate repair of common types of nonstructural earthquake damage, and the circumstances indicating the need for technical consultant assistance.

Chapter 6 describes common types of floor, ceiling, and roof construction, typical non-earthquake related conditions, typical types of earthquake-related damage, and common repair techniques. Guidelines are provided for conducting an inspection, appropriate repair of common types of nonstructural earthquake damage, and the circumstances indicating the need for technical consultant assistance.

Chapter 7 describes common types of fireplaces and chimneys, typical non-earthquake related conditions, typical types of earthquake-related damage, and common repair techniques. Guidelines are provided for conducting an inspection, appropriate repair of common types of earthquake damage, and the circumstances indicating the need for technical consultant assistance.

Chapter 8 describes common types of mechanical, electrical, and plumbing systems and components, typical types of earthquake-related damage, and common repair techniques. Guidelines are provided for conducting an inspection, appropriate repairs for common types of earthquake damage, and the circumstances indicating the need for technical consultant assistance.

Chapter 9 describes the various specialties of technical consultants that may be needed to assist with assessment and repair of earthquake damage, addresses interactions with technical consultants, including discussion of circumstances requiring a technical consultant, resources for locating technical consultants, expectations regarding qualifications, terms of the technical consultant engagement, and an outline for a comprehensive technical consultant's report.

Appendix A provides a Building Occupant Questionnaire, which presents a series of questions intended to assist building occupants in recording their earthquake experiences during the earthquake. Appendix B lists useful earthquake damage inspection tools. Appendix C includes the General Earthquake Damage Inspection Checklist, which is intended to provide guidance for a systematic visual inspection of a building and site. Appendix D and Appendix E provide the Crawlspace Earthquake Damage Inspection Checklist and the Attic Earthquake Damage Inspection Checklist, respectively, which provide guidance for the systematic visual inspection of these spaces. Appendix F includes safety guidelines when inspecting an attic or crawlspace.

Appendix G provides recommendations for crack repair by epoxy injections in residential concrete. An appendix with a Glossary and Acronyms—providing definitions of key terms used in this document—and a list of References are provided at the end of the report.

1.2 Post-Earthquake Assessment

Three distinct types of post-earthquake assessments are commonly performed on buildings that have been subjected to strong ground motions:

- urban search and rescue assessments,
- safety assessments, and
- damage assessments (the focus of this document).

Urban search and rescue assessments focus on assessment of severely damaged buildings for purposes of location and extraction of potential trapped victims. Safety assessments focus on the safety of a building for continued occupancy, without regard to the extent of possible non-safety-related damage. Damage assessment focuses on determination of the nature, extent, and appropriate repair of all earthquake damage, whether safety related or not. While the focus of this document is damage assessment, key aspects of urban search and rescue and safety assessment are summarized below for background.

1.2.1 Urban Search and Rescue Assessment

Following a major earthquake in which occupied buildings are known to have collapsed, specially trained urban search and rescue teams will be dispatched to the most heavily damaged areas to search for and extract trapped victims. In the course of that effort, many buildings may be evaluated and searched, with the results of those efforts typically indicated by spray-painted markings on the building near the main entry. Such markings are relevant only in the context of search and rescue and should not be confused with safety assessment posting, or "tagging," which evaluates the safety of the building for ongoing occupancy, as discussed below.

1.2.2 Safety Assessment

Following a moderate to major earthquake, local or state building departments have the responsibility for conducting safety assessments where there is a concern over whether a building is still safe to occupy. To augment the relatively limited staff of these departments, some states such as California have well-organized systems whereby specially trained and pre-certified volunteer engineers, architects, and building inspectors are dispatched to the most seriously affected areas to assist local governments in performing safety assessments of buildings. The result of that assessment is a green, yellow, or red "tag," or placard, that is posted on the building to indicate its relative safety. Buildings posted with a red tag (UNSAFE) or yellow tag (RESTRICTED USE) have one or more recognized types of safety-related damage. Buildings posted green (INSPECTED) may have sustained damage but are judged safe for continued lawful occupancy (i.e., not significantly more hazardous to the safety of the occupants than prior to the earthquake). If a building is posted with a tag, the damage assessment inspector should read the tag and then make an informed judgement as to how their inspection should proceed.

Generally, safety assessment evaluators are dispatched to the more heavily damaged neighborhoods to evaluate all buildings in the area within a week following the earthquake. Evaluations may vary in level of detail from only exterior observation to detailed walkthroughs. Buildings outside the more heavily damaged neighborhoods are generally evaluated only if the owner requests an assessment. If a building has not been evaluated and an owner or occupant has safety concerns, they should contact the local building department and request a safety assessment. The evaluator should explain any earthquake-related hazardous conditions found at the property to the owner or occupant. If a building has been posted red or yellow on the basis of a rapid assessment, the owner or occupant of a building may request a follow-up detailed safety assessment from the local building department to verify the appropriateness of, or revise, the original posting. Strong aftershocks are common in the weeks following an earthquake. If an aftershock causes significant additional damage, reassessment of the building is recommended. More detailed information regarding safety assessment procedures and postings is available from the Applied Technology Council's (ATC) website: https://www.atcouncil.org/atc-20

Safety assessments do not address non-safety-related earthquake damage that may have occurred. Even if a building is deemed safe to occupy, it may have sustained damage that necessitates assessment, as discussed in the following section. By way of analogy, consider a car that has been in an accident. You (or your mechanic) may determine that all essential systems (e.g., brakes, steering, engine) in the car still work fine, and it is safe to drive (the safety assessment), even if the trunk is jammed shut and bumpers and fenders are dented and need replacement. The extent and cost of repairs necessary to restore the full function and appearance of the car will be determined by a body shop (damage assessment).

It is important that users of the *General Guidelines* do not comment on the safety of a dwelling, unless the user has the necessary experience and licensure to make such statements.

1.2.3 Damage Assessment

One of the goals of the *General Guidelines* is the efficient identification of earthquake-induced damage. Accordingly, emphasis is placed upon identification of common modes of damage caused by earthquakes and distinguishing earthquake-induced damage from damage resulting from other causes. This document specifically does not address in detail issues of code compliance, construction defects, deterioration, obsolescence, seismic retrofits, voluntary upgrades, or other non-earthquake-induced conditions. The intent is not to minimize the significance of these items, but rather to maintain a manageable scope for this document and a well-defined and manageable scope of services for any technical consultants who are called upon to perform damage assessments.

Inspector and Inspection

In this document, the terms "inspector" and "inspection" are used in a generic sense to refer to the people and process associated with conducting post-earthquake damage assessment and should not be confused with the more specific terms "building inspector," "special inspector," "building inspection," or "special inspection" associated with inspection of building construction for compliance with building code requirements.

In this document, earthquake damage is defined as an adverse, non-trivial, physical change in the safety, serviceability, appearance, or repairability of a component or portion of a building caused by earthquake ground shaking or earthquake-induced permanent ground deformation. For the building structure, damage is considered *structurally significant* when it results in a non-trivial, adverse change in the ability of the building to sustain load or resist future earthquake shaking. *Nonstructural damage* (or structurally insignificant or cosmetic damage) is all other damage to the structure that does not meet the threshold of structurally significant damage, although it may still pose a safety hazard. Examples of nonstructural damage that poses a safety hazard are architectural features that could be falling hazards and railings that are no longer appropriately anchored.

Pre-existing damage believed to have been worsened by an earthquake should only be considered as damage needing to be repaired when the earthquake effect has made the damage categorically different, such that the repair recommendations in this document would call for a different type of repair for the pre-earthquake and post-earthquake conditions. For example, consider a vertical crack in a concrete stemwall up to 1/16-inch wide with no out-of-plane offset. Such a crack is characteristic of normal concrete shrinkage and would reasonably be categorized as non-earthquake damage. Even if it were considered earthquake damage, Table 4-1 in Chapter 4 indicates no repair.

If upon investigation following an earthquake, a crack is found with characteristics of shrinkage cracks but with a width still less than 1/8 inch, it might be argued that the earthquake widened the pre-existing shrinkage crack, but Table 4-1 would still require no repair. Since the repair (or lack of repair, in this case) would be the same for the pre-earthquake and post-earthquake conditions, the crack would be categorized as damage not needing repair. In contrast, if a similar crack is found upon investigation with a width up to 1/2 inch, Table 4-1 would call for repair by epoxy injection. Assuming the widening can be reasonably ascribed to the earthquake, this crack would be categorized as new damage even though the concrete was already cracked from shrinkage.

For building mechanical systems (such as the furnace and ductwork), only safety and serviceability are of concern since these systems have no structural function.

The appropriate level of effort for earthquake damage assessment will depend upon the nature of the existing construction and the extent of the damage. An assessment should typically begin with a visual assessment by an owner, general contractor, or insurance claim representative using the criteria presented in this document. If this initial visual assessment identifies conditions that indicate the need for technical consultant assistance, the appropriate technical consultant(s) should be retained for further assessment; otherwise, repairs may proceed with the methods presented in this document. In some circumstances, destructive investigation may be recommended by the technical consultant to reliably determine the nature and extent of possible earthquake damage to concealed elements, such as wall framing behind finishes. Figure 1-1 presents a flowchart that identifies the key steps and their relationships in the post-earthquake damage assessment process envisioned by the *General Guidelines.* The assessment performed under the *Engineering Guidelines*, after the retention of a technical consultant, is represented at the bottom of the flowchart.

If the initial assessment is conducted by someone other than the owner or occupant, the inspector should interview the property owner or occupant. The purpose of the interview is to obtain pertinent information regarding the condition of the property prior to the earthquake, experiences during the earthquake, disruption of and damage to contents, and observations regarding cracks, potential damage, or unusual conditions observed at the property (or adjacent properties) following the earthquake. Appendix A presents a series of questions in checklist format intended to assist building occupants in recording their experiences during the earthquake and their observations made immediately following the earthquake.

Next, a visual inspection of all accessible areas of the property should be completed. In preparation for this inspection, the inspector may recommend that the building owner or occupant mark potential earthquake damage with tape that is easily removed without damaging the surface to which it is applied. This accomplishes three important things. First it provides the owner or occupant a productive role in the post-earthquake inspection process. Second, it speeds up the inspection process and decreases the likelihood of earthquake damage being overlooked by the inspector. And third, if the owner or occupant has marked damage the inspector believes is not related to the earthquake, it allows the owner or occupant and inspector to resolve the issue at the time of the inspection.

A thorough visual inspection of outdoor areas and the building exterior should be completed. If it is considered safe to enter the building, a visual inspection of interior conditions should be performed. Appendix B lists specific equipment that can facilitate the inspection. Appendix C presents a checklist to provide guidance for a systematic visual inspection of a building and site.

For some types of damage, such as to wall finishes or foundations, the recommended repair depends on the size of cracks, among other factors. Documenting the maximum size of cracks during the visual inspection can help later in preparing repair recommendations.

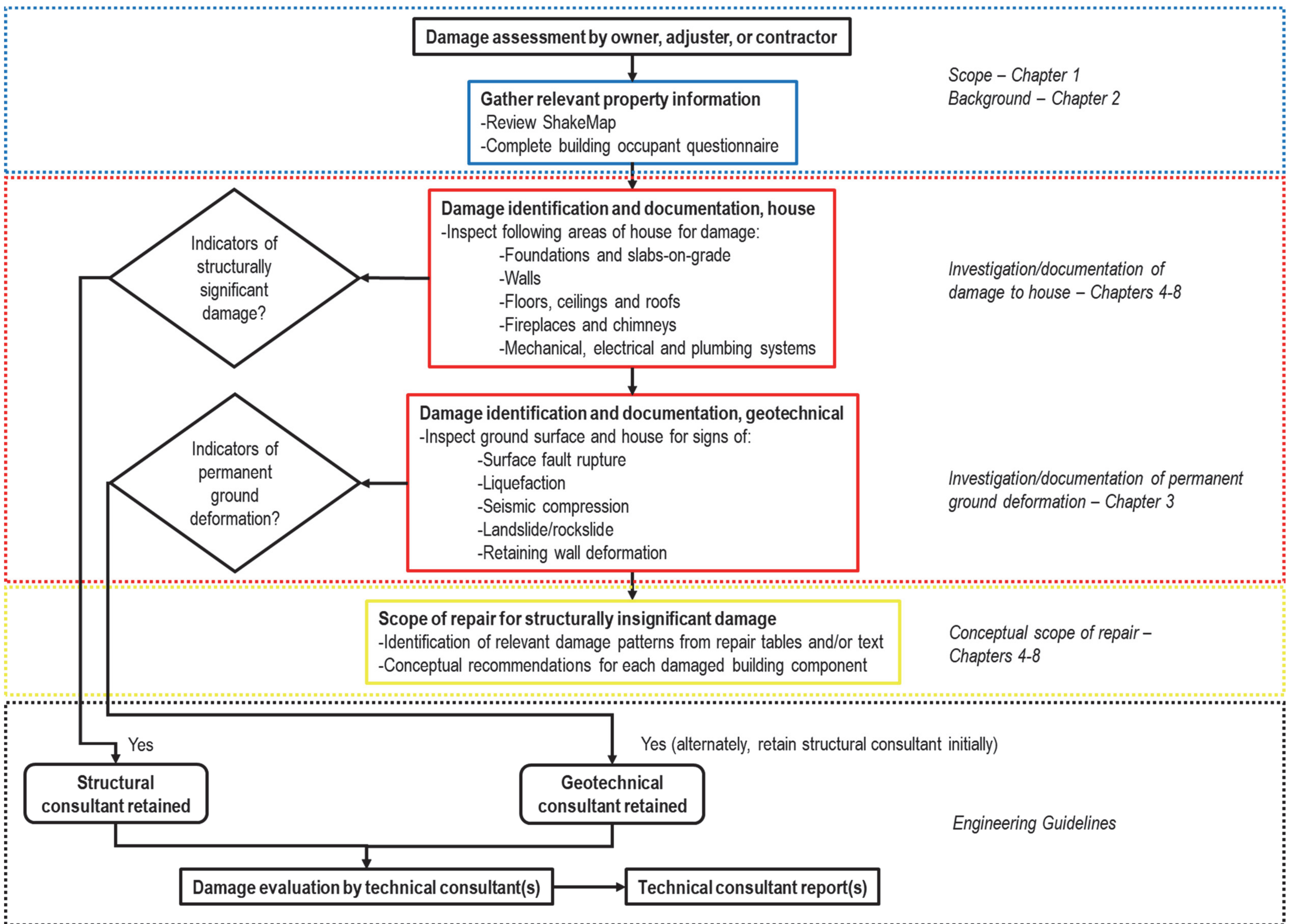


Figure 1-1 Post-earthquake damage assessment process envisioned by the *General Guidelines*.

Clear photographs or video are extremely useful for documenting conditions. Photographs should include overall views of the property and any observed earthquake-induced damage as well as any unusual conditions. Photographs should be taken of damaged as well as undamaged areas, and where necessary, field notes should identify the area or item photographed. In many cases, combining overall views with close-up views of building features is an effective method for identifying the location of earthquake damage for later reporting purposes. Photograph numbers may also be recorded on a sketch of the floorplan so that the location of a photograph within the building can be later identified. Including a tape measure or crack gauge in a photograph is helpful in depicting the size of the item or damaged area.

1.2.4 Attic and Crawlspace Inspections

Earthquake-induced damage within attics or crawlspaces, in the absence of conspicuous visible external damage, is unlikely. In addition, there are hazards associated with entry into these areas. Accordingly, in the absence of external visible damage, entering attics and crawlspaces for post-earthquake inspections is not recommended. If an attic or crawlspace inspection is conducted, it should be performed by an individual qualified by training or experience. Appendix D and Appendix E present checklists to provide guidance for systematic visual inspections of crawlspaces and attics, respectively. Damage and abnormal conditions should be documented with photographs.

Due to safety concerns associated with entry into a confined space, inspection of these areas may require the presence of a second individual or assistance from the owner or occupant. Inspectors should be equipped with appropriate personal protective equipment and be knowledgeable of appropriate safety precautions. Safety precautions for attic and crawlspace inspections are presented in Appendix F.

Evaluating basements is outside the scope of this document, but the guidance on foundations, walls, and other components might be applicable to basements, depending on conditions.

1.2.5 Technical Consultant Assistance

If damage patterns or obviously unsafe conditions indicating the need for technical consultant assessment (as described in detail in subsequent chapters) are observed, a technical consultant should be retained to investigate. The investigation should include, at a minimum, a detailed visual inspection, measurements, and photographs, as described in subsequent chapters. The technical consultant may recommend additional investigation, possibly including destructive investigation (see Section 1.2.6).

There are various specialties of technical consultants. The most common specialties involved in assessment and repair of earthquake damage in residential wood-frame buildings are the structures specialist and the soils specialist. Structures specialists include licensed civil engineers specializing in structural engineering, licensed structural engineers (civil engineers who have satisfied additional experience and testing requirements and are authorized to use the title structural engineer), and licensed architects with expertise in structures. Soils specialists include civil engineers specializing in soils (or geotechnical) engineering, geotechnical engineers (civil engineers who have satisfied additional experience and testing requirements and are authorized to use the title geotechnical engineer), and engineering geologists with expertise in geotechnical engineering. See Section 9.3 for additional discussion.

In buildings constructed prior to 1980, where repairs may involve disturbing certain finishes or building materials that contain asbestos or lead-based paint, the services of an appropriate, qualified, and licensed environmental consultant should be procured. This consultant may recommend that testing and proper abatement be conducted. There are legal requirements for such evaluations and procedures when the work is being done by contractors, or if the amount of material being disturbed is larger than a few square feet. See Section 9.2.4 for additional information.

1.2.6 Destructive Investigation

Destructive investigation or testing (also known as "invasive inspection") is an investigative technique that can be used to inspect the condition of those parts and portions of a building that may be concealed from direct observation. Common types of destructive investigation include removal of carpeting and padding to inspect concrete floor slabs, extraction of core samples from concrete slabs and foundations, removal of wall finishes to inspect concealed framing, excavation of soil test pits, and drilling soil borings. Destructive investigation should be necessary only in those instances when the technical consultant is either unable to rule out or reasonably assume earthquake damage based on non-invasive means. Before pursuing destructive investigation, the benefits and costs of the undertaking should be understood and evaluated. There should be a clear understanding of the nature of the testing and associated costs, the nature and significance of information to be obtained, the nature and extent of damage to finishes associated with the destructive investigation, and responsibility and standards for repair of that damage.

1.3 Earthquake Damage Repair Standards

In addition to the goal of damage assessment discussed above, another goal of these *General Guidelines* is the appropriate repair of earthquake-induced damage. Accordingly, emphasis is placed upon repair of common patterns of earthquake-induced damage. This document specifically does not address repair of damage or deficiencies resulting from non-earthquake causes. The intent is not to minimize the significance of such items, but rather to maintain a manageable scope for this document and a well-defined and manageable scope of services for any technical consultants retained to conduct post-earthquake damage assessments. The guidance presented in this document is strictly limited to facilitating objective determination of earthquake damage and proper determination of appropriate repair (but not the cost of that repair) to restore the building to its pre-earthquake condition. Other considerations, such as requirements for building permits or other government agency approvals, application of particular insurance policy terms, or decisions regarding building replacement or remodeling in lieu of repair are outside the scope of this document.

There are varying types and degrees of repair that may be pursued following an earthquake, ranging from minor cosmetic repair that is deferred until the next cycle of repainting, to repair or replacement in kind, to retrofits or upgrades that bring the property up to current code or improve the expected future performance of the building.

1.3.1 Like Kind and Quality Repair

Like kind and quality repairs restore the function and appearance of the damaged component to that which existed before the earthquake using materials similar to those of the original construction. In those cases where the damage weakens the building, a structural repair will be necessary. In all other cases, nonstructural repair is appropriate. Where one of the functions of an element is cosmetic, repairs should include work that is necessary to assure a reasonably uniform appearance after the repairs are completed. The repair methods described in these *General Guidelines* are intended to restore the nonstructural function and appearance to that which existed prior to the earthquake. Technical consultants should be consulted where stabilization of soils or repair of structurally significant damage is necessary, or where repairs will disturb materials that potentially contain asbestos or lead-based paint.

In certain circumstances, like kind and quality repairs may be impractical or undesirable due to changes in construction practices and technology. Common examples are replacement of older lath and plaster wall and ceiling finishes with modern drywall, and replacement of masonry fireplaces and chimneys with prefabricated fireplaces and metal flues.

Repair Standards Defined by Insurance Policies

For situations involving earthquake insurance policies, repair standards may be defined by policy language. For example, the 2016 California Earthquake Authority Homeowners policy includes the following definition of replacement cost: "With respect to structures, the lesser of the reasonable cost at the time of loss to repair or replace covered damaged or destroyed property, without deduction for depreciation: (i) at the location of the residence premises; (ii) for the same use; and (iii) with materials of like kind and quality. With respect to personal property and wall-to-wall carpeting, the cost, without deduction for depreciation, of: (i) new property identical to the damaged property; or (ii) if identical property is not obtainable, of new property of like quality and of comparable usefulness as the damaged property."

1.3.2 Code-Triggered Upgrades

In addition to normal changes in the building code over time, some jurisdictions have building code requirements that mandate varying degrees of upgrades if certain damage thresholds are exceeded. The repair guidelines presented herein are intended to represent prevailing best practices and do not include jurisdiction-specific requirements. The local building department should be contacted to determine the existence of any applicable local requirements. Where utilized, technical consultants should be asked to address any code-triggered upgrades that may be required to comply with applicable local building code requirements as part of the repair of earthquake damage.

1.3.3 Voluntary Upgrades

In general, like kind and quality repair of earthquake damage will not prevent or limit recurrence of damage in future earthquakes or provide compliance with codes for new construction. A building repaired exactly to its pre-earthquake condition will, theoretically, sustain the exact same damage in a future repeat of the original earthquake and will sustain more severe damage in a stronger future earthquake. For older buildings with known seismic vulnerabilities, consideration of voluntary seismic upgrades to address potentially life-threatening vulnerabilities is strongly encouraged. Technical consultants may be asked to identify conditions (related or unrelated to actual earthquake damage) that they recommend be addressed to improve the expected future performance of the building. If made, such recommendations should be clearly identified in the technical consultant's report as optional or voluntary upgrades to the building that will improve future performance of the building.

1.4 Earthquake Basics

The fundamental manifestation of earthquakes is ground shaking that can result in direct effects on people and the built environment by frightening people, disturbing building contents, and causing nonstructural and structural damage to buildings and other man-made improvements. Earthquakes can also trigger other effects on people and the built environment, such as fires, ground failures, tsunamis, and seiches.

Earthquakes occur when a geologic fault in the bedrock of the earth's crust ruptures suddenly and the sides of the fault slip with respect to each other over an area of a fault called the rupture surface. The rupture begins at a point on the fault plane called the hypocenter, which can be located miles beneath the ground surface. The epicenter is the point on the ground surface directly above the hypocenter. The rupture releases energy that has accumulated in the rock mass over time. The process is much like that of snapping fingers; before the snap, you push your fingers together and sideways. Because you are pushing them together, friction keeps them from moving apart; when you push sideways hard enough to overcome this friction, your fingers move suddenly, releasing energy in the form of sound waves that set the air vibrating and travel from your hand to your ear, where you hear the snap. A similar process occurs in an earthquake—over time stress accumulates in the earth's crust along earthquake faults. The friction across the surface of a fault locks the fault and prevents movement as the stress accumulates. Eventually enough stress builds up to overcome the friction, and the rock along the fault slips suddenly, releasing the stored energy. The energy is released in the form of seismic waves that radiate away from the fault rupture and travel through the earth's crust at very high speeds. When these seismic waves reach the ground surface, they result in shaking of the ground surface. This shaking is what we perceive as an earthquake.

Faults are characterized by the direction of relative slip across the fault. In a strike-slip fault, the two sides of the fault move horizontally with respect to each other, as shown in Figure 1-2. During the 1906 San Francisco earthquake, the ground surface was displaced (i.e., slipped) horizontally as much as 21 feet across the surface rupture of the San Andreas Fault, but in most earthquakes the amount of displacement is much less.

With dip-slip faults, opposite sides of the fault slip vertically with respect to each other. A thrust fault is a special category of dip-slip faults, in which one side of the fault is thrust over the other side of the fault due to compressive stresses that have built up across the fault. Thrust faulting is responsible for mountain building—following an earthquake, the ground on one side of the fault will be at a slightly higher elevation than before the earthquake. Over geologic time, the cumulative effect of thousands of such earthquakes is a mountain range. Faults that do not extend to the ground surface are known as blind faults, as shown in Figure 1-3. The 1994 Northridge earthquake in the Los Angeles area occurred on a blind thrust fault. The ground above a blind thrust fault may bend instead of breaking, so that the surface manifestation of the fault over geologic time is only rolling hills rather than a surface rupture.

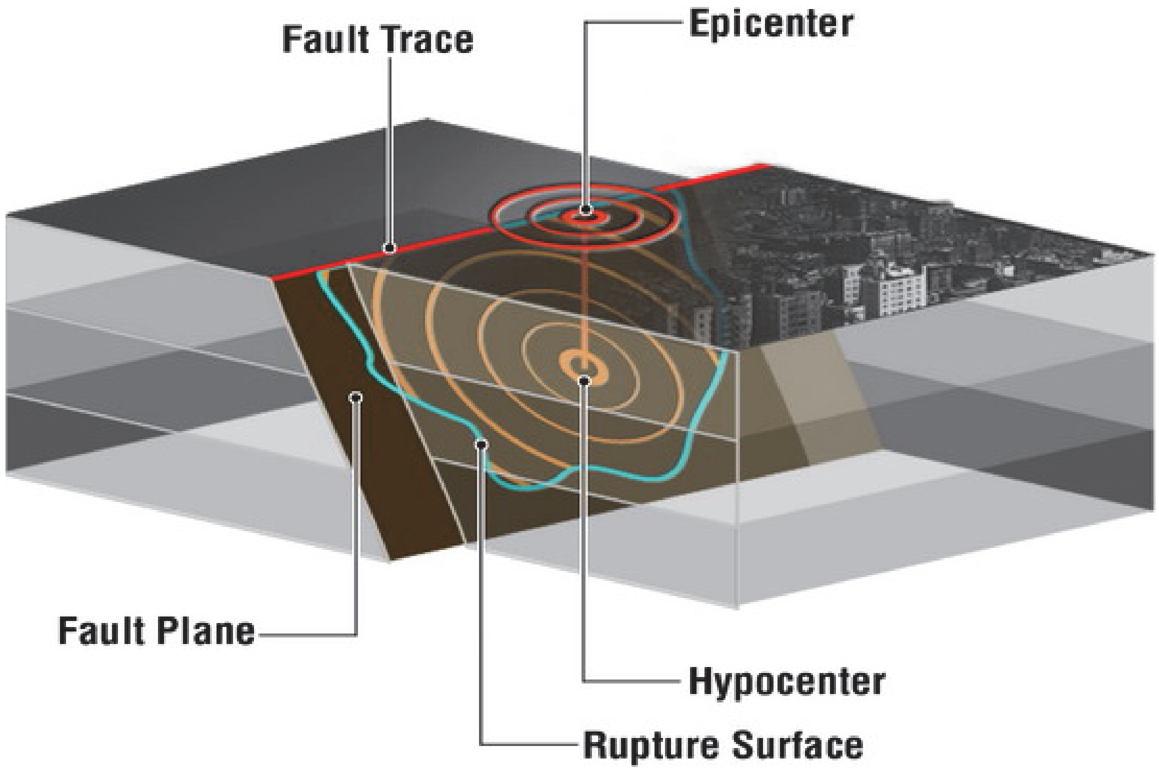


Figure 1-2 Illustration of a strike-slip fault (image credit: Exponent).

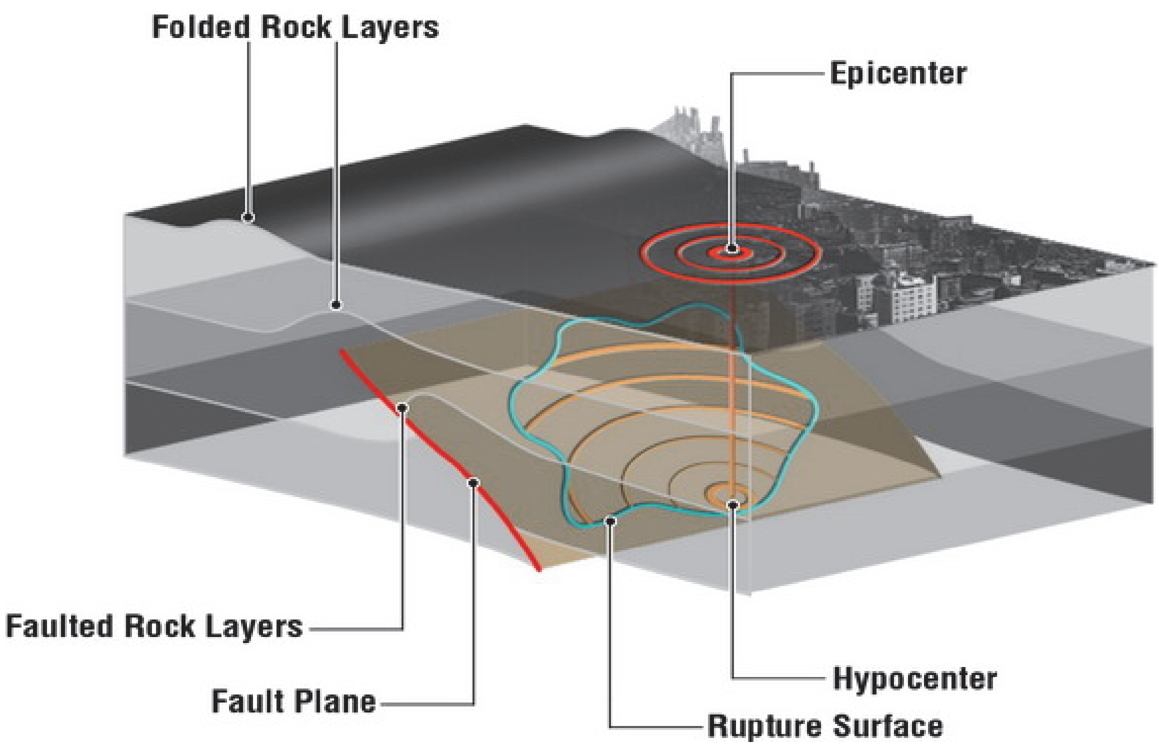


Figure 1-3 Illustration of a blind thrust fault (image credit: Exponent).

The shaking of the ground surface during an earthquake is caused by the combined effect of the passage of several types of waves that cause the ground surface to oscillate, or vibrate, from side to side and up and down. The shaking may produce strong ground accelerations, but, in the absence of ground failure, typically produce small ground deformations. That is, the ground moves as a relatively rigid surface and does not significantly bend. Despite occasional accounts to the contrary, seismic waves at the ground surface are usually too subtle to be discernable to the naked eye. Absent ground failure, damage to buildings is caused by the rapid vibrations of the ground surface, not distortions of the ground surface.

1.4.1 Earthquake Damage

The primary cause of damage during an earthquake is the effect of ground shaking on buildings and components. Earthquake damage can also be caused by earthquake-induced ground failure, earthquake-induced disturbance of bodies of water, and fires following the earthquake that are triggered by earthquake-induced damage to buildings and utilities. The following sections summarize how earthquakes cause damage.

Effects of Ground Shaking on Buildings

The key to understanding earthquake damage is knowledge of the interaction between ground acceleration, building mass (or roughly speaking, the weight of the building), inertia, and flexibility (that is, brittleness versus ductility). To get an intuitive feel for the effect of ground acceleration, let’s take a ride on a bus in heavy traffic. Start off by standing in the aisle, facing forward without holding onto anything. As long as the bus is at rest, or traveling straight at a steady speed, this is easy to do. However, as the bus accelerates or decelerates (i.e., brakes), it is difficult to remain upright without grasping a bar or moving your feet. Here is what’s happening: as the bus accelerates, you begin to tip backwards—your feet move with the bus but the rest of your body wants to remain at rest. This is the principle of inertia. The same thing happens when the bus brakes—your body wants to keep moving, but your feet are stuck to the floor, so you begin to tilt forward. Now imagine ten or fifteen rapid cycles of accelerator-brake/accelerator-brake … and you have some “feel” for what a building goes through during an earthquake. Notice that you (hopefully) did not get damaged during this experiment because in response to the acceleration you were able to flex or grip a grab bar. Imagine what would have happened to a six-foot-tall pile of bricks next to you on the bus. The physics described above is illustrated in Figure 1-4.

To carry the analogy further, try traveling with two associates—one standing and one lying on the floor. Note the one standing has the most difficulty with acceleration while the one on the floor has no trouble whatsoever. This illustrates a second principle—that the effect of earthquake forces is a function of the height of the building above the ground, as well as the weight of the building. The effect of earthquake forces generally will be greater on a taller structure than on a shorter structure or components built at-grade, such as floor slabs and pavement. To further illustrate the effect of mass and height, you could repeat the experiment wearing a heavy backpack. If it was difficult to remain upright before, the added weight of the backpack makes it virtually impossible to remain upright without gripping a hand hold.

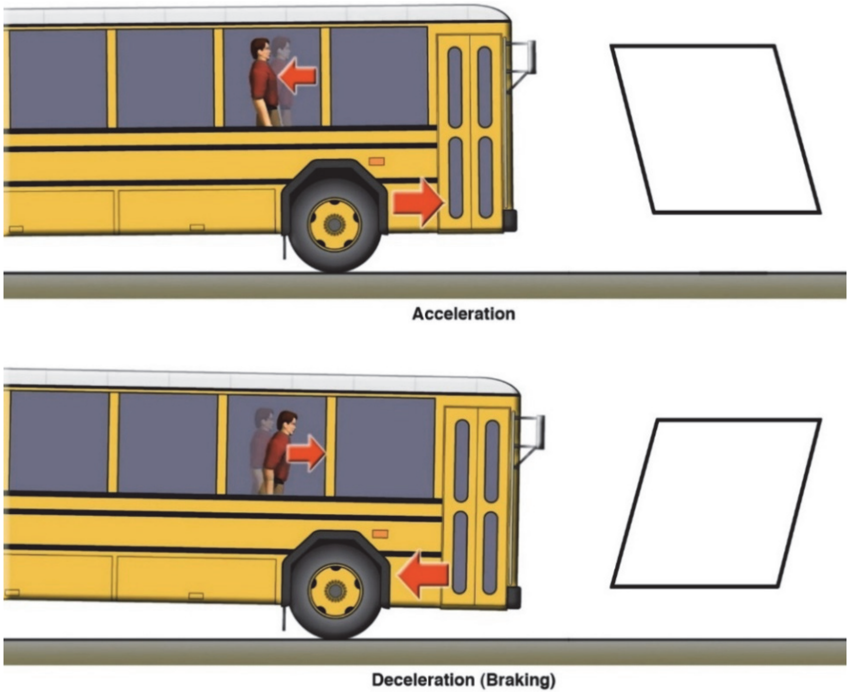


Figure 1-4 Effect of acceleration and deceleration (i.e., braking) on vertical objects, where the red arrows indicate the direction of force (image credit: Exponent).

One last point before we leave the bus. You may have noticed that the ride over some rough pavement was rather bumpy, which caused the bus and you to bounce up and down. These are vertical accelerations as opposed to the horizontal, or lateral, accelerations you experienced as the bus was accelerating, braking, or turning corners. Even though some of the vertical accelerations going over bumps are much greater than the lateral accelerations of stop-and-go driving, you have no difficulty standing. You are used to the constant vertical forces caused by gravity, and a little additional force acting vertically is easy to resist. This illustrates another principle—vertical accelerations usually cause no or little damage in earthquakes because buildings, like people, can support more than their own weight in the vertical direction, but only a fraction of their own weight in a lateral direction.

Now, back to the world of buildings. The rapid movement back-and-forth and side-to-side of the ground surface creates inertial forces in buildings as the building attempts to "keep up" with the rapidly moving ground. These inertial forces tend to rack, or distort, the walls of residential wood-frame construction, as illustrated in Figure 1-5. In contrast to the walls, the horizontal elements (e.g., roof, floors, foundation, and pavement) move as essentially rigid units relative to the ground. As a result, the horizontal elements experience relatively little distortion and consequently experience relatively low forces during earthquake ground shaking. Thus, for most wood-frame residential buildings, earthquake damage is typically concentrated in the first-story walls; although there are notable exceptions where the weak link occurs elsewhere in a building. The response of a typical two-story wood-frame building is shown schematically (and greatly exaggerated) in Figure 1-6. Typical racking (or "out-of-plumb") distortions range from a fraction of an inch per story in buildings with cosmetic damage to several inches per story in buildings with widespread, structurally significant damage.

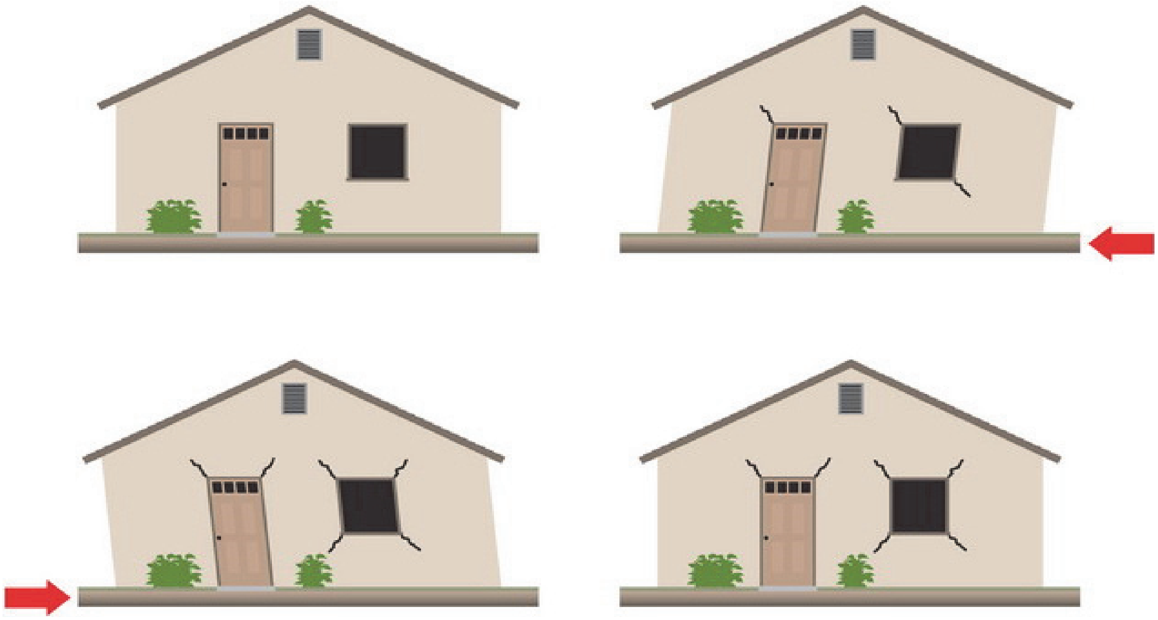


Figure 1-5 Illustration of racking distortion in walls caused by earthquake ground motions, shown as red arrows. The amount of racking shown in this figure is greatly exaggerated for clarity (image credit: Exponent).

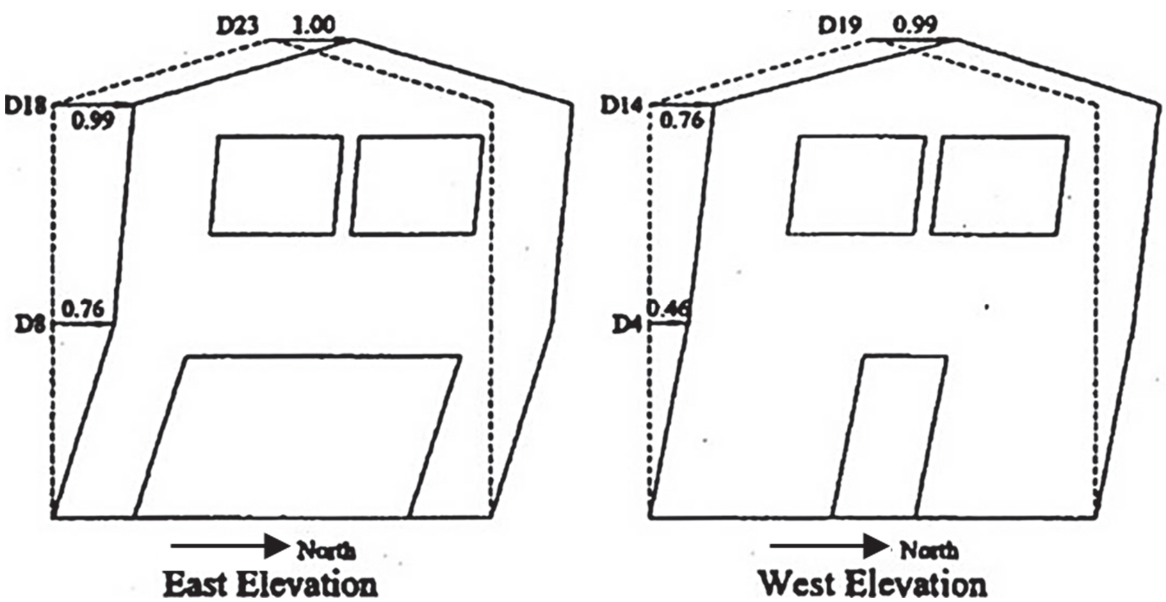


Figure 1-6 Out-of-plumb deformation patterns in a full-scale shake-table test of a two-story wood-frame building. Horizontal deflections indicated are in inches (image credit: Consortium of Universities for Research in Earthquake Engineering, or CUREE).

> **Do Building Codes Prevent All Damage in Earthquakes?**
>
> Modern building codes presume that in an infrequent but very severe earthquake, a properly designed and constructed building will perform safely but will likely sustain some degree of damage. The damage could be so severe that the building is no longer occupiable. Designing a building to prevent all damage during very severe shaking is generally considered too expensive for all but the most critical public facilities, like hospitals.

The forces generated by an earthquake in a building are roughly proportional to the mass (or weight), height, and stiffness of the building. Thus, heavier, and stiffer buildings, such as multi-story masonry buildings, are subject to greater forces during an earthquake than low, lightweight, and flexible buildings, such as single-story wood-frame houses. Consider two tract homes, adjacent and identical except that one has a lightweight wood-shingle roof and the other has a heavy clay-tile roof. The weight of the clay tiles is five-to-ten times that of the wood shingles, thus the home with the clay tile roof will experience higher inertial forces from the earthquake and, most likely, suffer more damage, all other factors being equal.

Earthquake forces are sometimes compared to wind forces. They are similar in that both act to bend or move the building sideways. But there the analogy ends. One primary difference is that the wind is a pressure that acts on surface area, like a billboard or the side of a barn, while earthquakes act on the mass (or weight) of an object. Thus, a strong wind will tear a flag to shreds and leave a brick chimney unscathed, while a strong earthquake will do just the opposite. The same analogy holds for the wood shingles and clay roof tile—high winds will tear off the shingles and leave the clay tile unscathed, while a strong earthquake may dislodge the clay tile but leave the wood shingles unscathed. Further, strong wind tends to come from a predominant direction while earthquake ground motion changes direction rapidly, resulting in cyclic stresses in buildings that constantly reverse in direction. Lastly, a properly designed building is expected to resist strong winds (but not tornadoes or hurricanes) without damage, while a properly designed building *is expected* to sustain some damage in a major earthquake.

But forces are only the first half of the earthquake damage story—the flexibility and strength of the building is the other. Inertial forces cause stress in, and deformations of, the building. As long as the deformations and stresses generated do not exceed the capacity of the building materials and components, the building will shake to the consternation of its occupants and detriment of its contents, like bookshelves, but will not sustain any damage. However, if the deformations and stresses are greater than the capacity of the building materials and components, earthquake damage in the form of cracking, permanent deformation (such as out-of-plumb walls), and even collapse can occur. Materials such as unreinforced masonry and plaster are brittle and very weak in tension and will crack at much lower deformations and stresses than wood or steel.

The locations in the building where the stresses and deformations first exceed the capacity of the structure are referred to as the weak links in the lateral load path through the structure. A sufficiently strong earthquake will find the weak links in a structure, just as water will invariably find any holes in its container. Knowledge of the typical location of weak links in various types of buildings in past earthquakes provides the road map for inspection of buildings following future earthquakes.

Figure 1-7 illustrates the main components of a typical wood-frame house. To be effective, each part of the seismic-force-resisting system of a building must be adequate and properly connected to the other parts in the system. For example, the connections from the roof diaphragm to the shear walls below must be strong enough to transfer the roof diaphragm force to the shear wall. At the base of the building, shear walls must be adequately connected to the foundation to be able to transfer building forces to the foundation. The foundation in turn must be large enough and strong enough to transfer the forces into the soil.

The path that the force takes, from roof to soil, can be thought of as a chain. It is only as strong as its weakest link. The roof and floor diaphragms and shear walls are two links in the chain, as shown in Figure 1-8. The connections between the roof, walls, floors, and foundation are additional links. These additional links serve as the connective points that complete the chain. The connections are just as important as the diaphragms and shear walls themselves. The seismic forces imparted to a building must successfully pass through all of these elements in order to reach the ground and effectively resist an earthquake's damaging forces. In other words, the force path or chain must be continuous and complete. There can be no missing links in the force path.

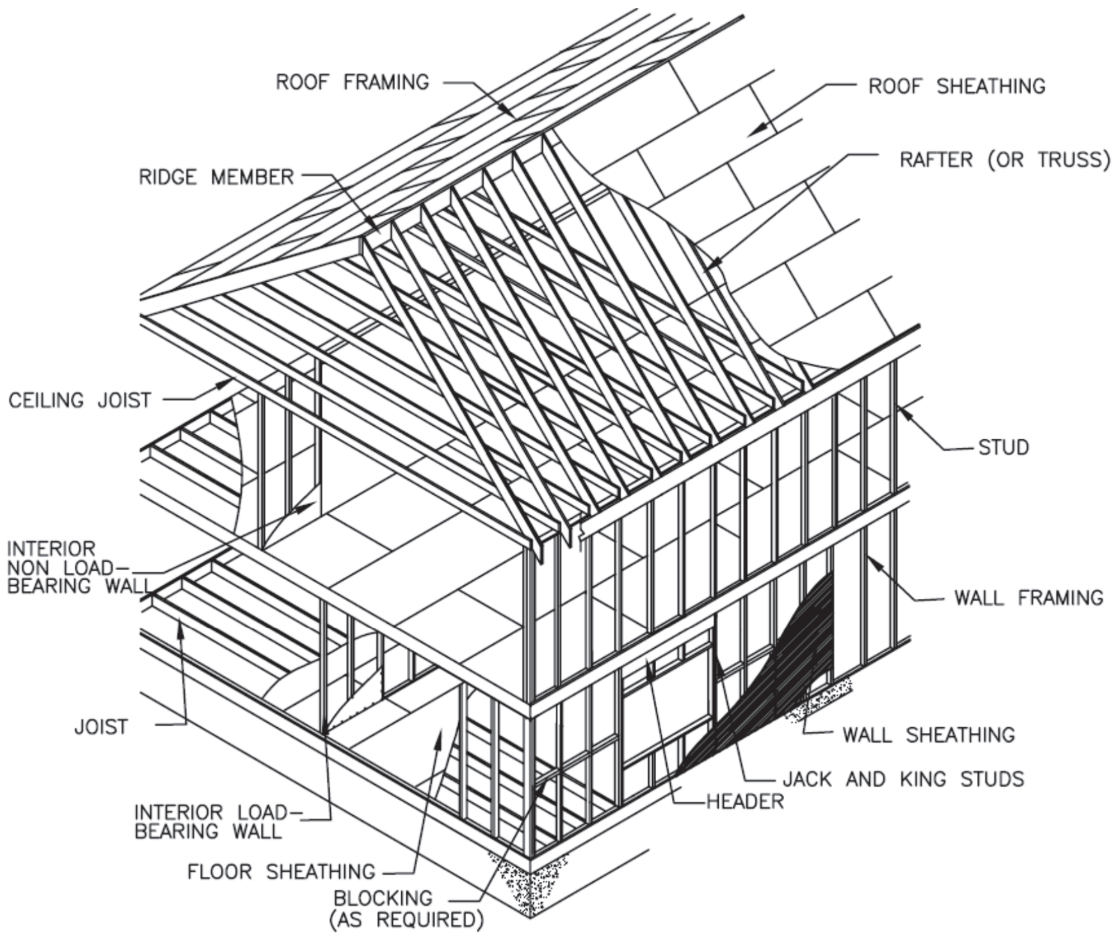


Figure 1-7 Elements of a typical wood-frame house (image credit: U.S. Department of Housing and Urban Development).

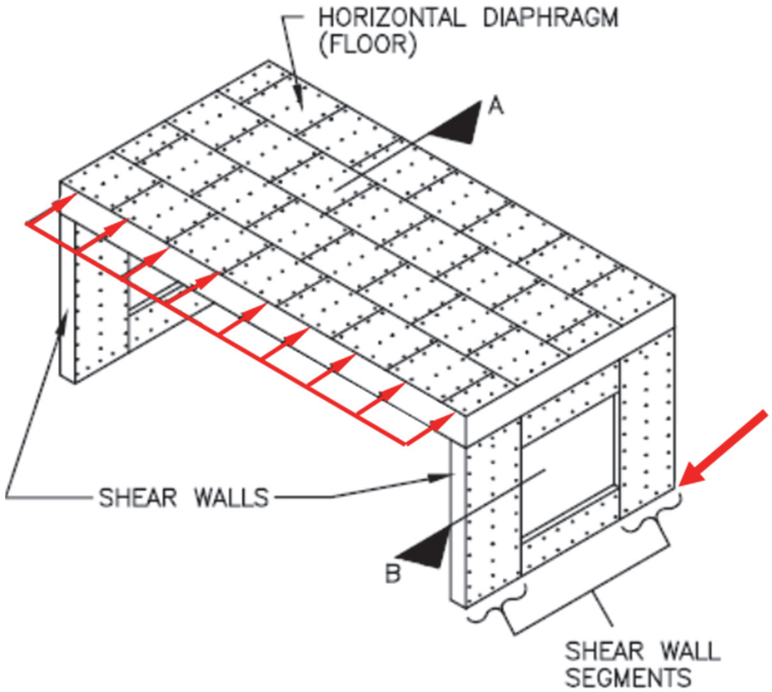


Figure 1-8 Schematic of the role of horizontal diaphragms (e.g., floors or roofs) and shear walls in resisting earthquake forces, where the red arrows indicate the direction of forces (image credt: U.S. Department of Housing and Urban Development).

Structural weak links, or vulnerabilities, can significantly affect a building's response to ground shaking. The following is a list of common vulnerabilities of wood-frame houses and house configurations that, if not detailed properly, may be vulnerable to earthquake damage:

- houses that are not bolted to their foundations,
- houses with unbraced cripple walls between the foundation and first floor,
- split-level houses,
- houses on steep hillsides,
- houses with open floor plans, and
- houses with large openings or large expanses of windows on one or more elevations, such as houses with living spaces over a garage.

In summary, heavy, tall, stiff, and weak components, such as unreinforced masonry chimneys and narrow plaster walls in multi-story houses, are the most vulnerable to damage during earthquakes. Typical modern wood-frame houses are light, flexible, low-rise, and strong, if properly designed and built. Accordingly, serious structural damage in these buildings during earthquakes is uncommon, and collapse is extremely rare. This does not mean that wood-frame houses are indestructible; rather that very intense shaking, ground failure, or the presence of significant structural defects are necessary to cause serious structural damage or collapse.

Ground Failure

Ground failure is permanent deformation of the ground surface triggered by the earthquake and includes the following phenomena, which are discussed in detail in Chapter 3:

- surface fault rupture,
- liquefaction,
- earthquake-induced rockslides and landslides,
- earthquake-induced ground cracking, densification and settlement, and
- ridge-top shattering.

Ground failure can cause rupture of underground utilities, cracking or buckling of at-grade pavements, and severe damage to above-grade improvements. As discussed in Chapter 3, surface fault rupture, liquefaction, and landslides generally occur in areas of known and mapped vulnerabilities. Densification and settlement generally occur in areas of loose and dry native soils or certain types of fills. Ridge-top shattering can occur in certain topographic configurations in close proximity to the fault.

Earthquakes can also cause damage to retaining walls, as discussed in Chapter 3.

Fire Following

Fires ignited by damaged natural gas or electrical utilities can be a severe effect of earthquakes. Fire following earthquake caused extensive damage in San Francisco in 1906, Tokyo and Yokohama in 1923, and Kobe in 1995. Relatively recent earthquakes striking near urban areas in California have caused numerous fire ignitions. For example, about 60 fires are attributed to the 1989 Loma Prieta earthquake, and about 100 fires were caused by the 1994 Northridge earthquake (CSSC, 2001). Favorable weather conditions and the quick response of fire departments prevented fires triggered by both earthquakes from developing into large conflagrations.

Disturbance of Bodies of Water

Earthquakes can disturb various bodies of water, ranging from backyard swimming pools to the ocean, potentially causing considerable damage.

Tsunamis are the most notorious and deadly form of earthquake-induced disturbance of water. Tsunamis are waves caused by rapid large-scale vertical movement of the seafloor during earthquakes. Like earthquake waves on land, tsunami waves travel across the open ocean at great speed (several hundred miles per hour) and have maximum heights of only several feet. Thus, at the surface of the open ocean, a tsunami is of little consequence. As these waves approach shore and the depth of water decreases, the speed of the wave decreases but its height increases. In some areas, a tsunami can create a near vertical wall of water tens of feet in height that rushes far onto shore with catastrophic effects. Unlike normal coastal waves, a tsunami wave can be thousands of feet from front to back, like an extreme tide or rapidly moving flood of water that keeps coming for many seconds or minutes, rather than breaking and dissipating all at once. One of the largest tsunami on record was the Indian Ocean tsunami of December 2004, which was generated by a magnitude 9.1 earthquake off the west coast of Sumatra, Indonesia, and caused the deaths of an estimated 200,000 people.

Seiches are similar to tsunamis except that seiches are earthquake-induced waves in enclosed bodies of water, such as lakes, reservoirs, and swimming pools. Seiches can occur in two ways. First, like a tsunami, a seiche can be created when a fault causes a permanent vertical offset beneath a lake or reservoir. Second, a seiche can occur when the seismic waves traveling in the earth match the natural period of oscillation of the water in an enclosed body of water. With the latter mechanism, seiches can occur at great distances from the source of an earthquake. The 1964 Alaska earthquake caused waves in lakes thousands of miles away in Louisiana and Arkansas. In that earthquake, another cause of a seiche was demonstrated when a huge earthquake-induced landslide suddenly slid into a bay and caused a wave that extended over a thousand feet up the mountain on the other side of the bay.

Strong earthquake shaking can also cause failure of dams, leading to flooding of downstream areas.

CHAPTER 2

Earthquake Ground Motions and Damage Potential

2.1 Introduction

Damage to buildings and contents during an earthquake is a function of the intensity of ground shaking and the ability of the buildings and contents to resist that shaking. The principal objectives of this chapter are to summarize measures of ground shaking intensity that are readily accessible and to summarize the relationship between the intensity of ground shaking, building vulnerabilities, and the potential for damage. In general, greater intensity of shaking increases the likelihood of damage, and buildings with known vulnerabilities are more likely to sustain serious damage than typical buildings. The U.S. Geological Survey (USGS) and other organizations monitor earthquake activity throughout the United States using a variety of methods, including instruments that measure and record the ground shaking. In California, for example, there is an especially extensive network of strong motion instrumentation managed by the USGS and the California Geological Survey. The data obtained from strong motion instruments can be used to characterize the earthquake ground shaking intensity and are typically available online within minutes following an earthquake.

2.2 Measuring Earthquakes

Earthquakes, like hurricanes or tornadoes, are complex natural phenomena subject to great variability in their characteristics and effects on the built environment. Over the years, many parameters have been developed to better quantify the characteristics and effects of earthquakes. Those most relevant to the assessment of damage to wood-frame houses are discussed in the following subsections.

2.2.1 Earthquake Magnitude

The magnitude of an earthquake is essentially a measure of the size of the earthquake in terms of the total amount of energy released at the rupture surface, reported as a single decimal number, such as 6.7 (see Figure 2-1). The size of an earthquake, in general, is related to the surface area of the fault rupture and the amount of displacement over that rupture surface. In terms of the analogy given in Chapter 1 of two books laid back to back on a table and shoved sideways to suddenly lurch, the rupture area is the contact area between the spines of the

Earthquake Magnitude

There are several definitions of magnitude, such as the Richter magnitude, moment magnitude, and body-wave magnitude. The Richter magnitude scale developed by Charles Richter is the most widely known and is based on the record of an earthquake from a standardized seismograph, corrected for distance. Values typically reported by the USGS for modern earthquakes are based on the moment magnitude scale, which is based on the area of the rupture and its displacement, along with the rigidity of the rock. The differences between the various magnitude scales are subtle and not of major significance outside the world of seismology and earthquake engineering.

> **Area Impacted by an Earthquake**
>
> The adverse effects of an earthquake are concentrated over a much smaller area than the area over which the earthquake is felt, and the majority of the energy released by an earthquake is also concentrated over a much shorter time period than the full duration of the shaking.

books and the displacement would be the distance one book slides vis-a-vis the other. Ruptures with small displacements over small areas result in imperceptible ground shaking lasting mere seconds, while ruptures with larger displacements over hundreds of square miles of a fault can cause ground shaking that is felt over thousands of square miles and lasting upwards of a minute, So, one logical measure of earthquakes is the size of and displacement across the rupture surface—the fundamental basis of the magnitude scale commonly used nowadays.

On the magnitude scale, a unit increase in magnitude (e.g., from 6.0 to 7.0) corresponds to approximately a 32-fold increase in energy release. A two-unit increase (e.g., from 6.0 to 8.0) corresponds to a 1,000-fold increase in energy release! Greater energy release generally means longer duration shaking over a larger area. The largest earthquake ever recorded was a magnitude 9.5 earthquake in Chile on May 18, 1960, and the largest earthquake ever recorded in the United States was the Alaska earthquake on March 27, 1964, with magnitude 9.2. In comparison, the Loma Prieta earthquake (also known as the World Series earthquake) in Northern California on October 17, 1989, had a magnitude of 6.9, and the Northridge earthquake in Southern California on January 17, 1994, had a magnitude of 6.7. The smallest of these earthquakes in magnitude, the Northridge earthquake, caused the greatest economic damage due to its location in a heavily urbanized region.

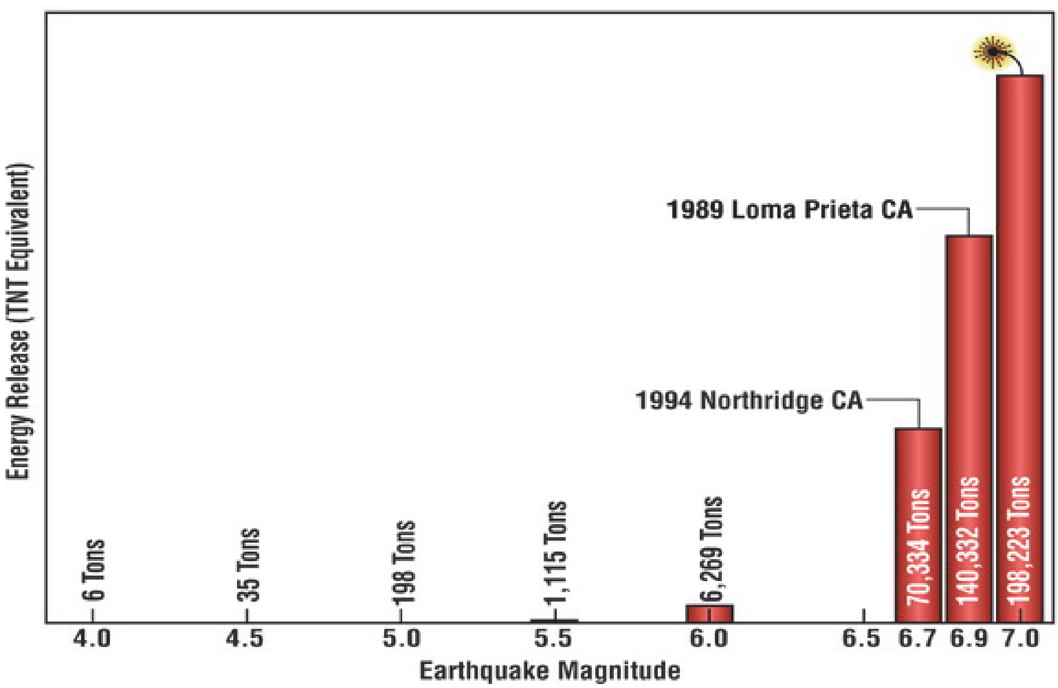


Figure 2-1 Illustration of total energy release as a function of earthquake magnitude (image credit: Exponent).

In general, the larger the magnitude, the more severe the impacts. However, the magnitude of an earthquake is not particularly helpful for damage assessment purposes. Ground shaking is a complex phenomenon, based on many factors that include the size and type of rupture, the distance of the site from the rupture, direction of rupture propagation relative to the direction to the site, the regional geology and topography, and the local soil conditions. At a particular site, the ground motion may be strong or weak, long or short, and jerky or rolling.

2.2.2 Intensity of Ground Shaking

While the magnitude of an earthquake provides a general sense of its relative size and potential for damage, magnitude alone does not provide sufficient information to assess the character of ground shaking at a particular site. Thus, it is necessary to look to other, more descriptive measures of earthquake ground shaking to capture the geographic variations in ground shaking associated with an earthquake. Intensity is the term generally used to qualitatively characterize the local level of ground shaking (i.e., the damage potential of the ground shaking at a particular location). Earthquake intensity varies from place to place depending on various site-specific and earthquake characteristics. For example, the most intense shaking experienced during earthquakes generally occurs near the epicenter and decreases with distance away from the fault, a phenomenon known as attenuation. However, all sites located equidistant from the epicenter of an earthquake do not typically experience the same intensity of ground shaking because of individual site characteristics or propagation characteristics of the seismic waves.

By way of analogy, consider a collection of model boats floating on a small pond into which a rock is tossed. The boats are equivalent to our buildings. The magnitude is equivalent to the size of the rock—the larger the rock, the bigger the splash, the larger the energy released at the source, and the higher the waves. Boats close to the point of impact of the rock are likely to be swamped, if the rock is of sufficient size. Boats farther from the point of impact are less likely to be swamped although they may experience a wild ride. With increasing distance, the effect of the waves decreases to little ripples. To understand the effect of our rock on a particular boat, we need to know the size of the waves at the location of the boat and how seaworthy our boat is. Likewise, for earthquakes, to understand the effect at a particular site, we need to know the intensity of ground motion as well as the seismic vulnerability of our building.

Magnitude and distance from the fault rupture are the most important determinants of intensity—larger magnitudes correspond to ground shaking of greater strength and longer duration for a given site at a given distance from the fault rupture. The strength of ground shaking generally decreases rapidly with distance from the rupture plane. In California, for example, the strong shaking near a fault can become half as strong at a distance of only about 8 miles from the fault. The rate of this decrease is strongly influenced by regional geology, being much more rapid along the West Coast than east of the Rocky Mountains. In other words, for the same magnitude event, an earthquake in the eastern United States will affect a much larger area than an earthquake in California. For example, the San Francisco earthquake of 1906 (Magnitude 7.8) was felt 350 miles away in the middle of Nevada, whereas the New Madrid earthquake of December 1811 (Magnitude 8.0) in the Mississippi Valley is reported to have rung church bells in Boston, Massachusetts, 1,000 miles away.

In addition to the magnitude of the earthquake and distance of a site from the rupture plane, the intensity of shaking in a given region also depends heavily on the local topographic and soil conditions, termed site effects. Deep, soft soils can amplify bedrock motions, causing stronger shaking at the surface than an area equidistant from the epicenter but underlain by firm ground or bedrock. Thus, an area underlain by deep, soft soil deposits can often experience more severe damage than the surrounding areas. Examples of this type of amplification occurred during the 1989 Loma Prieta earthquake. While the epicenter was 60 miles away and most of the San Francisco Bay Area escaped serious damage, ground motions in portions of Oakland and in the Marina district of San Francisco underlain by soft soils were more than ten times stronger than at neighboring sites on rock.

To characterize the overall effect of all of the foregoing influences on the local damage potential of an earthquake, various intensity scales have been developed which, as discussed below, provide a combined measure of ground motion and building vulnerability. While each earthquake has a single magnitude, the intensity of ground shaking for that earthquake varies throughout the area affected. Thus, ground shaking intensity data are typically presented as maps illustrating the variation of intensity throughout the affected area.

2.2.3 Modified Mercalli Intensity Scale

The Modified Mercalli Intensity (MMI) scale has been the most widely used intensity scale in the United States since the 1930s. The scale is based on the observed local effects of ground motions on people, building contents, buildings, and the environment. The scale ranges from I to XII, as shown in a condensed version presented in Table 2-1, with I being imperceptible and XII being total destruction of the built environment. (Note that the total destruction of a city of buildings constructed in accord with modern earthquake-resistant design standards has never occurred; this description was originally developed in the context of nineteenth century cities of buildings constructed of unreinforced stone and brick masonry.)

Each level of intensity is characterized by certain effects (i.e., many small objects overturned and fallen) that are commonly observed at that intensity level. The same effect may occur less frequently or less strongly at lower intensity levels and occur more frequently and more strongly at higher intensity levels. For example, at MMI VI, overturned furniture occurs in many instances; at MMI V and below, occurrences of overturned furniture are rare, whereas, at MMI VII and above, occurrence of overturned and possibly damaged furniture is common. Humans are much more sensitive to ground shaking than contents or buildings; humans typically begin to feel the shaking at MMI III. In areas where the intensity of shaking is below MMI V, damage to buildings or contents is extremely unlikely. At MMI V, some damage to contents but no damage to buildings would be expected. Minor damage to some buildings occurs at intensity VI. Progressively more building and contents damage occurs at MMI VII through IX. MMI X through XII are generally associated with ground failure and very severe damage to buildings and contents. By observing the local effects of the earthquake in any affected area, the MMI of that area can be determined by finding the description in Table 2-1 that most accurately describes the overall local effect of the earthquake.

Table 2-1 Abridged Modified Mercalli Intensity Scale

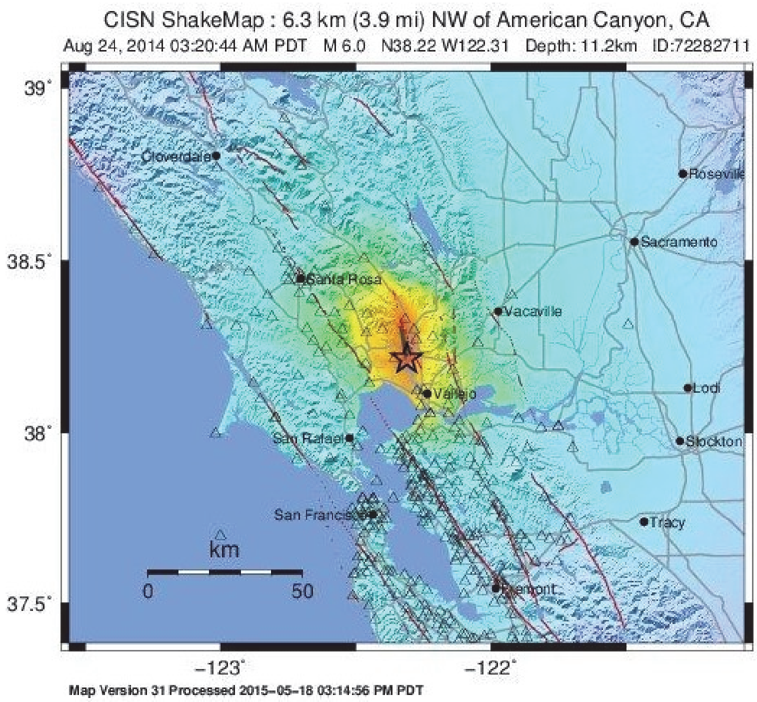
MMI	*Abridged Description*
I	Not felt except by a very few under especially favorable circumstances.
II	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
III	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing automobiles may rock slightly. Vibration like passing of truck. Duration estimated.
IV	During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing automobiles rocked noticeably.
V	Felt by nearly everyone, many awakened. Some dishes and windows broken; cracked plaster in a few places; unstable objects overturned. Disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.
VI	Felt by all, many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster and damaged chimneys. Damage slight.
VII	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving cars.
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving cars disturbed.
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; damage great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from riverbanks and steep slopes. Shifted sand and mud. Water splashed, slopped over banks.
XI	Few, if any, structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.
XII	Damage total. Waves seen on ground surface. Lines of sight and level distorted. Objects thrown into the air.

Note: https://earthquake.usgs.gov/learn/topics/mercalli.php

2.2.4 Instrumental Intensity

Ground shaking of earthquakes in urban areas of California and some other states is recorded by seismic instruments at hundreds of locations throughout the area affected by the earthquake. Much of that data is transmitted in real time and available for processing within minutes after a major earthquake. One of the products of this data processing is a USGS-produced ShakeMap, which presents the variation in intensity of ground shaking based on interpolated data from available instruments and a model of the topography and geology of the area. The intensities derived in this process are termed Instrumental Intensities and are correlated with MMI. Figure 2-2 presents the ShakeMap of the 2014 South Napa, California earthquake.

People over a large area felt the earthquake and were even awakened, but buildings and infrastructure over a small area suffered damage. This is represented by the large region colored blue contrasted with the relatively small region colored yellow or red.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.1	0.5	2.4	6.7	13	24	44	83	>156
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	11	22	43	83	>160
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Wald, et al.; 1999

Figure 2-2 ShakeMap showing the instrumental intensities for the 2014 South Napa, California earthquake (image credit: USGS).

In addition to the speed at which a ShakeMap is generated following a significant earthquake, it has the advantage of being objectively based on the readings of strong motion instruments rather than the personal accounts of individuals. ShakeMaps can be found on the USGS website, which also includes an archive of previous earthquake ShakeMaps.

For an inspector involved in a post-earthquake damage assessment, review of the ShakeMap prior to the inspection provides a good sense of likely damage to buildings in the vicinity of the site, as well as a good sense of the shaking intensity experienced by the owner or occupant. When the damage observed at a specific building is not consistent with the expected damage given the intensity of shaking shown on a ShakeMap for the area, the inspector should look for other contributing factors, such as a building configuration that is particularly vulnerable to earthquake damage or the presence of earthquake-induced ground failure. It is important to remember that a ShakeMap is not a definitive predictor of damage at a particular building, but rather an indicator of likely damage.

2.2.5 Community Internet Intensity

The Community Internet Intensity (CII) map was developed to rapidly estimate the MMI of an earthquake using the Internet. In this process, responses to an online questionnaire based on the MMI scale are compiled from citizens in earthquake-affected (or "felt") regions. The responses are summarized in the form of a map, which shows the assigned MMI level for each ZIP code. An example of the CII map for the 2014 South Napa earthquake is presented in Figure 2-3. The CII map may provide insight into the intensity of shaking in areas without seismic instruments, as well as the intensity of shaking in areas beyond the geographic limits of the ShakeMap. By hovering a mouse over the Zip code block shown on the map, one can get a sense of the intensity of shaking felt at a house.

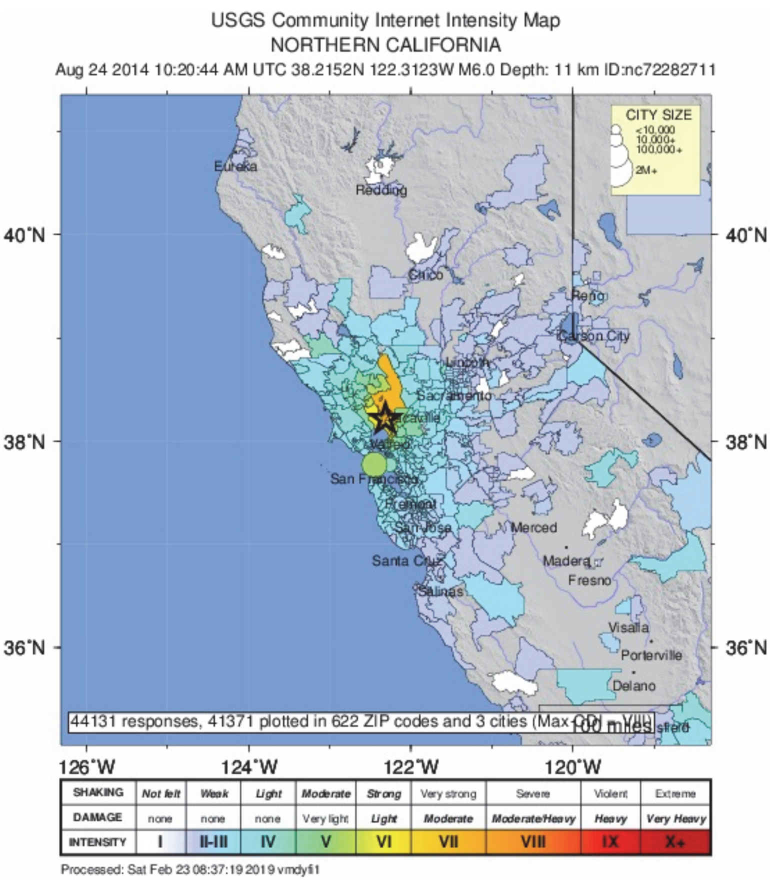


Figure 2-3 Community Internet Intensity Map for the 2014 South Napa, California earthquake (image credit: USGS).

2.2.6 Instrumental Records

To collect detailed numerical data, various agencies install sensitive automated recording instruments (accelerographs) in known seismic areas to collect detailed records of earthquake ground motion when it occurs. Accelerograms are the records of the ground acceleration (typically recorded on three axes—north/south, east/west, and up/down) at the location of the instrument during the earthquake. In addition to their use in the production of ShakeMaps, accelerographs are used by specialized consultants to perform analysis of ground response (for ground failure) and building response to earthquake ground shaking.

2.2.7 Ground Surface Strains

The passage of seismic waves during earthquakes cause rapid ground movements but small ground deformations. Despite occasional accounts to the contrary, seismic waves at the ground surface are usually too subtle to be discernable to the naked eye—the length of the waves is generally on the order of thousands of feet while the amplitude (height) of the waves is typically on the order of a few inches. This is unlike our analogy with the model boats on the pond, where the waves noticeably distort the water's surface. As a practical matter, the ground does not bend, twist, or stretch over the length of typical wood-frame houses. The land under the building can be visualized as a relatively rigid plate shaking back and forth and somewhat up and down in various directions during the earthquake. In all but the most severe shaking, distortions are very brief undulations of the ground surface and are too small to cause damage to structures on the scale of wood-frame houses.

2.3 Vulnerabilities and Damage Potential in Houses

In typical houses, earthquake forces are collected in floor and roof diaphragms and transferred to the foundations by sheathed walls. Figure 1-7 illustrates the framing and sheathing elements in a typical house. Traditional house construction has characteristics that make many houses prone to certain earthquake damage mechanisms, such as the sliding of walls relative to their foundations. The following subsections address many of the most commonly encountered of these mechanisms, organized by configuration vulnerabilities in houses that enable the mechanisms to occur. An understanding of these mechanisms in relation to a house's overall configuration can aid the effort to find damage, evaluate it, and recommend appropriate repairs.

2.3.1 Inadequate Anchorage of Superstructure at Foundation

The sill plates of older houses were not always (or adequately) attached to the concrete or masonry foundation. Even in more modern houses, sill plates of interior walls may have minimal attachment to a foundation or floor slab. During earthquakes, these sill plates can slide relative to the foundation or floor slab, resulting in residual displacement, splitting of the sill plate, damage to the wall finishes or framing, and misalignment of doors and windows along the wall. Adding steel post-installed anchor bolts along unanchored sill plates is a common retrofit measure to mitigate this earthquake vulnerability.

Figure 2-4 shows substantial sliding, readily observed, with fracture of the sill plate and conspicuous damage to the wall finishes along the sill plate. Figure 2-5 shows less obvious sliding, initially noticed only because of inoperable doors within the affected wall line.

Figure 2-4 Earthquake-caused sliding of superstructure at foundation. The wall has shifted to the right several inches relative to the foundation, stucco wall finishes have cracked and spalled along the sill plate, and the sill plate is fractured near the right end of the wall (photo credit: Exponent).

Figure 2-5 Earthquake-caused sliding of superstructure at floor slab. The wall has shifted less than 1 inch to the left, as evidenced in the left photo by the tapered gap between the left side of the door and doorjamb and in the right photo by the gap between the carpet and doorjamb (photo credit: Exponent).

2.3.2 Unbraced Cripple Wall

A cripple wall is a wood-frame wall between the foundation and the underside of the first-floor framing, enclosing a crawlspace. Where the cripple wall is inadequately braced, permanent drift over the height of the cripple-wall is a common (and costly) earthquake damage mechanism. Where the drift is moderate, it is typically associated with damage to the wall finishes that provide nominal strength and stiffness to an otherwise unbraced cripple wall (Figure 2-6), damage to the cripple wall framing, and damage to connections between the cripple wall and the wall or floor framing above. If the in-plane cripple wall drift in one direction becomes large, the cripple walls in the other direction will lean out-of-plane and be prone to collapse (Figure 2-7). In addition to structural damage, large cripple wall drift or collapse may damage mechanical, electrical and plumbing components commonly located in the crawlspace. Adding plywood or oriented strand board (OSB) along the interior faces of cripple walls is a common retrofit measure to improve the earthquake performance of the house with respect to this earthquake vulnerability.

Figure 2-6 Damage to cripple wall finishes caused by the 2014 South Napa, California earthquake (photo credit: Exponent).

Figure 2-7 Cripple wall collapse caused by the 1994 Northridge, California earthquake resulting in widespread related damage in upper-story framing and relative movement between the main house and the covered porch (photo credit: Federal Emergency Management Agency, or FEMA).

2.3.3 Hillside House

Hillside houses typically incorporate stepped or sloped perimeter foundations (or stemwalls) along their sides (Figure 2-8). Posts or wood-frame walls enclosing the underfloor area along these lines may range in height from twenty or more feet at the downhill end to effectively zero at the uphill end, where the floor framing is attached to the uphill foundation with a sill plate or ledger. The tall posts or walls, if inadequately braced, may allow excessive deformation at the downhill end, causing torsional response (overall twisting) and increasing demands on the uphill framing-to-foundation connections. This damage mechanism typically includes framing deformation and damage (Figure 2-8), and in the worst cases, localized loss of support for floor framing at the uphill end (Figure 2-9) or complete separation of the house from the uphill foundation resulting in collapse. Hillside houses with no sidewalls, or only short sidewalls at the uphill end, are particularly prone to this damage mechanism. In addition to structural damage, mechanical, electrical, and plumbing components commonly located below the house can also be damaged.

Figure 2-8 Damaged framing enclosing the underfloor area of a hillside house caused by the 2003 San Simeon, California earthquake. The damage includes detachment of the stucco relative to the wall framing and both in-plane and out-of-plane lean of the wood-frame walls (photo credit: Exponent).

Figure 2-9 Damage at uphill end of a hillside house caused by the 2003 San Simeon, California earthquake. The floor framing detached and pulled away from the uphill foundation, causing the floor to sag (photo credit: Exponent).

2.3.4 Narrow Wall Pier

Where window and door openings leave only narrow wall segments to resist earthquake forces, wall lines can be prone to excessive in-plane drift (Figure 2-10) and possibly collapse. Where wider wall segments are not possible, newer houses avoid this vulnerability by using portal frame systems, proprietary engineered wall piers, or even structural steel elements. This mechanism can result in damage to wall pier finishes and sheathing, damage to the wall pier framing, damage to connections at the tops and bottoms of the wall piers, and inoperability of doors and windows within the racked wall line.

Figure 2-10 Large in-plane drift of narrow wall piers at garage door opening caused by the 1971 San Fernando, California earthquake (photo credit: National Information Service for Earthquake Engineering, or NISEE).

2.3.5 Living Space Over Garage

Multi-story houses with attached garages often have living space directly over relatively open garage area. Where only narrow wall segments are provided on either side of a wide garage door, the additional weight of the upper story can make an already weak condition even more prone to excessive drift (Figure 2-11) and possibly collapse.

Figure 2-11 Damage related to living space over garage caused by the 2014 South Napa, California earthquake. In-plane racking of the front wall line of the garage caused cracking and possible framing damage in the narrow wall segments on either side of the garage door (photo credit: Exponent).

2.3.6 Framing Discontinuity

Earthquake damage is often concentrated where structural framing is discontinuous from one story to the next or between wings of a house in plan. Earthquake damage associated with these framing discontinuities includes concentrated damage to finishes, residual separations, and framing damage. In split-level houses, where the floor or roof framing is discontinuous between the one-story and two-story portions, differential movement and lack of effective connection between the portions can lead to damage. Where the common wall between the portions provides support for the lower-story floor or roof, the separation can result in local collapse. Where two wings of a house join, relative movement between the wings can lead to damage along the intersection (Figure 2-12).

Figure 2-12 Left: Adjoining wings of a house create a framing discontinuity. Right: Separation of wood siding at intersection of adjoining wings caused by the 2014 South Napa, California earthquake. The separation was not structurally significant because there was no continuous framing or structural connection between the wings (photo credit: D. Bonowitz).

2.3.7 *Masonry Chimney*

Though they are not considered structural elements, masonry chimneys are among the most vulnerable elements of houses. Unreinforced chimneys are vulnerable to cracking near the roofline (Figure 2-13), sometimes breaking away and falling. If the top portion of a chimney falls onto the roof, it can cause damage to the roofing and roof framing. Reinforced chimneys can separate from the wall of the house (Figure 2-14) and exhibit residual outward leaning following an earthquake. Many chimneys were built with steel straps embedded in the masonry and attached to floor or roof framing. Where inadequately connected, the straps can pull out, damaging the framing members or roof sheathing.

Figure 2-13 Earthquake-induced fractured chimney near the roof line. The brace between the chimney and roof, visible behind the chimney, was not adequate to prevent the damage (photo credit: Exponent).

Figure 2-14 Separation of chimney from house caused by the 2014 La Habra, California earthquake. The separation was relatively minor, and the chimney remained attached to the house (photo credit: Exponent).

2.3.8 Appurtenances

Earthquake damage tends to concentrate where parts of a house with different construction abut or attach to each other. This often occurs at appurtenances, such as exterior decks, porch roofs, carports, or patio covers, where the damage is likely to include cracked finishes, damage to ledgers or fasteners, and residual separations. An appurtenance with no seismic-force-resisting system of its own can be vulnerable to collapse if its attachment to the main structure is damaged (Figure 2-15). Damage to an appurtenance, such as a deck at an entry door, can block ingress and egress to a house.

Figure 2-15 Earthquake-caused detachment of the carport from the house wall, resulting in collapse (photo credit: California Office of Emergency Services).

CHAPTER 3

Geotechnical Aspects

3.1 Quick Guide

This section provides a summary of where to look, what to look for, and when a technical consultant might be needed regarding geotechnical aspects of a damage assessment. A more detailed discussion begins at Section 3.2.

3.1.1 Where to Look

1. Exposed ground surface, including sloped as well as terraced portions and hardscape (e.g., driveways, walkways, patios, pool decks) of the subject property.
2. Above-grade improvements, including exposed building floor slabs, foundations, building walls, retaining walls, masonry walls, and fences.
3. Exposed ground surface and hardscape (e.g., sidewalks, curb, gutter, and street pavement) of surrounding public property and adjacent properties (if possible), including upslope and downslope areas if applicable.

3.1.2 What to Look For

If any of the following conditions exists, a technical consultant may be needed.

1. Earthquake-induced permanent ground deformation in the exposed ground surface, including:
   a. fresh-appearing deposits of sand, commonly referred to as “sand boils” or “sand volcanoes,”
   b. straight or jagged cracks, either parallel to a slope or behind the top of slopes or retaining walls,
   c. noticeable slumping, rising, or bulging of the ground surface,
   d. evidence of landslides or rock falls, or
   e. ground movement or wet areas indicating broken underground utility lines (e.g., water, gas, sewer).
2. Fresh cracking in or movement of:
   a. at-grade hardscape (i.e., paved areas) such as driveways, street pavement, public and private walkways, public curbs and gutters, patios and pool decks,
   b. retaining walls,
   c. exposed surfaces of concrete floor slabs, footings, or foundation stemwalls, or
   d. above-grade finishes, such as stucco, drywall, masonry block walls, in a pattern consistent with ground failure or occurring in an unusual pattern (i.e., damage concentrated in portions of the building).

3. Patterns of cracking that extend across the ground surface and into adjacent hardscape and other improvements.
4. Indication of septic tanks surfacing, landslide, liquefaction, fault rupture, differential settlement, or other permanent ground deformation.
5. Any fresh-appearing cracks in the ground surface, hardscape, or swimming pool shell or separations of construction joints wider than 1/4 inch.
6. Any fresh-appearing out-of-levelness in exterior improvements, such as driveways, street pavement, public and private walkways, public curb and gutter, patios and pool decks.
7. Any fresh-appearing cracks in concrete foundation elements wider than 1/2 inch or offset by more than 1/16-inch out of plane (the thickness of a nickel).
8. Recent collapse, rotation, or sliding of retaining walls.
9. Indications of damage to underground utility lines in the vicinity of the property, such as seepage onto the ground surface indicative of broken water lines, or odors that may be indicative of broken sanitary sewer or gas lines.

3.1.3 Repair Guidelines

When there is evidence that earthquake-induced permanent ground deformation has occurred, a technical consultant should generally be retained. In some instances, it may be desirable to retain a structural specialist first, who can then determine the need for a soils specialist. If significant earthquake-induced permanent ground deformation has occurred, the soils specialist will recommend the nature and extent of remedial work, if any, required to stabilize the ground or improvements at the property. See Section 3.8 for a discussion of repair methodologies.

3.2 Overview

Many buildings in California experience some amount of earth movement during their service life, which is caused by a variety of common geotechnical processes, including settlement, expansive soil movement, slope creep, landslides, and retaining wall movement. In addition to their strong shaking, earthquakes can also cause permanent ground deformation that may result in damage to buildings and surrounding improvements. The main mechanisms by which earthquakes induce permanent ground deformation include surface fault rupture, liquefaction, landslides, ridge-top shattering, seismic compression (soil densification), and retaining wall failure. Earthquake-induced permanent ground deformation generally occurs in limited areas with specific vulnerabilities, such as loose saturated soil adjacent to bays and rivers, steep terrain, or along the fault.

Damage caused by non-earthquake earth movements may appear similar to earthquake-induced permanent ground deformations (i.e., horizontal or vertical permanent ground deformation). While inspecting a property after an earthquake, it is important to distinguish between long-term earth movements that occurred prior to the earthquake and those that occurred due to the earthquake. Many long-term soil conditions are relatively benign and do not require remedial work, while certain earthquake effects can cause damage to buried utilities or create slope instabilities. For example, ground settlements and heave caused by expansive soil need to be differentiated from ground settlements associated with liquefaction or seismic compression. Similarly, investigations of sloping sites must distinguish between long-term slope creep or retaining wall deformations, and instabilities from earthquake-induced slope or retaining wall movements.

When looking for indications of earthquake-induced permanent ground deformation, the best course of action is to inspect the deformation-sensitive elements throughout the property. These include hardscape—such as driveways and sidewalks, utility lines, swimming pools, and foundations—and building finishes, such as stucco. In addition to a thorough inspection of the subject property, it is also important to examine the neighboring areas for similar indications of earthquake-induced permanent ground deformation in the curbs, street pavements, and other similar features.

If indicators of earthquake-induced permanent ground deformation have been identified on the property, or if there is concern about the stability of the site, a technical consultant should be contacted to assess the damage and develop an appropriate repair plan, if necessary. This assessment may involve subsurface investigation and laboratory testing to complete the necessary analysis. Appropriate repairs may address damage to soil, rock, or improvements at the site necessary to restore pre-earthquake stability.

3.3 Limitations

This section of the *General Guidelines* addresses only geotechnical conditions and earth retaining walls commonly associated with conventional residential wood-frame development. Assessment of unusual geotechnical or geological conditions or other types of engineered retaining structures and foundation systems should be conducted by a suitably qualified soils specialist.

3.4 Description of Geotechnical Aspects

All buildings and other improvements rely upon the strength and stability of the underlying soil and rock for satisfactory performance. Building foundations distribute the weight of the building to the underlying ground (i.e., fill, soil, or rock). Foundations will prevent damaging levels of differential movement or settlement, if properly designed and constructed for building loads and actual site ground conditions. Movement or deformation of these underlying materials beyond the amounts assumed in design may damage the supported buildings and improvements. Some houses are constructed on sites, such as those on hillsides or on expansive soils, where the ground is subject to long-term movements, which can result in varying degrees of distress to improvements constructed on the site.

A common condition in hilly or mountainous areas is the terraced building pad constructed with “cut-fill” grading, where earth excavated from the higher part of the lot (the “cut”) is placed as fill on the lower part of the lot, as illustrated in Figure 3-1. The location on the ground surface where the undisturbed native soil transitions to the fill material is referred to as the “cut-fill line” or “cut-fill boundary.” Such sites may experience problems with long-term differential settlement as well as increased levels of damage during earthquakes because the fill soil at the site may be less dense than the native soil or rock in the cut areas.

During their lives, all buildings experience some amount of earth movement, which is caused by a variety of long-term geotechnical processes. Long-term earth movements are discussed in Section 3.5 and include settlement, shrink or swell of expansive soil, slope creep, and landslides.

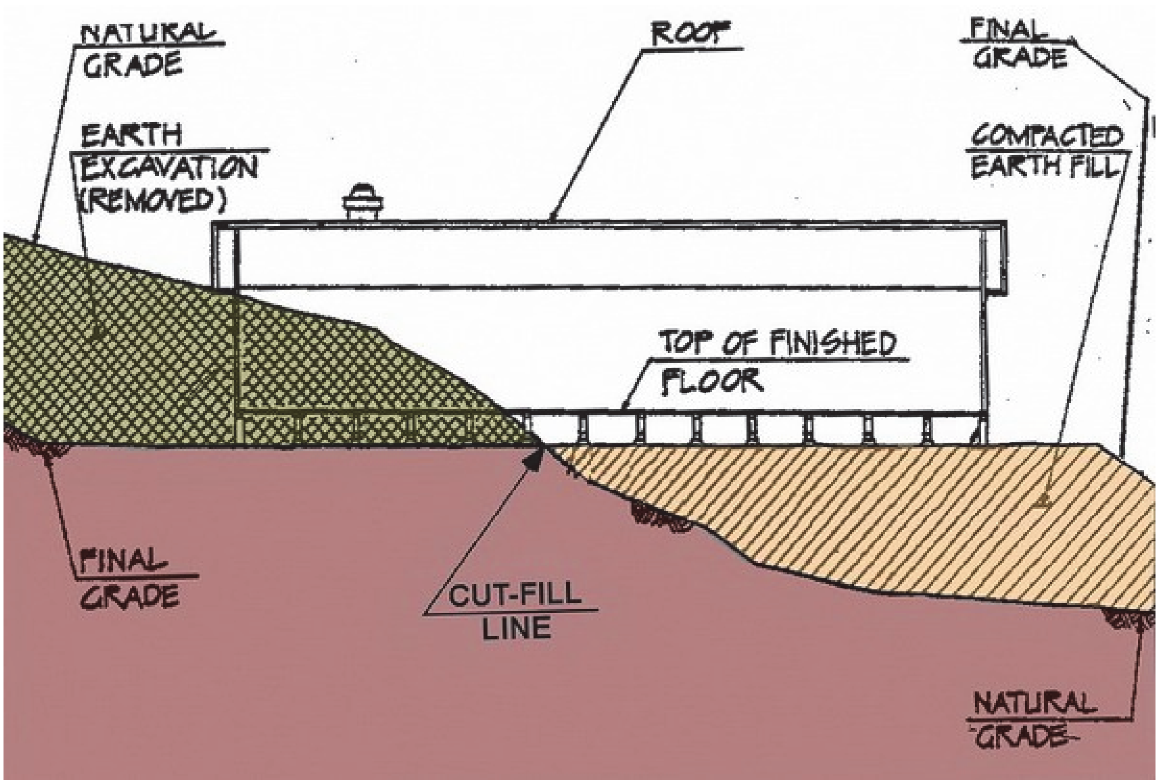


Figure 3-1 Schematic cross-section of a cut-fill building pad (image credit: Exponent).

Soil and rock are also widely used as construction materials—structural fill material placed under controlled conditions to terrace hillsides, build roads, and create level building pads upon which to build houses. While most fills are quite stable, some have experienced varying degrees of poor performance over time, ranging from minor differential settlements to large-scale landslides. In general, the quality of structural fills has improved in recent decades, although many residential areas are constructed on fills of varying degrees of quality. Some areas, such as portions of San Francisco, have been constructed on landfill placed many years ago, prior to the advent of modern engineering knowledge and quality control.

To accommodate abrupt changes in grade, retaining walls are constructed. Retaining walls are subject to sustained, long-term horizontal (or lateral) pressure from the soil behind the wall and short-term horizontal forces from earthquake ground shaking. The walls must be designed to resist the lateral pressures without excessive deformation or failure. In addition, retaining walls must have an adequate foundation to transfer their loads into the supporting soil beneath the wall without exceeding the strength of the foundation soil. Adequate drainage behind retaining walls helps to reduce hydrostatic pressures and increase stability of the retained soil.

3.5 Long-Term Sources of Earth Movement

Both native soil and engineered fills in many areas of California are unstable to some degree, resulting in a number of long-term geotechnical processes that damage buildings and improvements, as discussed in the following subsections.

3.5.1 Settlement

Settlement is downward vertical movement of the ground surface resulting from densification of soft or loose soil. Settlement may occur in soft natural ground but more commonly occurs in earth fills or as a result of inadequate compaction of the fill during construction. Damage to buildings and improvements occurs when one portion experiences greater settlement than the rest of the building or improvement, a condition referred to as differential settlement. This occurs when fill thickness or material properties, such as density or degree of compaction, vary across the property.

3.5.2 Expansive Soil Movement

Shrinking or swelling of expansive soil occurs when the water content of the soil is reduced (drying) or increased (wetting). Certain clays are particularly sensitive to water content changes. Cycles of shrinking and swelling may occur in soil layers near the ground surface that are subjected to evaporation, transpiration, rainfall, or rising or falling groundwater table (Figure 3-2 and Figure 3-3). The water content variation can be seasonal (e.g., summer to winter) or can follow a long-term trend (e.g., from changes in landscaping and vegetation or installation of pavements that change surface drainage patterns) or can be more transient, such as from irrigation or utility line leaks. A good indication that expansive soils are present at a site is desiccation cracking (a web-like network of cracks as shown in Figure 3-4) in the soil surface during dry seasons of the year.

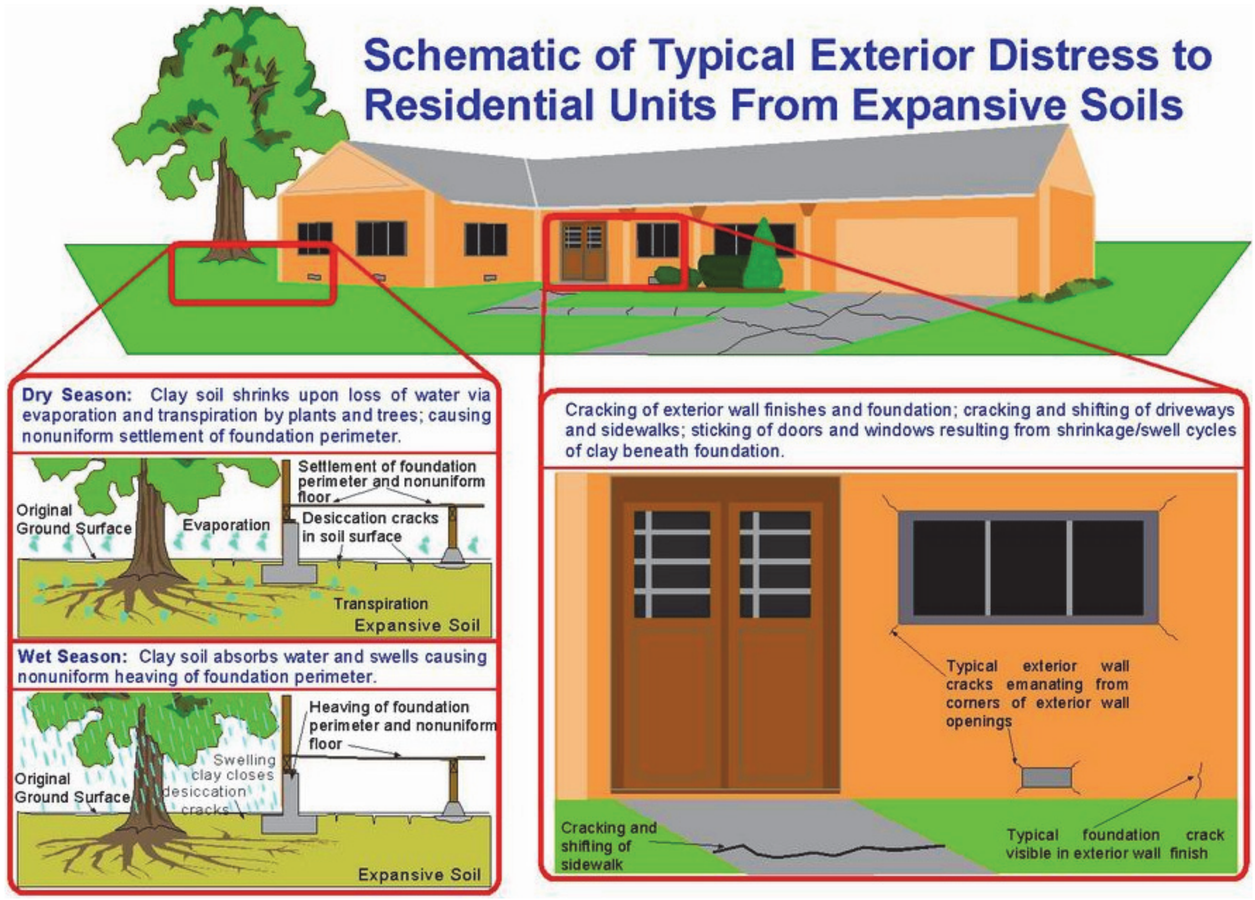


Figure 3-2 Schematic of typical long-term, non-earthquake distress caused by expansive soil to the exterior of a residential building with a perimeter concrete foundation (image credit: Exponent).

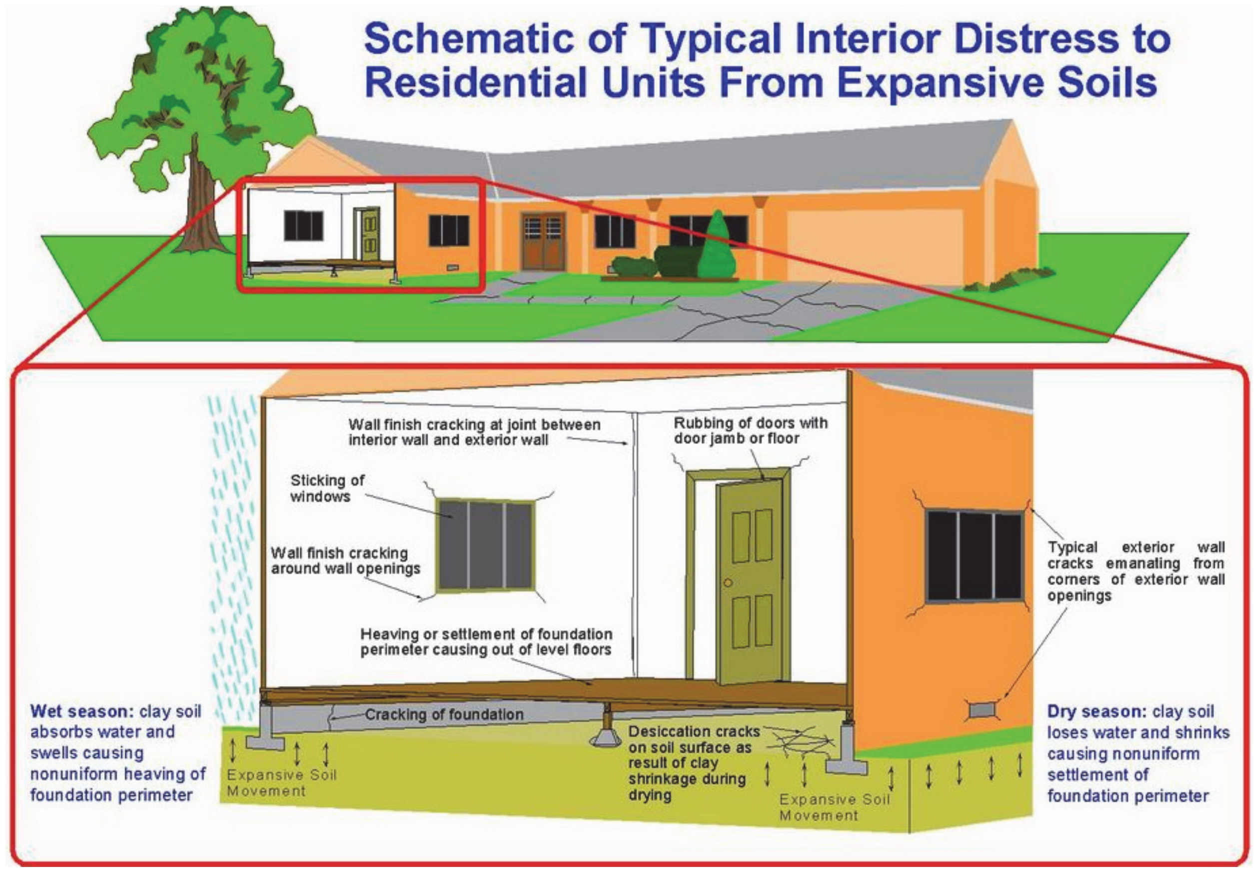


Figure 3-3 Schematic of typical long-term, non-earthquake distress caused by expansive soil to the interior of a residential building with a perimeter concrete foundation (image credit: Exponent).

Figure 3-4 Long-term, non-earthquake desiccation cracking of expansive soil within a crawlspace (photo credit: Exponent).

3.5.3 Slope Deformation (Creep)

Slope deformation may sometimes occur due to soil creep—the slow down-slope movement of fill, soil, or rock, usually confined to areas along a slope face or near the top of slope (Figure 3-5). Some creep takes place in almost all steep earth and rock slopes. The rate of creep is dependent on factors such as material type, slope inclination, and water content fluctuations within the slope. Slope creep occurs within shallow soil or rock materials, and hence damage is generally confined to areas along a slope face or near the top of the slope.

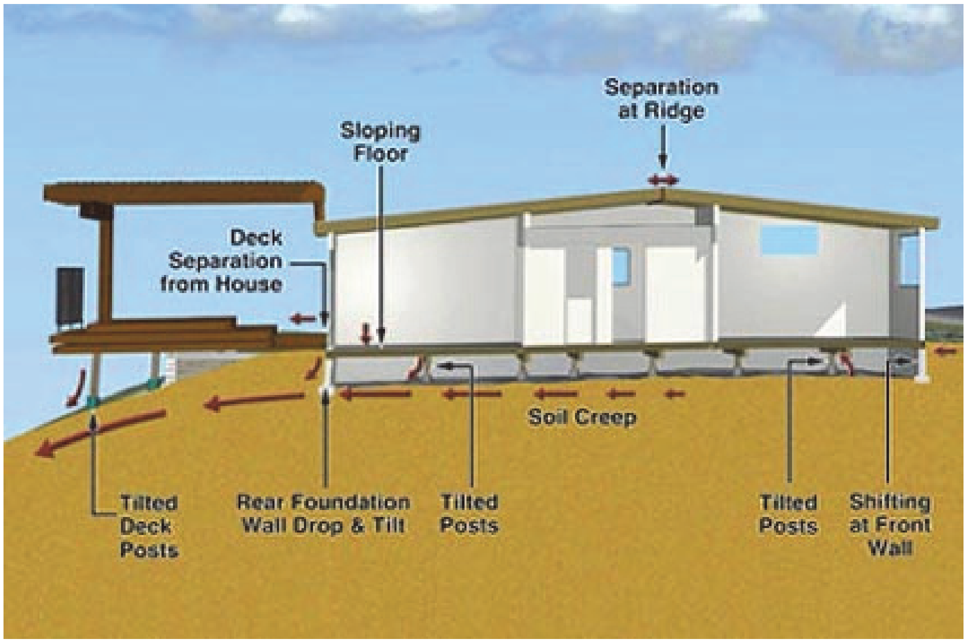


Figure 3-5 Schematic of damage to residence resulting from long-term, non-earthquake soil creep (image credit: Exponent).

3.5.4 Slope Instability (Landslide)

Slope instability (i.e., landslide or rockslide) refers to the relatively rapid movement of a mass of soil or rock down a slope. Landslides can occur in natural slopes, manmade cut slopes, or manmade fill slopes. Landslides can be triggered by changes in slope geometry (i.e., excavation near slope toe), loading of the top of slope, and increased water pressure within the slope. Historically, periods of heavy rain in California have triggered numerous landslides.

3.5.5 Retaining Wall Deformation or Instability

The quality of residential retaining walls ranges from modern, well-engineered walls designed for long-term performance to poor quality walls constructed without benefit of basic engineering. Those retaining walls that are not adequately designed or constructed to resist long-term lateral forces from the retained soil may tilt outward, bend, slide, or crack over time. Many retaining wall failures are due to the buildup of water pressure behind the wall due to inadequate drainage or excessive water infiltration behind the wall. Walls constructed of wood will also deteriorate over time. Significant movement of retaining walls will result in soil deformation and ground cracking behind the walls. Note that some movement should be anticipated for all retaining walls over time. However, significant movement due to earthquake or lateral earth pressures should be evaluated by a soils specialist.

3.6 Earthquake-Induced Permanent Ground Deformation

For the purpose of this document, earthquake-induced permanent ground deformation is defined as any permanent ground deformation caused by earthquake ground shaking or fault rupture that results in damage to improvements. Larger soil failures affect broad areas, damaging buildings, pavements, and buried utilities. However, the area which experiences soil failure due to an earthquake is typically a very small percentage of the entire area affected by the earthquake. While often dramatic, earthquake-induced permanent ground deformation only occurs in limited areas with specific vulnerabilities, such as loose saturated soil adjacent to bays and streams, steep terrain, or along the fault. Following are the various modes of earthquake-induced permanent ground deformation.

3.6.1 Surface Fault Rupture

Earthquakes result from relative displacement (i.e., slip) of blocks of rock on opposite sides of the fault surface deep within the earth's crust. Surface fault rupture occurs when these displacements reach the surface of the ground (Figure 3-6 to Figure 3-10).

Figure 3-6 Surface fault rupture from the 1971 San Fernando, California earthquake and associated damage to pavement and buildings (photo credit: National Information Service for Earthquake Engineering, or NISEE).

Figure 3-7 House damaged by surface fault rupture from the 1971 San Fernando, California earthquake (photo credit: Applied Technology Council, or ATC).

Figure 3-8 Waterline break along fault rupture from the 1972 Managua, Nicaragua earthquake (photo credit: NISEE).

Figure 3-9 Surface faulting midway between El Centro and Holtville from the 1940 El Centro, California earthquake (photo credit: NISEE).

Figure 3-10 Sidewalk displaced by distributed faulting from the 1972 Managua, Nicaragua earthquake (photo credit: NISEE).

If ground rupture is confined to a relatively narrow zone, then the total offset will appear as a linear feature that makes the rupture easier to identify. Any buildings, pavements, or utility lines crossing the fault could be destroyed (Figure 3-6 and Figure 3-7). Sometimes fault rupture occurs along multiple branch traces or movement is distributed across wider zones, hundreds of feet wide. In this case, the total offset is distributed across a larger area making it difficult to identify the exact location of ground rupture (Figure 3-10).

Faults are generally well-defined and documented; however, earthquakes have occurred on faults that were not previously known or were thought to have been inactive. Maps of known faults are published online by the USGS, the California Geological Survey, and other state geological surveys. Maps of the location of epicenter, causative fault, and the surface trace of the fault rupture are published online by the USGS after significant earthquakes.

3.6.2 Liquefaction

Strong shaking in loose, water-saturated sandy soil can cause the soil to liquefy, a phenomenon similar to quicksand, caused by a build-up of water pressure as the loose soil begins to densify. When liquefaction occurs, the strength of the soil decreases, and the water-soil mixture temporarily behaves as a liquid rather than a solid and is able to flow. If the pressurized soil-water mixture finds a conduit to the surface, it will vent to the surface and form sand deposits on the ground surface referred to as "sand boils" (Figure 3-11 to Figure 3-13). Other phenomena that are associated with liquefaction include ground settlement and cracking in level ground, and lateral movement in sloping ground (flow failure and lateral spreading). The loss of strength associated with liquefaction can result in loss of bearing capacity of the soil underlying a building, which can cause the building to settle and tilt, or an increase in buoyancy of in-ground structures, such as buried tanks, which can cause them to float to the surface.

Figure 3-11 Sand boils at Kawaihae Harbor from the 2006 Kiholo Bay, Hawaii sequence of earthquakes (photo credit: UHM).

Figure 3-12 Sand boil due to liquefaction of old, poorly compacted, water-saturated fill during the 1989 Loma Prieta, California earthquake (photo credit: G. Plafker, USGS Denver Library Photographic Collection).

Figure 3-13 Tennis court damage with ejection of wet sand from soil liquefaction (site is adjacent to a river) during the 1989 Loma Prieta, California earthquake (photo credit: NISEE).

3.6.3 Seismic Compression (Soil Densification)

While liquefaction occurs only in soil below the ground water table, soil above the ground water table can also sustain permanent deformation during an earthquake. Some dry soils that experience strong shaking may decrease in volume, resulting in ground surface settlements and potential lateral movements near slopes (Figure 3-14 to Figure 3-17). This process is termed seismic compression and is especially prevalent in loose sands but has also been observed in certain types of engineered fills. The process is similar to what happens to the loose contents of a box of cereal during the vibration of shipment, thus the label "contents may have settled during shipment." The magnitude of seismic compression is directly related to the thickness of the susceptible material; hence, seismic compression can be more apparent in deeper fills. For example, during the 1994 Northridge earthquake, significant seismic compression was observed in relatively modern, well-compacted fills that were approximately 100-feet thick and in older, poorly compacted fills approximately 50-feet thick.

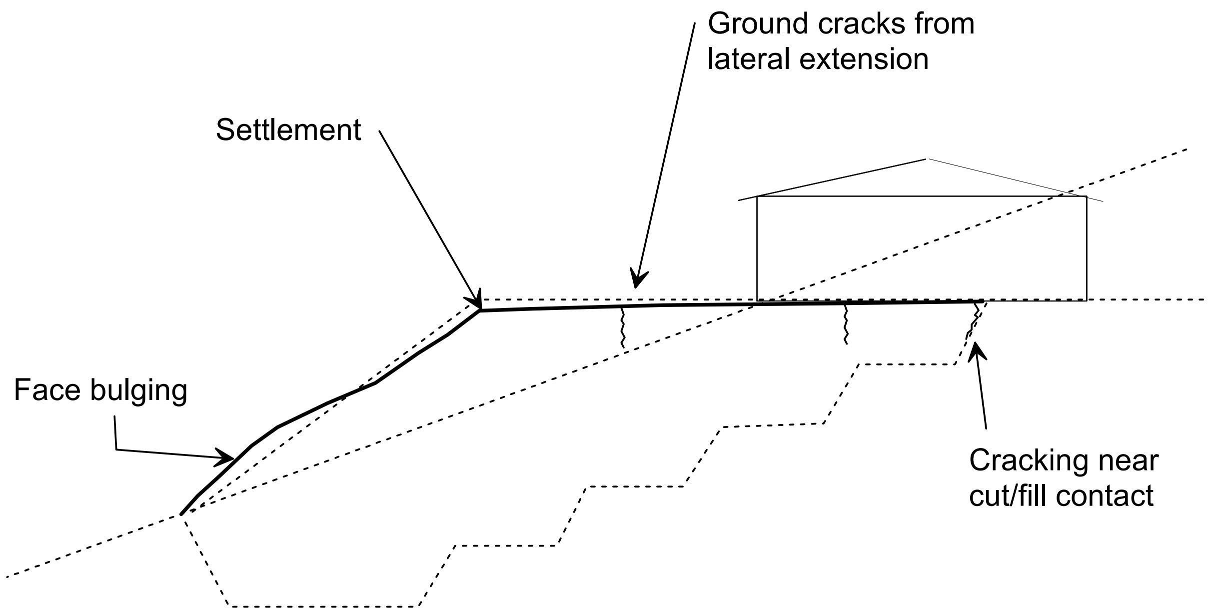


Figure 3-14 Schematic showing possible earthquake damage to a fill slope (image credit: J. Stewart).

Figure 3-15 Building damaged by movements in hillside fill during the 1994 Northridge, California earthquake (photo credit: NISEE).

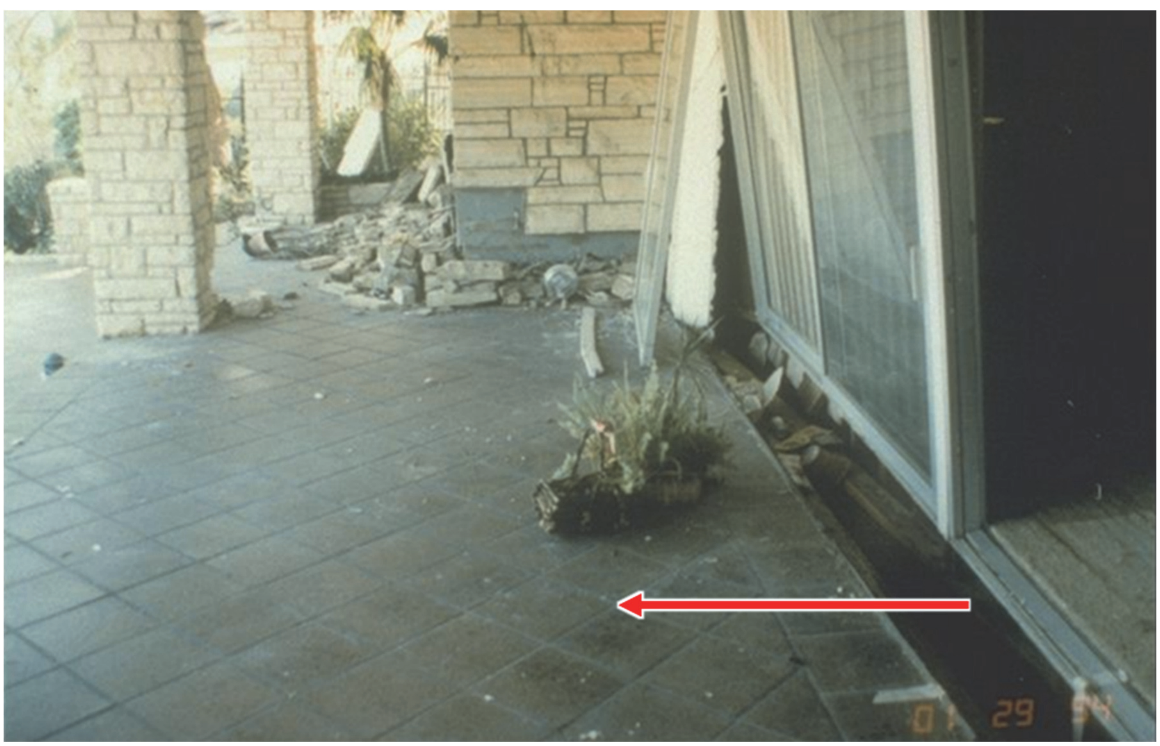


Figure 3-16 Evidence of lateral ground movement in the direction of the arrow, near back of building shown in Figure 3-15 (photo credit: NISEE).

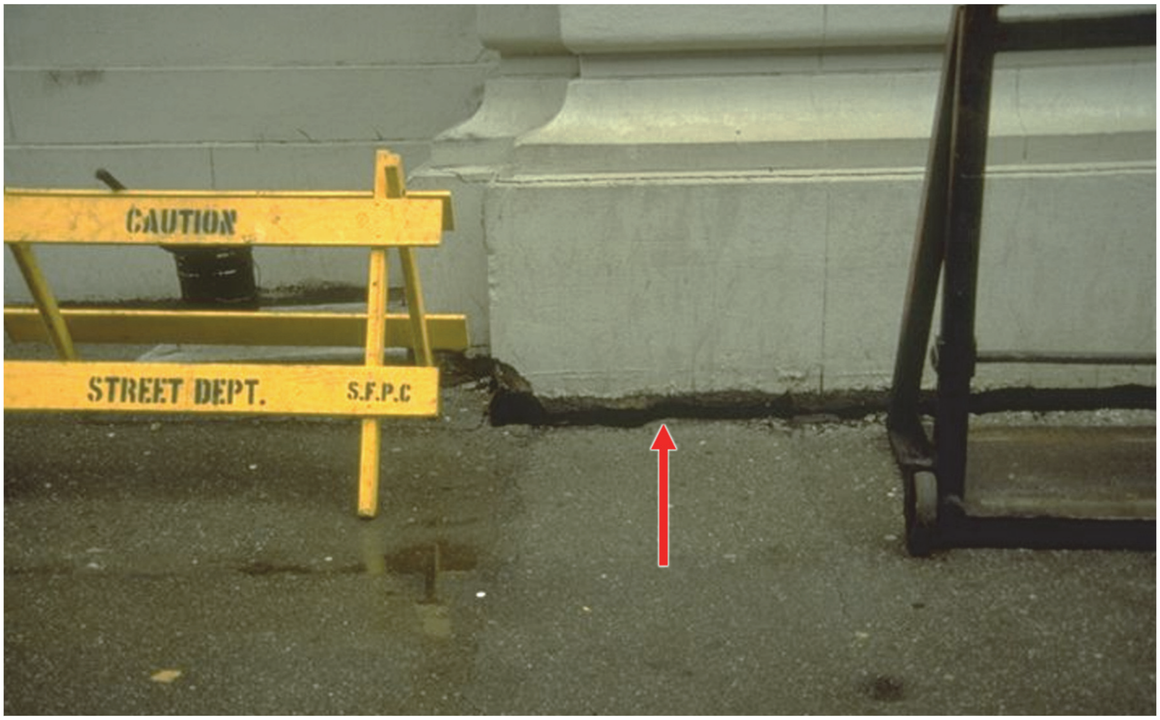


Figure 3-17 Minor settlement caused by densification of loose sandy fill in San Francisco during the 1989 Loma Prieta, California earthquake; the building is pile-supported (photo credit: NISEE).

If the soils are not uniform across a certain area (i.e., some areas are fill while other areas are native or some areas have been more densely compacted than other areas), the ground surface can compress more in the areas of looser soil or thicker fills. This type of settlement imposes a differential elevation across the building (and is thus called differential settlement), which can cause significant distress to the building and can also damage or break underground utilities, such as pipes.

3.6.4 Earthquake-Induced Slope Instability (Landslide)

Inertial forces introduced during strong earthquake shaking can cause slopes to experience downslope movement (Figure 3-18 to Figure 3-21). This movement can occur in slopes consisting of fill, soil, or rock and can range in size from a few feet across to spanning hundreds of acres. Buildings located near the moving part of the slope can be taken down with it, and those beneath the slope can be pushed aside or covered with the debris. Less dramatic movement is also possible. Depending on the level of shaking, geometry and soil conditions, the slope response can include toe bulging at the bottom of the slope, cracking near the crest and some downhill movement of mass near the crest. Homes located very close to the toe of an unstable slope can be damaged by the lateral forces imposed by the bulging mass near the toe. Near the crest, the foundation of a home can be pulled apart or distorted by cracks near the crest of the slope. If left unrepaired, it is possible that minor earthquake-induced ground cracking on or behind a slope or minor earthquake-induced slope movement could lead to the slope being more susceptible to rain-induced landsliding.

Figure 3-18 House displaced by large blocks of soil uplifted at toe of L Street landslide, Anchorage district, during the 1964 Alaska earthquake (photo credit: USGS).

Figure 3-19 Rockfall from the 1970 Peru earthquake (photo credit: G. Plafker, USGS Denver Library Photographic Collection).

Figure 3-20 Rockfall from the 2016 Kaikoura, New Zealand earthquake (photo credit: D. Dizhur and M. Giaretton, EERI Library).

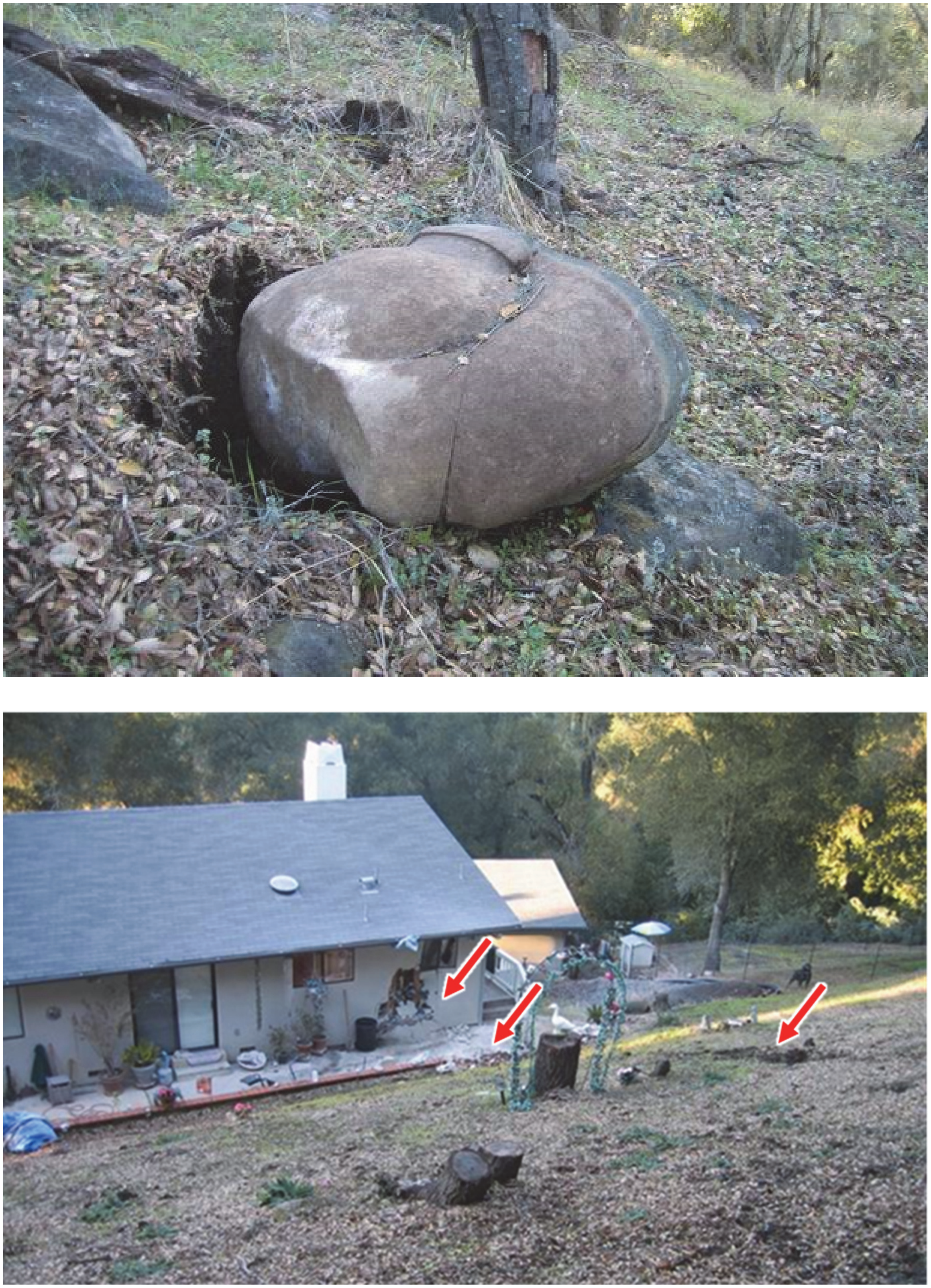


Figure 3-21 Top: rockfall from the 2003 San Simeon, California earthquake; bottom: similar rockfall occurred downslope and impacted the pictured house—impact marks on slope and house indicated by arrows (photo credit: Exponent).

3.6.5 Ridge-Top Shattering

Ridge-top shattering is a result of focusing of earthquake shaking at the crest of a slope due to local topographic effects. This effect is commonly most pronounced at the top of narrow ridges. The ground surface can resemble plowed ground or be disrupted into chunks or blocks of soil. The indications of ridge-top shattering are similar to the indications of landslides in steep terrain.

3.6.6 Retaining Wall Deformation or Instability

During an earthquake, ground shaking can generate lateral forces in the soil behind retaining walls that combine with the sustained, long-term pressures on the wall, resulting in sliding, rotation, bending, or settlement of the wall, all of which can lead to damage to structural elements of the wall (Figure 3-22 to Figure 3-24). In those cases where a retaining wall supports a building, movement of the wall can also cause damage in the supported building. The seismic performance of retaining walls depends on the soil properties, water drainage features, structural properties of the wall, and the level of strong shaking during the earthquake. Cantilever and gravity retaining walls can move by sliding or tilting or both. Reinforced soil slopes/walls deform in a ductile manner without formation of a distinct failure surface and may produce minor settlement of the backfill, face bulging or spalling, and minor cracking in the backfill.

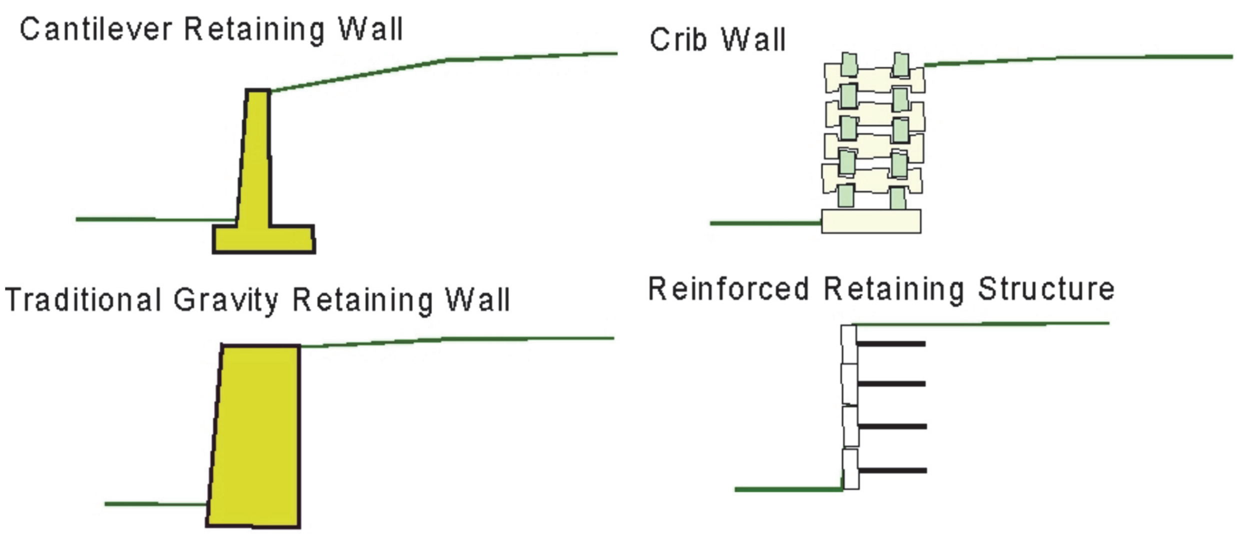


Figure 3-22 Examples of different types of retaining walls utilized in residential construction (image credit: Exponent).

Figure 3-23 Retaining wall damage during the 2003 San Simeon, California earthquake caused backfill to spill from a new crack in the retaining wall (photo credit: Exponent).

Figure 3-24 Collapse of unmortared and unreinforced stone retaining wall in Honokaa, Hawaii, during the 2006 Kiholo Bay, Hawaii sequence of earthquakes (photo credit: UHM).

3.7 Assessment Guidelines and Methodologies

Earthquake-induced permanent ground deformation can range from dramatic destruction of buildings to more subtle cracking or differential settlement. Assessment of more subtle damage is more challenging, given the similarities between the effects of earthquake-induced permanent ground deformation and long-term non-earthquake effects on buildings. The objective of this section is to provide assessment guidance sufficient to permit an individual lacking geotechnical expertise to perform geotechnical triage or sorting—to distinguish between those sites that merit further investigation by a technical consultant from those sites with no evidence of earthquake-induced permanent ground deformation.

3.7.1 Site Inspection

An initial inspection for possible earthquake-induced permanent ground deformation should be conducted as soon as possible after a major earthquake. At this point, any potential earthquake-induced cracks in the ground and hardscape will be "fresh" and therefore readily distinguishable from cracks due to other causes that pre-existed the earthquake. The initial inspection should include examination of those elements most likely to exhibit damage from ground movement (Figure 3-25). These include hardscape, utility lines, swimming pools, exposed building floor slabs and foundations, and building finishes as discussed in more detail below:

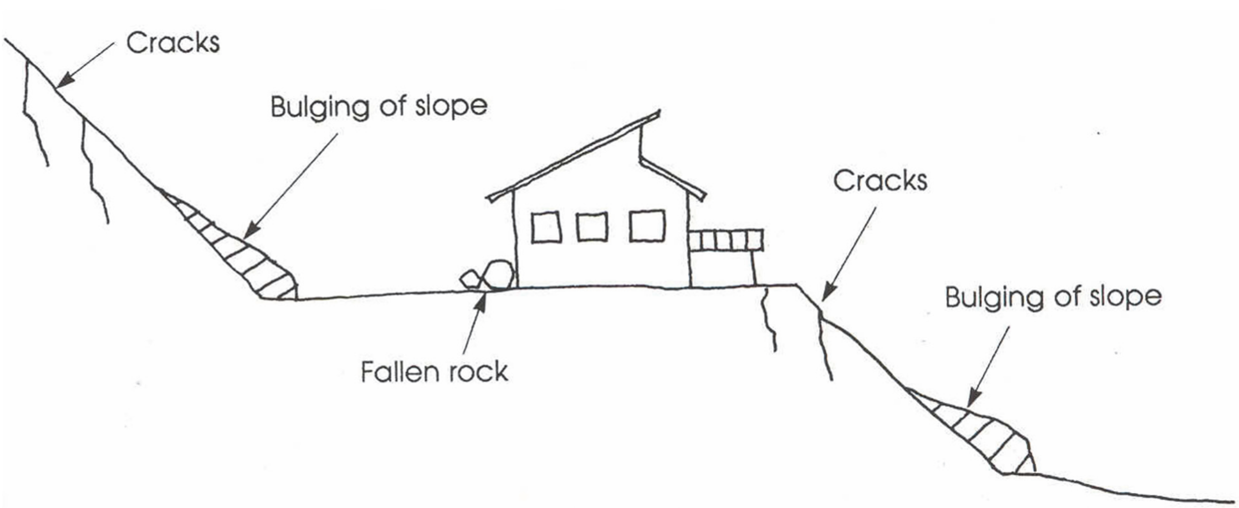


Figure 3-25 Schematic illustration of evidence of possible earthquake-induced ground failure (image credit: ATC).

- **Hardscape (e.g., driveways, patios, sidewalks).** Fresh cracks in hardscape, or the significant widening of pre-existing cracks and construction joints, are good indicators of earthquake-induced permanent ground deformation (Figure 3-26 to Figure 3-33). Also, fresh out-of-levelness in driveways, patios, decks, and other hardscape not consistent with normal construction practices (e.g., patios adjacent to buildings are usually sloped away from the building for drainage) (Figure 3-34) or evidence of movement of exterior improvements relative to the building (Figure 3-35 through Figure 3-37) are indicators of possible earthquake-induced permanent ground deformation. Features such as paint or debris within cracks, previous patching of cracks, and previous releveling of wood decks are indicators of a pre-existing condition, possibly associated with non-earthquake geotechnical processes (e.g., consolidation or slope creep, Figure 3-38 and Figure 3-39). See Section 4.7.2 for guidance on determining whether a fracture is recent.

- **Utility Lines.** Damage to underground utility lines on the property, such as water service lines, sanitary sewer lines, and gas lines, are indicators of possible earthquake-induced permanent ground deformation (Figure 3-8, Figure 3-40, and Figure 3-41). The condition of these lines, and serviceability of the lines (i.e., recent clogging of sewer lines) relative to their condition prior to the earthquake are also important and can be indicative of earthquake-induced damage. Although uncommon, underground utilities can also be damaged by transient earthquake ground movements, without any accompanying permanent ground deformations.

- **Swimming Pool.** Swimming pools can be an effective means by which to assess recent changes in the levelness of at-grade improvements (Figure 3-42). Typically, swimming pool waterline tiles are installed reasonably level (good workmanship is ± 1/4 inch for waterline tile) and significant deviations from level may be indications of earth movement, earthquake-induced or otherwise (Figure 3-42) (NSPI, 2004). Chemical residues, if present on the waterline tile, can indicate the pre-earthquake water surface location. The degree to which these residues form a non-level surface may indicate whether swimming pool movement occurred prior to or as a result of the earthquake. Fresh-appearing out-of-levelness of the pool coping not consistent with construction tolerances and fresh-appearing cracking of the pool shell are indicators of possible earthquake-induced permanent ground deformation.

- **Foundations.** Typical residential foundation types are discussed in Chapter 4. Indicators of earthquake-induced permanent ground deformation related to foundation performance include the following:

  - Fresh cracking or the significant widening of pre-existing cracks in concrete stemwalls or footings (Figure 3-43 to Figure 3-46).

  - Soil deformations adjacent to foundations (e.g., bulging or tension cracks).

  - Out-of-levelness consistent with conspicuous earthquake damage to adjacent wall finishes (Figure 3-32, Figure 3-47 to Figure 3-50). The presence of patched cracks, debris within cracks, and evidence of previous releveling (Figure 3-51) are indicators of long-term, recurring ground movement unrelated to the earthquake. Careful attention to detail is necessary to distinguish the effects of long-term foundation movement from movement associated with earthquake-induced permanent ground deformation.

  The first and third indicators (i.e., fresh cracking and out-of-levelness of floors) are present in virtually every foundation. Accordingly, care must be exercised to distinguish possible damage due to earthquake-induced permanent ground deformation from pre-earthquake conditions. In some cases, the distinction may not be clear, particularly if reconnaissance is performed many months or years following the earthquake.

- **Building Finishes.** Finish elements that should be inspected and documented include wall finishes (as discussed in Chapter 5) and masonry block walls or fences—elements that tend to be vulnerable to shaking-induced damage. Hence, the presence of damage to such elements is not necessarily indicative of earthquake-induced permanent ground deformation. To assess the possible contribution of earthquake-induced permanent ground deformation to damage in these elements, a pattern of cracking consistent with settlement—such as vertical cracks coincident with ground cracks or parallel diagonal cracks—should be present that is consistent with an earthquake-induced ground deformation mode (Figure 3-32, Figure 3-43, Figure 3-44, and Figure 3-47 to Figure 3-49).

3.8 Repair Methodologies

If the inspector's assessment of site conditions indicates the possible existence of earthquake-induced permanent ground deformation, a soils specialist can provide recommendations for dealing with that deformation. Recommendations for a particular site are entirely dependent upon the nature and extent of the earthquake-induced permanent ground deformation.

In many cases of earthquake-induced permanent ground deformation, the ground surface will be slightly distorted from its original condition, but the stability and capacity of the soil to support the building are unaffected. Thus, there is no damage in the soil to repair. However, there may be damage to improvements that requires repair, as discussed in other sections of these *General Guidelines*.

Where an earthquake has destabilized soil, such as with a landslide, repairs will typically involve either stabilization of the landslide or construction of a retaining structure to support the ground beneath the building. For severe damage, such as a large landslide or surface fault rupture, an engineered repair is possible, but abandonment of the site may be the only practical or legal alternative, given applicable building and zoning regulations.

Figure 3-26 Asphalt pavement rupture as a result of a deep rotational slope failure in fill during the 2014 Iquique, Chile earthquake (photo credit: Gabriel Candia A., EERI Library).

Figure 3-27 Street and house damaged by several inches of landslide displacement during the 1971 San Fernando, California earthquake; displacement is readily visible as street crack in photograph (photo credit: ATC).

Figure 3-28 Pavement patching and damage to adjacent sidewalk in San Fernando following the 1971 San Fernando, California earthquake (photo credit: NISEE).

Figure 3-29 Offset sidewalk from the 1971 San Fernando, California earthquake (photo credit: NISEE).

Figure 3-30 Damaged street, gutter, and curb from the 1971 San Fernando, California earthquake (photo credit: NISEE).

Figure 3-31 Buckling of driveway due to liquefaction during the 1989 Loma Prieta, California earthquake (photo credit: NISEE).

Figure 3-32 Projection of liquefaction-induced ground cracking through a building in the city of Chimbote during the 1970 Peru earthquake (photo credit: NISEE).

Figure 3-33 Driveway cracking following the 1971 San Fernando, California earthquake (photo credit: USGS Denver Library Photographic Collection).

Figure 3-34 Driveway cracking and differential settlement following the 1989 Loma Prieta, California earthquake (photo credit: NISEE).

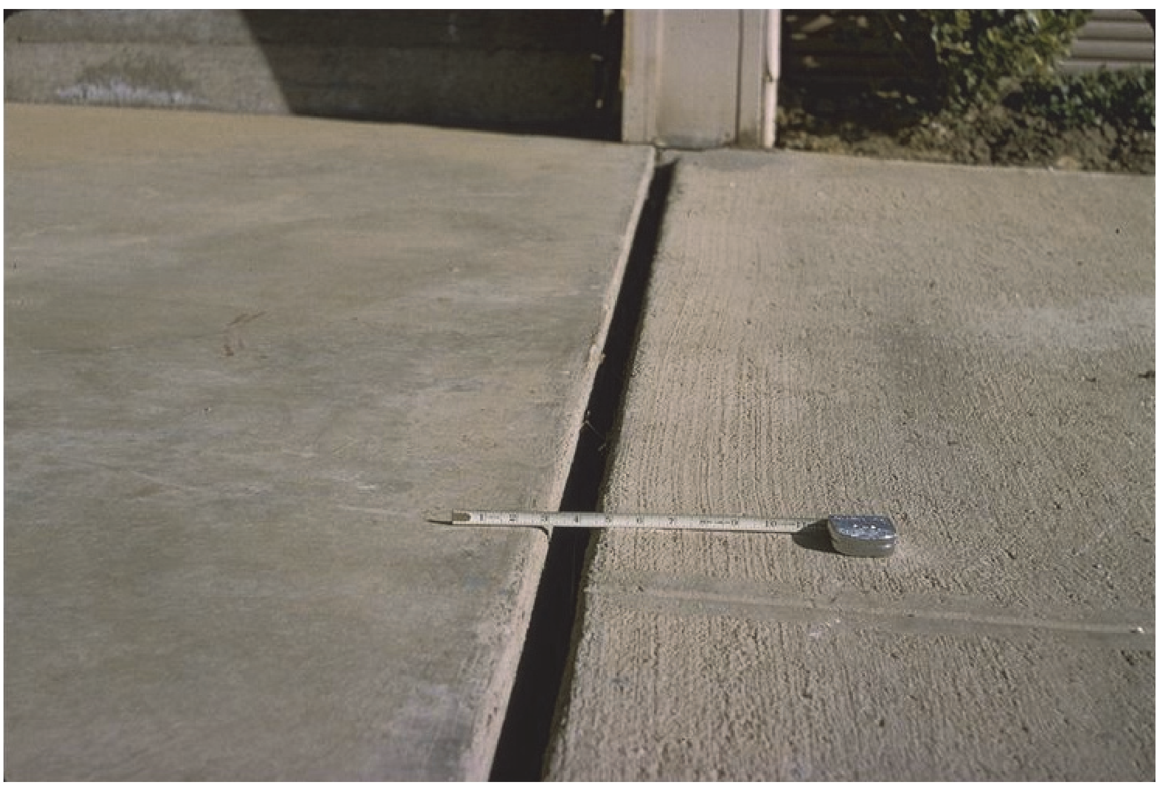


Figure 3-35 Two-inch separation at the construction joint between the garage slab and driveway slab following the 1957 Daly City, California earthquake (photo credit: NISEE])

Figure 3-36 Concrete porch and steps offset from original position by earthquake-induced permanent ground deformation, as evidenced by exposed foundation concrete (photo credit: Exponent).

Figure 3-37 Dropping of entry walkway supported on poorly compacted backfill during the 1994 Northridge, California earthquake (photo credit: Exponent).

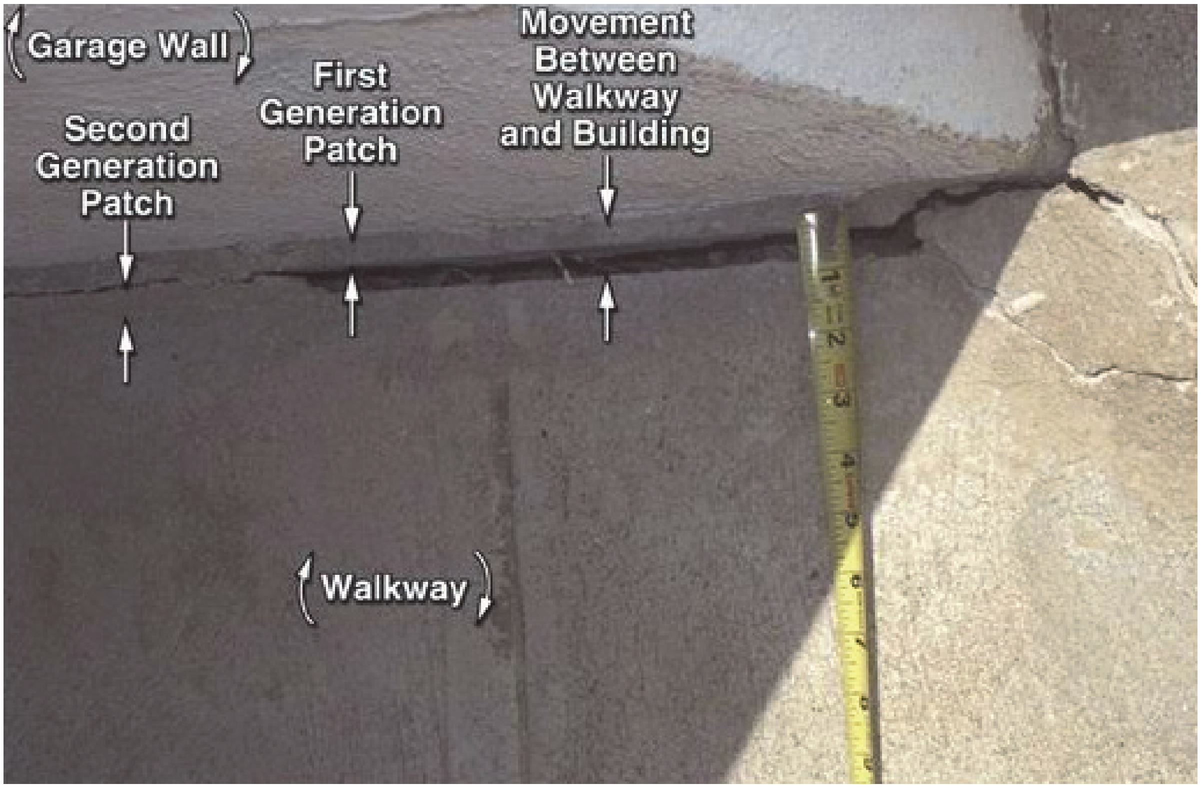


Figure 3-38 Different vintages of grout between a sidewalk and residence near a top of slope indicating a history of lateral movement as a result of slope creep rather than earthquake damage (photo credit: Exponent).

Figure 3-39 Grout within driveway slab-on-grade crack indicating long-term problem with expansive soil beneath driveway rather than earthquake damage (photo credit: Exponent).

Figure 3-40 Utility pipe ruptured by lateral spreading from the 1994 Northridge, California earthquake (photo credit: NISEE).

Figure 3-41 Pipe failures and resulting pavement distress and settlement from the 1971 San Fernando, California earthquake (photo credit: NISEE).

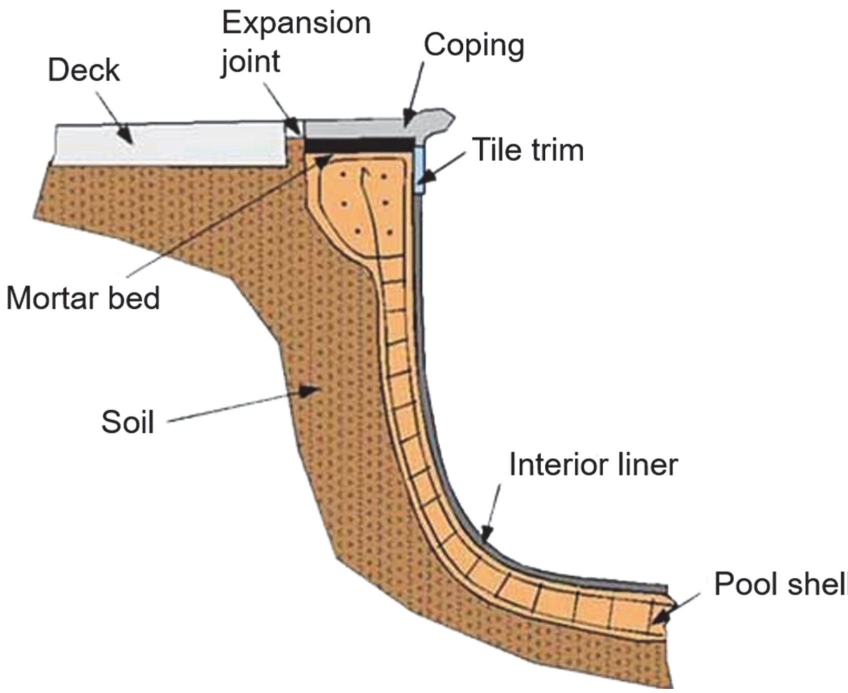


Figure 3-42 Schematic cross-section of typical in-ground swimming pool (image credit: Exponent).

Figure 3-43 Damage to house foundation from lateral spreading in Wakami, Japan, during the 1983 Nihonkai-Chubu, Japan earthquake (photo credit: NISEE).

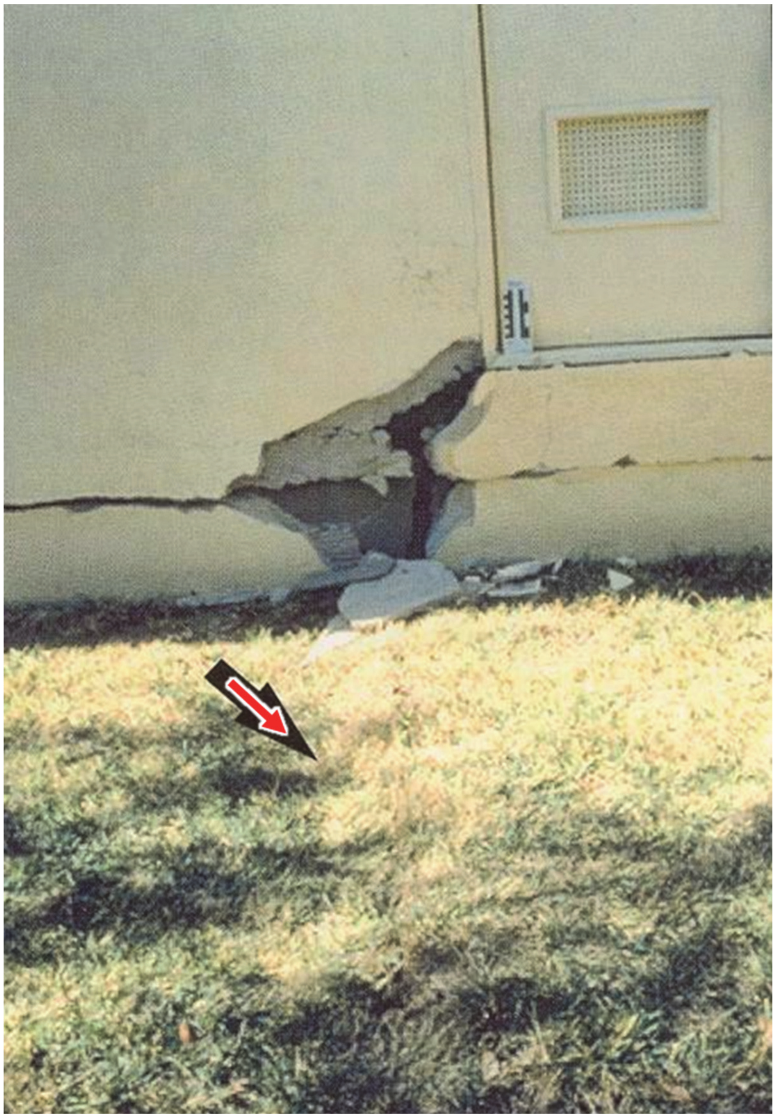


Figure 3-44 Damage to foundation slab and wall of house by small settlement and ground cracking evident in the lawn (arrow) during the 1994 Northridge, California earthquake (photo credit: USGS).

Figure 3-45 Foundation and ground cracking following the 2003 San Simeon, California earthquake; bottom shows the out-of-plane offset present across the foundation crack shown in top photograph (photo credit: Exponent).

Figure 3-46 Foundation and ground cracking following the 2003 San Simeon, California earthquake (photo credit: Exponent).

Figure 3-47 One-story masonry house damaged due to differential settlement caused by liquefaction in the town of Caucete during the 1977 Caucete, San Juan, Argentina earthquake. Damage to the interior slab is shown in Figure 3-48 (photo credit: NISEE).

Figure 3-48 Damaged concrete slab-on-grade floor of the house shown in Figure 3-47; sandy mud ejected by liquefaction covers part of the floor (photo credit: NISEE).

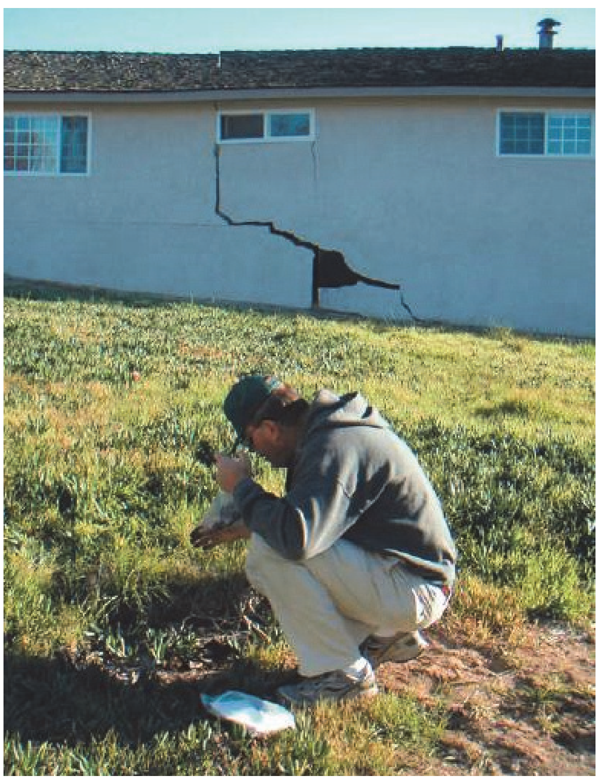


Figure 3-49 Damage to a residence from lateral spreading following the 2003 San Simeon, California earthquake (photo credit: USGS).

Figure 3-50 Damage to a slab-on-grade from liquefaction during the 1971 San Fernando, California earthquake (photo credit: J. Meehan).

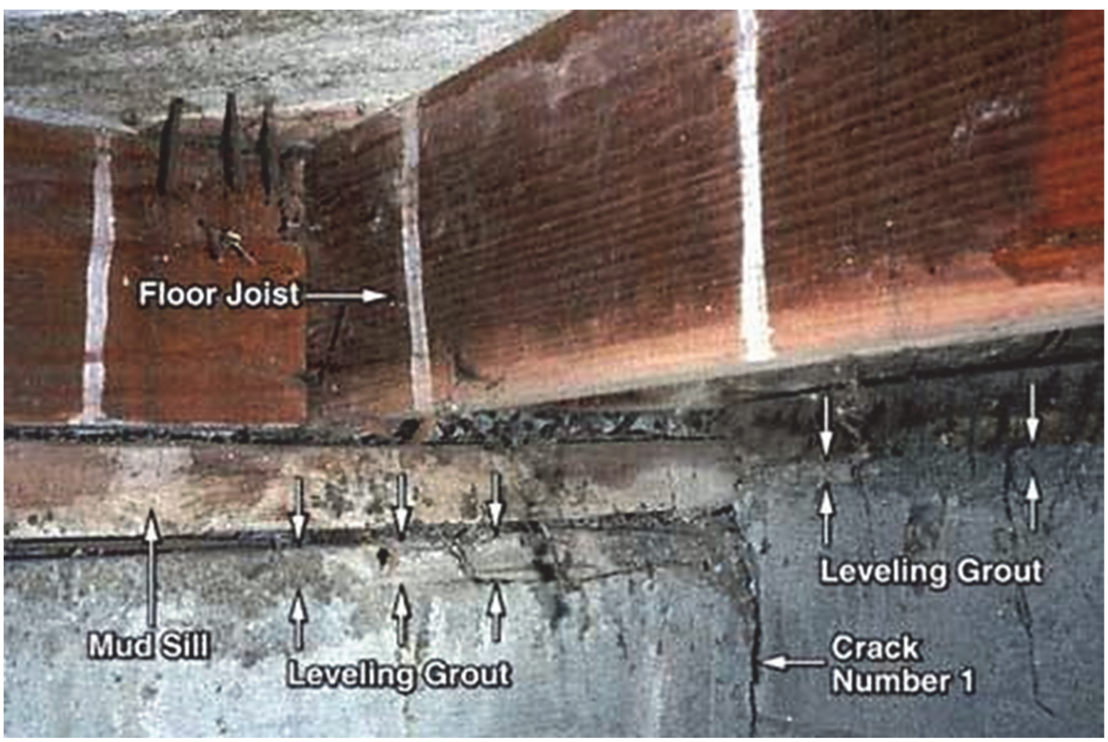


Figure 3-51 Releveling of foundation indicates prior settlement and possibly on-going deformation mode rather than earthquake damage (photo credit: Exponent).

CHAPTER 4

Foundations and Slabs-on-Grade

4.1 Quick Guide

This section provides a summary of where to look, what to look for, and when a technical consultant might be needed regarding foundation and slab-on-grade aspects of a damage assessment. A more detailed discussion begins at Section 4.2.

4.1.1 Where to Look

1. The exposed surfaces of concrete footings or stemwalls, to the extent that they are visible from outside the house or from inside an attached garage, crawlspace, or basement.
2. The edge of the concrete floor slab, to the extent that it is visible from outside the house or from inside an attached garage.
3. Exposed floor slabs, such as in closets, utility rooms, or attached garages.
4. Slab-on-grade floors finished with brittle materials (e.g., ceramic tile, slate, marble, brick pavers).
5. Slab-on-grade floors finished with semi-brittle materials (e.g., sheet vinyl, vinyl floor tile, adhered wood flooring).

4.1.2 What to Look For

If any of the following conditions exists, a technical consultant may be needed.

1. Signs of fresh cracking in, or displacement of, concrete foundations and floor slabs (see Section 4.7.2 for guidance on determining whether a crack is recent).
2. Signs of recent sloping, sagging, settlement, or displacement of floors, patios, or decks.
3. Extensive or large cracks (with signs of recent movement) in the foundation far in excess of what would be expected from normal shrinkage and settlement (see Section 4.5).
4. Any fresh-appearing crack in footings, foundation stemwalls, or exposed floor slabs wider than 1/2 inch or offset by more than 1/16 inch out of plane (the thickness of a nickel), or fresh-appearing cracks in basement walls more than 1/8 inch, that had not been noticed before the earthquake.
5. Any fresh-appearing spalling in footings, foundation stemwalls, or exposed floor slabs that had not been noticed before the earthquake.
6. Perceptible slope in a floor or slab-on-grade (other than intentional slopes for drainage) that had not been noticed before the earthquake.

4.1.3 Repair Guidelines

Structurally insignificant earthquake damage can be addressed as described in Section 4.8.

4.2 Overview

Foundations are those elements between the soil and the wood framing that support the weight of the house. Most residential buildings in California are built on shallow foundations that extend less than about two feet into the near-surface soil. Shallow foundations are typically used either in conjunction with slab-on-grade floors or to support wood framing over a crawlspace. Buildings with crawlspaces can be identified from the exterior by the presence of screened or louvered vents on the building exterior below the elevation of the first floor.

Cold Joints and Control Joints

Cold joints are the intersections between two vintages of concrete, where fresh concrete was cast against hardened concrete without intentional preparation of the existing concrete surface, resulting in little or no bond across the interface. *Control joints* are tooled grooves, saw-cuts, or inserts cast into the slab to create planes of weakness that force straight cracks to form in prescribed locations, rather than the relatively random, jagged pattern that would form otherwise. The grooves extending across a sidewalk at regular intervals are an example of control joints.

Concrete slabs-on-grade, which are concrete slabs cast directly on the ground, are used in virtually all residential construction for walkways, patios, driveways, garage floors, basement floors, rat slabs in crawlspaces, and, in milder climates, they are often used for the at-grade floor of the house. With the exception of certain post-tensioned slabs, slabs-on-grade are not considered part of the building foundation. Even though concrete is often used as a structural material, the purpose of a house slab-on-grade is generally not to carry structural loads but to provide a durable barrier between the soil and the inhabited space and a serviceable subfloor surface.

Concrete shrinks slightly as it cures, and virtually all concrete develops cracks ranging in width from imperceptible hairlines to significant and visible cracks of 1/8 inch or more. Shrinkage cracking of concrete members is a normal and expected condition. In addition, settlement, heave, or creep of the supporting soils can cause shrinkage cracks to widen and additional cracks to form over time. These causes are independent of, and occur in the absence of, earthquakes.

Post-earthquake damage assessments must distinguish between pre-existing cracking and cracking caused by the earthquake. In addition, a distinction should be made between earthquake-induced damage, and that resulting from permanent ground deformation. Even in severe ground shaking, the stresses from shaking induced in residential foundations and slabs-on-grade are typically small compared to the concrete strength. Consequently, most earthquake-related damage to foundations and slabs-on-grade is a result of earthquake-induced permanent ground deformation or the effects of earthquake shaking on elements that had been undermined or otherwise weakened by prior earth movement. There is some evidence that slabs-on-grade that span cut and fill transitions on a hillside site may be particularly susceptible to shaking-induced cracking, even in the absence of differential permanent ground displacement. Otherwise, there is scant field evidence of shaking-induced cracking of concrete foundations and slabs-on-grade in the absence of permanent ground deformation. However, in areas of intense ground shaking, relative transient movement across cold joints, control joints, or pre-existing cracks has been documented, resulting in damage to brittle finishes spanning those joints or cracks. Previously unnoticed cracks are often “discovered” after major earthquakes due to a heightened awareness and careful inspection specifically for cracks.

Post-earthquake inspection of residential concrete foundations and slabs-on-grade consists of visual inspection of exposed concrete surfaces, including any exposed foundation or floor slab at the building perimeter and any brittle or semi-brittle floor surfaces applied directly to a slab-on-grade. Because ordinary cracks in residential concrete are extremely common, attention to detail is necessary to distinguish between pre-existing cracks and earthquake-induced cracks. Key indicators of earthquake-induced cracking are the freshness of the crack surfaces, associated settlement, and a consistent pattern of cracking in adjacent finishes. When apparently fresh cracks are found, it is necessary to determine whether the cracking is minor and repairable with standard methods or whether the cracking indicates possible structural damage that requires evaluation by a structures specialist. In general, apparently fresh cracks wider than 1/2 inch or offset by more than 1/16 inch out of plane merit a more detailed investigation by a structures specialist. Here, out-of-plane offset means that the original surface is offset across the crack—in a slab example, the surface on one side of the crack would be higher than the surface on the other side of the crack.

Cracks in residential concrete foundations and slabs-on-grade are commonplace. Other than as an indicator of possible permanent ground deformation (either long term or earthquake induced), cracks in residential concrete are generally not a structural safety concern. Accordingly, repair generally consists of repair or replacement of brittle finishes spanning the crack after the crack in the concrete is sealed against potential moisture intrusion or insect pest entry, or left as-is. Structural repair of foundations and slab-on-grade cracking is generally not required to restore or maintain pre-earthquake capacity or function. Where structural repair of earthquake-induced cracking is required, epoxy injection with proper procedures, quality control, and quality assurance is an effective method of repair. Instances of more severe damage necessitate evaluation by a structures specialist and possibly the use of other repair techniques.

4.3 Limitations

These *General Guidelines* primarily address only conventional, cast-in-place concrete foundations, although aspects of the discussion may be applicable to other foundation systems. Damage to other types of foundation systems, such as concrete block, brick, or stone, may need to be assessed by a structures specialist.

4.4 Description of Typical Construction

Foundations are those elements between the soil and the wood framing that support the weight of the house. The vast majority of house foundations are constructed of concrete, although treated wood foundations are also occasionally used for new construction. Historically, foundations have also been constructed of redwood, adobe, brick masonry, concrete block masonry, and stone rubble.

The following types of concrete foundation elements, used in various combinations, are found in typical California houses:

- thickened slab edges around the perimeter of concrete slab-on-grade floors (Figure 4-1),
- continuous strip footings around the perimeter of a slab-on-grade (Figure 4-2),
- continuous strip footings under wood-frame stud walls (i.e., cripple walls) that support the first-floor framing over a crawlspace (Figure 4-3),
- continuous stemwalls from the soil to the underside of the first-floor framing over a crawlspace (Figure 4-4),
- isolated pads or pedestals (sometimes pre-cast) supporting wood posts that support the first-floor framing over a crawlspace (Figure 4-5), and
- drilled piers and grade beams supporting wood floor framing over a crawlspace (this type of foundation is often visually indistinguishable from a stemwall foundation, although structurally it functions much differently; Figure 4-6).

Figure 4-1 Continuous footing at perimeter of a slab-on-grade—single-pour system (image credit: Exponent).

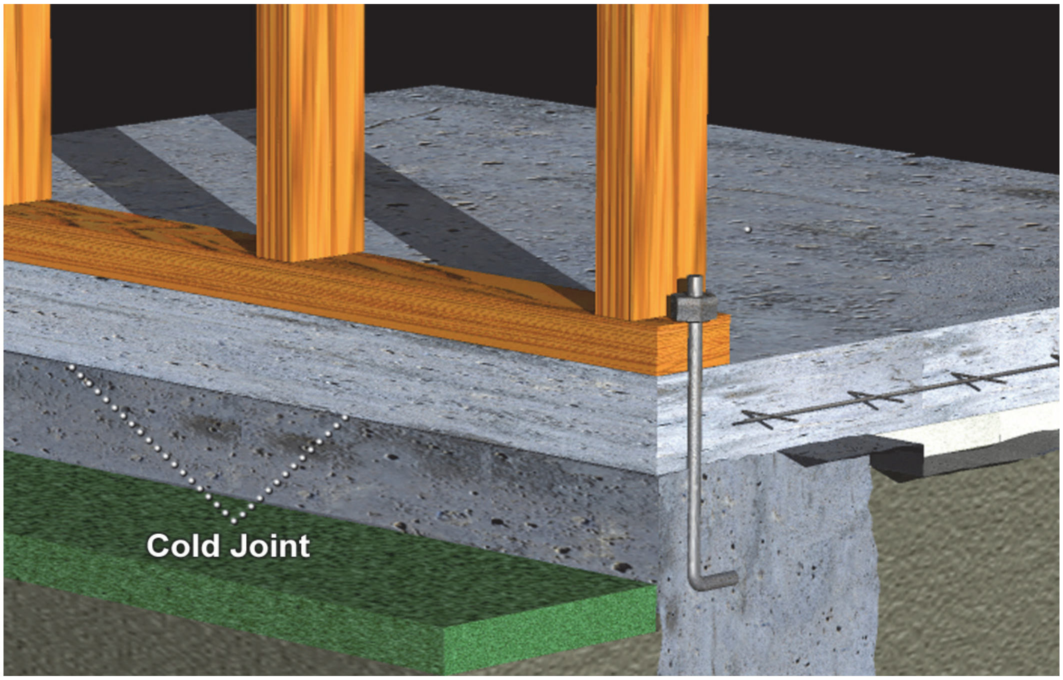


Figure 4-2 Continuous footing at perimeter of a slab-on-grade—two-pour system with cold joint between slab and footing (image credit: Exponent).

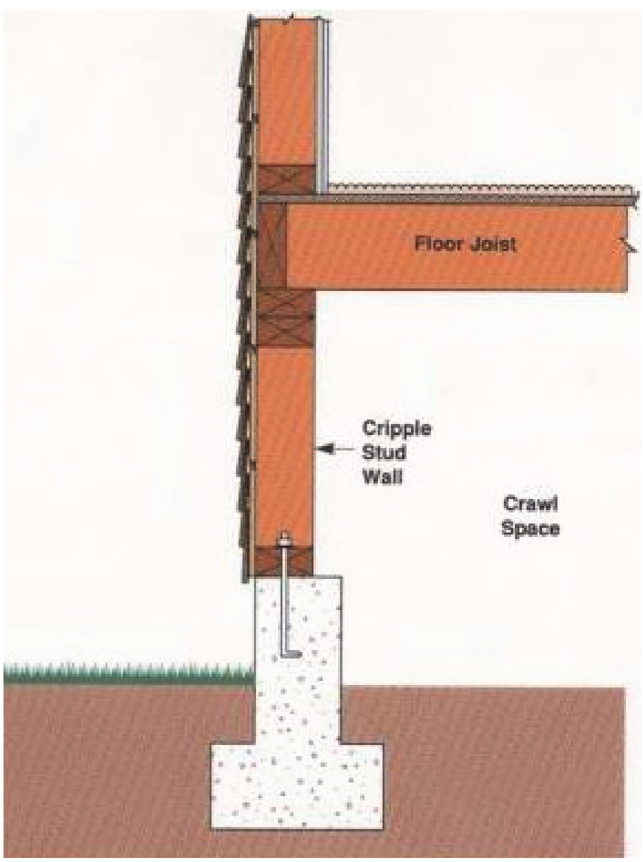


Figure 4-3 Continuous footing supporting wood-frame cripple wall (image credit: Exponent).

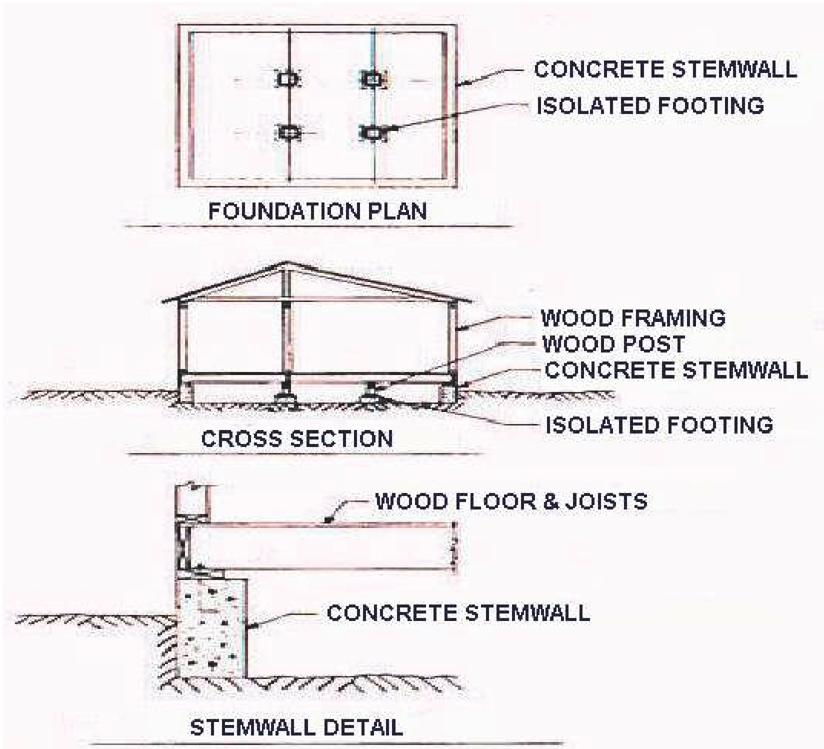


Figure 4-4 Stemwall supporting first-floor wood framing.

Figure 4-5 Isolated footings supporting wood posts of first-floor wood framing (photo credit: Exponent).

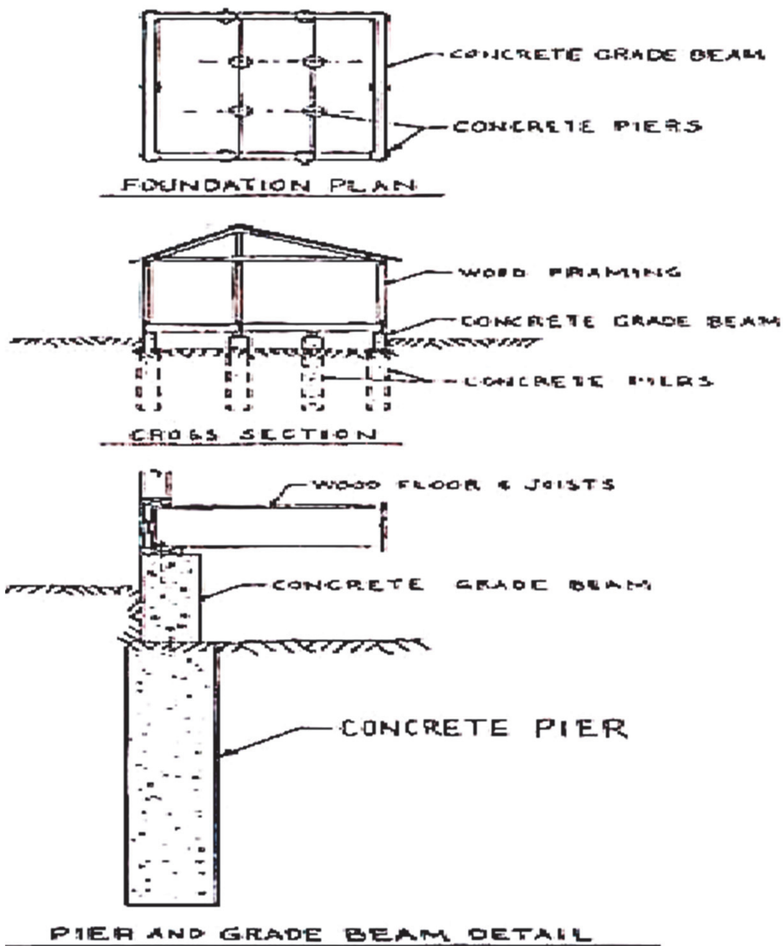


Figure 4-6 Drilled pier-and-grade beam foundation supporting first-floor wood framing.

Post-tensioned slabs-on-grade are an engineered variant of a slab with thickened edges. Steel cables embedded in the concrete are highly tensioned to strengthen the slab and minimize cracking. Before a post-tensioned slab is poured, high-strength steel strands or cables, called tendons, are laid in a tight grid. The tendons are sheathed in plastic so that they do not directly touch the concrete. The concrete is allowed to cure to about 75% of its design strength, at which point post-tensioning occurs. Each of the tendons is pulled tight using a hydraulic jack and anchored in pockets along the perimeter of the slab. The tensioning of the cables occurs after the concrete has mostly cured, hence the term “post-tensioned.”

After tensioning, the tendon is cut off and the pocket in which the anchors are located is filled with grout to protect them from corrosion. Most post-tensioned slabs will be stamped on the perimeter to alert the owner and any renovation contractors that the slab is post tensioned. Repair of post-tensioned slabs requires specific technical knowledge.

With the exceptions of the pier-and-grade beam foundation and post-tensioned slabs, concrete foundation elements have historically had very little, if any, steel reinforcing. In recent years, modest reinforcing of residential foundations has become more common in California.

Concrete residential foundations serve several functions, both structural and nonstructural. Structurally, foundations distribute the superstructure loads to the underlying soil. Nonstructural functions include providing a durable link between the ground and wood framing and providing a barrier against water and pest infiltration. Slab-on-grade floors provide a hard, flat, and durable floor surface.

Satisfactory performance of shallow foundations is dependent upon the strength, stiffness, and long-term stability of the underlying soils. Shallow foundations transfer and distribute superstructure loads to the soil to prevent settlement of the building into the soil, just as snowshoes allow a person to walk on top of the snow by distributing the person's weight over a sufficiently wide area.

4.5 Non-Earthquake Sources of Damage

The hardness, durability, and high compressive strength of concrete make it a nearly ideal foundation, floor slab, and pavement construction material, although its fundamental shortcomings of low tensile strength and shrinkage during curing and drying lead to cracking. Thus, virtually all concrete members have cracks of one sort or another. The causes of cracking in residential concrete slabs-on-grade and foundations are numerous, but the most common are restrained shrinkage and thermal movements, and long-term differential movement of the supporting soil.

Foundations and slabs-on-grade are particularly susceptible to cracking due to shrinkage. Shrinkage cracks develop at planes of weakness or emanate from openings or reentrant (inside) corners. In slabs, shrinkage cracks typically emanate from reentrant corners, at locations where plumbing pipes or heating ducts extend through the slab, from the corners of fireplaces, and diagonally across corners restrained by foundations. In the absence of these causes of stress concentration, shrinkage cracks develop in random locations, usually taking the shortest path across the slab, subdividing a large slab into smaller sections. Most of these cracks are well spaced and of uniform width, having no vertical offset across the crack. In addition, where slabs-on-grade are cast abutting a wall footing, as around the edge of a garage slab, the cold joint between the slab and the stemwall will often open as the slab shrinks away from the wall.

In footings and stemwalls, shrinkage cracks develop at openings for access, vents, plumbing, and ductwork, as well as at corners, "steps" (changes in elevation of the top of the stemwall) (Figure 4-7), anchor bolts (Figure 4-8), and recesses (or pockets) in the stemwall for supporting floor beam (Figure 4-9). Otherwise, cracks develop at essentially random locations along the length of the footing or stemwall, subdividing it into shorter lengths. Without aggravating soil conditions, the cracks are generally near vertical and of uniform width or slightly wider toward the top of the stemwall, having no offset across the crack.

Figure 4-7 Concrete shrinkage crack emanating from reentrant corner at a step in a perimeter stemwall (photo credit: Exponent).

Figure 4-8 Shrinkage crack in a concrete stemwall emanating from an anchor bolt (photo credit: Exponent).

Figure 4-9 Shrinkage crack in a concrete stemwall emanating from a beam pocket (image credit: Exponent).

Exposure to the sun and wind during curing will accelerate drying shrinkage of slabs-on-grade. The rate of concrete shrinkage is time dependent, occurring most rapidly in freshly placed concrete and decreasing with time. Accordingly, shrinkage cracks essentially become dormant after a few years. However, where concrete is subjected to large temperature fluctuations or seasonal soil movements, shrinkage cracks can continue to move and widen over time.

Common methods of controlling concrete shrinkage, or disguising its consequences, are typically not used in the construction of residential foundations and interior slabs-on-grade. The most common method of concealing the visible effects of shrinkage and thermal cracking is to provide control joints. Control joints are common in exterior slabs-on-grade (e.g., sidewalks, driveways, patios), although often ineffective because they are too shallow or too widely spaced. However, control joints have not been widely used in residential foundations or interior slab-on-grade floors because of the desire for a smooth surface for floor coverings and because shrinkage cracking is inconsequential and will ultimately be hidden from view. In some localities, the creation of concealed control joints using “zip strips” is becoming more common, especially for larger floor slabs, to better control the location of shrinkage cracks.

The other common method for controlling, but not preventing, shrinkage cracks involves additional steel reinforcing. A nominal amount of welded wire steel mesh is often, but sometimes ineffectively, used in slabs, as shown in Figure 4-10 and Figure 4-11. The intended purpose is to spread the inevitable shrinkage cracking evenly throughout the slab. Finally, another method of controlling shrinkage cracks is the use of a post-tensioned slab, although this type of slab-on-grade is more commonly used in houses to resist the effects of expansive soils. This approach is often effective where the maximum dimension is about 40 feet. When the dimension is greater than about 50 feet, cracks will often develop.

In addition to shrinkage cracks, foundations and slabs-on-grade commonly experience cracking and differential movement due to the long-term sources of earth movement discussed in Chapter 3. The most effective methods for minimizing the effects of long-term earth movement on foundations and slabs-on-grade include proper preparation of site soils and control of drainage around the perimeter of a foundation. Newer residential construction in areas with expansive soil often includes very thick slab-on-grade foundations (as much as 12-inches thick) or the use of post-tensioned slabs-on-grade.

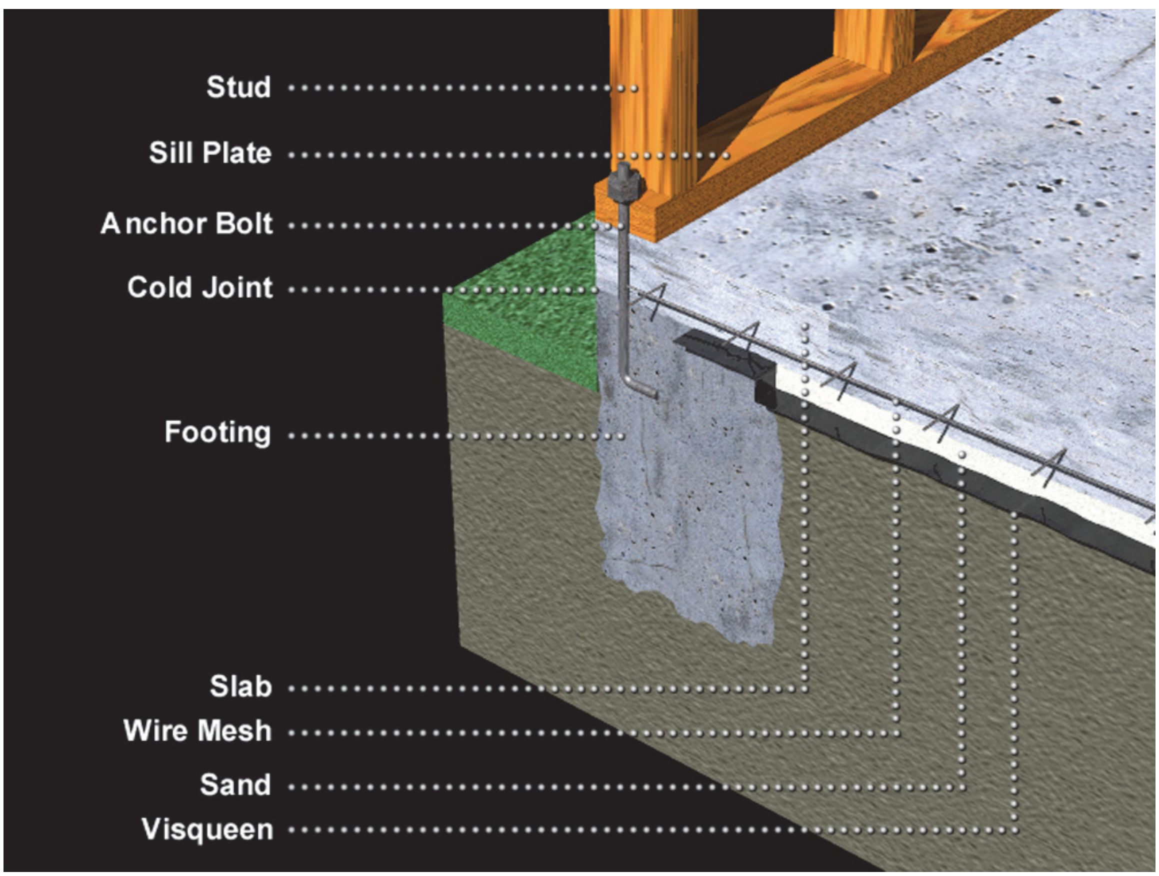


Figure 4-10 Slab-on-grade with independent perimeter footing and horizontal construction joint—two-pour system (image credit: Exponent).

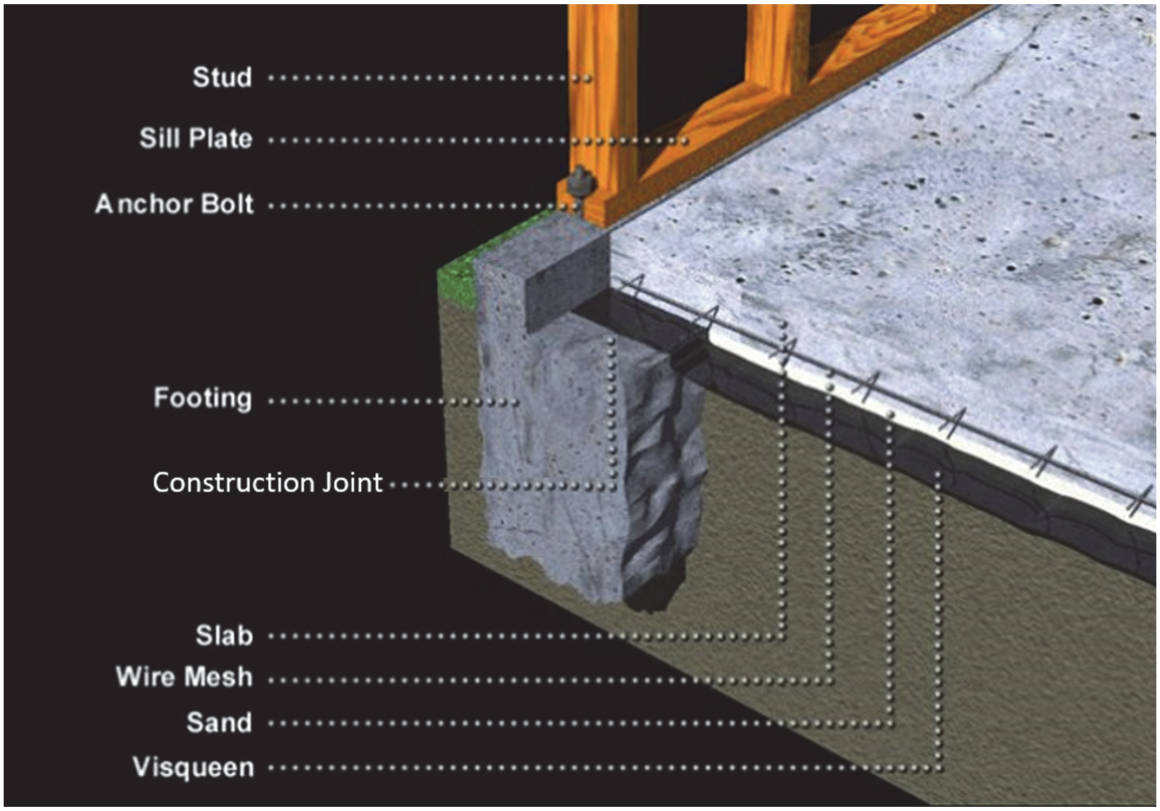


Figure 4-11 Slab-on-grade with independent perimeter footing and vertical construction joint—two-pour system (image credit: Exponent).

Other non-earthquake causes of and contributors to concrete foundation and slab damage include:

- corrosion of reinforcing steel, as shown in Figure 4-12, or anchor bolts (especially in marine environments or where deicing salts are used),
- tree roots, vines, or other vegetation, as shown in Figure 4-13,
- vehicle traffic loads, especially where the underlying soil has been eroded or softened, for example by a sprinkler system, as shown in Figure 4-14,
- changes in site drainage conditions or vegetation coverage and irrigation, including paving of areas adjacent to the foundation or slab that were previously vegetated, and
- extensive burrowing of gophers or other rodents.

Distinguishing between earthquake-related damage to concrete foundations and slabs-on-grade and damage that is pre-existing is addressed in Section 4.7.2. For example, paint or vegetation in cracks observed soon after an earthquake are good indicators of pre-existing damage.

Figure 4-12 Core extracted from concrete stemwall showing cracking caused by swelling pressure generated by corroding reinforcing steel (photo credit: Exponent).

Figure 4-13 Uplift and cracking of concrete sidewalk caused by tree roots (photo credit: Exponent).

Figure 4-14 Cracking due to vehicle loads on a concrete driveway over soft soil (photo credit: Exponent).

4.6 Earthquake-Induced Damage

Concrete slabs-on-grade and residential foundations have performed extremely well in past earthquakes at sites that did not sustain earthquake-induced permanent ground deformation. Following an earthquake, however, foundations and slabs may be scrutinized for the first time and under that scrutiny, numerous cracks are observed for the first time. Given the correlation between the earthquake and the fact that the first observation of cracks occurs right after the earthquake, it is easy to jump to the conclusion that the cracks were caused by the earthquake and perhaps represent serious structural damage. In reality, while earthquake-induced cracking of slabs and foundations can occur under certain circumstances, it is not common. Cracking of structural significance is even more uncommon. Actual earthquake-induced damage to residential foundations and slabs-on-grade is almost invariably associated with permanent ground deformation or conspicuous visible damage to the superstructure. One possible exception to this general statement is for slabs and foundations that span a cut-fill contact at a site. There have been field observations of slab and foundation cracking along the cut-fill line without measurable permanent deformation of the fill.

As most residential foundations rely on the strength and stability of the supporting soils for satisfactory performance, ground failure or permanent ground deformation (as distinct from the transitory deformation of soils and buildings that occurs while they are shaking during an earthquake) generally causes foundation damage as well. Mechanisms by which earthquakes can induce permanent ground deformation and damage buildings and their foundations are discussed in Chapter 3.

The most common effects of earthquake-induced permanent ground deformation on residential foundations are large displacements and cracks, which are visually obvious. If there are indications of earthquake-induced permanent ground deformations at a site, a technical consultant should be retained to investigate. Building damage patterns that indicate possible earthquake-induced permanent ground deformation include:

- fresh-appearing vertical or diagonal cracks in foundations or concrete floor slabs or visible differential foundation movement,
- fresh-appearing (i.e., inconsistent with the quality of construction, general level of maintenance, and normal aging) sloping, sagging, or settlement of floors, patios, or decks, and
- sloping, sagging, or settlement of floors, patios, or decks consistent with conspicuous earthquake damage to adjacent wood-frame walls.

Permanent ground deformation is not always necessary for earthquake-related foundation damage. Other vulnerable foundation conditions and their potential earthquake damage patterns are discussed in the following paragraphs. These patterns are generally of no structural significance if displacements are small, although cosmetic repair may be necessary.

The most common occurrence is minor relative movement across the horizontal construction joint between the footing and the slab-on-grade in two-pour systems. When the plastic vapor barrier or sand fill is extended over the top of the footing (Figure 4-15), the strength of the connection between slab and foundation is reduced. While the result of this movement is spalling and cracking of stucco or concrete patching material around the perimeter of the foundation (Figure 4-16) or cracking of brittle floor finishes at interior steps or floor level changes (Figure 4-17), there are, as a practical matter, no consequences beyond the need for cosmetic repair. Significant earthquake-induced sliding of the slab relative to the foundation will show as a consistent pattern of slab-footing offset and will likely be accompanied by spalling of concrete at anchor bolts, substantial damage to the house walls, and damage to utility lines that penetrate the floor slab.

Similar movement can occur in two-pour systems where the slab-on-grade is cast against, rather than on top of the foundation, as frequently occurs in garages and less commonly within living spaces. The movement is manifested by a development or widening of a narrow gap between the footing and slab-on-grade (Figure 4-18). If the house slab has this detail, any related movement will be visible only upon removal of carpets along the edge of the rooms. As a practical matter, the only consequence of this movement is the opening of a possible path of entry for insect pests.

Figure 4-15 Earthquake-induced relative movement at slab-footing interface in two-pour slab-on-grade construction due to sand covering the footing during construction (photo credit: Exponent).

Figure 4-16 Earthquake-induced differential movement and spalling at cold joint between stemwall and slab in two-pour construction (photo credit: Exponent).

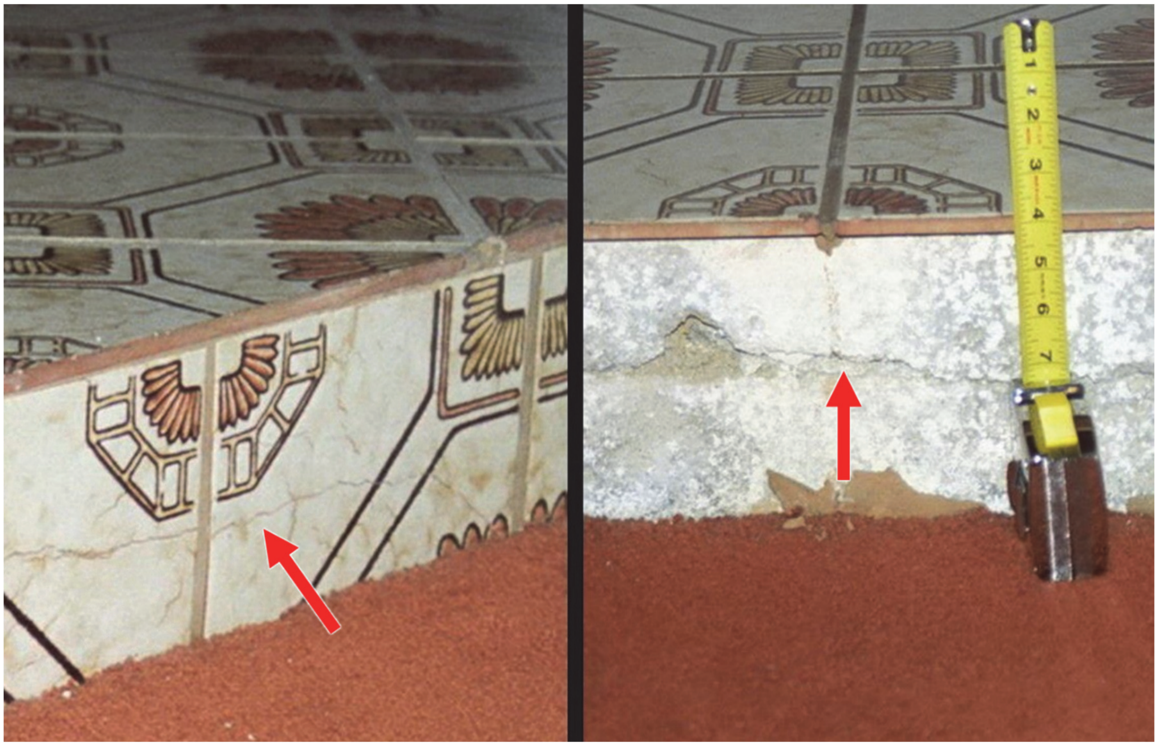


Figure 4-17 Earthquake-induced cracking of ceramic tile spanning the cold joint between the floor slab and the stemwall in a two-pour system (photo credit: Exponent).

Figure 4-18 Earthquake-induced opening of cold joint between floor slab and perimeter footing (photo credit: Exponent).

Application of brittle floor finishes (e.g., ceramic tile, slate, marble, other stone work, and brick-pavers) over concrete slabs-on-grade is common. Generally, such finishes are bonded directly to cracked slabs. Such installations are sensitive to even minor differential movement across the cracks in the slab. Due to temperature effects and minor soil movements, over time the finish materials will develop hairline cracks that follow the cracks in the slab, a phenomenon known as "telegraphing." Telegraphing of cracks can also occur in areas of intense ground shaking, as shown in Figure 4-19. Close inspection often reveals a wider crack in the slab than in the finish materials. The difference in width between the two cracks indicates the width of the slab crack at the time the finish was installed, a condition that allows distinction between finish cracking caused by telegraphing of an existing crack and fresh cracking of the underlying concrete slab.

Finally, intense earthquake shaking can cause movement across cracks that had formed prior to the earthquake, due to various non-earthquake causes discussed above. Such movement might be substantial enough to make pre-existing cracks or slopes noticeable. If the earthquake contribution changes the scope of repair necessary to correct the condition, that additional movement would be properly classified as earthquake damage. However, unless the earthquake contribution widens the crack beyond 1/2 inch or creates an out-of-plane offset greater than 1/16 inch, the additional movement should be considered structurally insignificant.

Figure 4-19 Earthquake-induced cracking of ceramic tile on a slab-on-grade (photo credit: Exponent).

4.7 Assessment Guidelines and Methodologies

Initial assessment of foundations and slabs-on-grade consists primarily of visual examination of the patterns and details of visible cracks. This initial assessment should be accomplished by a visual inspection of the perimeter of the building and inspection of any visible areas of the foundation within a garage.

Before focusing on the foundation and slab-on-grade, however, it is helpful to understand relevant features of the site. A generally hilly area indicates that a level lot was probably graded by cutting or filling the original terrain. The cut-fill boundary is a likely place to find foundation and slab-on-grade damage.

It is also necessary to identify relevant details of the foundation construction. If the house has a raised foundation, are there wood cripple walls over concrete footings (Figure 4-3), or is the crawlspace enclosed by full-height stemwalls (Figure 4-4)? Is the interior of the house supported in the same way as the perimeter, or are there individual wood posts on concrete or masonry piers (Figure 4-5)? In addition to the raised portion, does the house also have a more recent slab-on-grade addition?

In a slab-on-grade house, is there evidence of a two-pour system (Figure 4-2, Figure 4-10, and Figure 4-11)? Can the location of the horizontal cold joint between the slab and the footing be distinguished, or is it obscured by finishes or adjacent construction?

In the course of an overall visual inspection of the house, those portions of the foundation and slab-on-grade that are readily visible should be examined for signs of fresh cracking or recent differential movement. Readily visible locations include:

- exposed slabs, such as in closets, utility rooms, or attached garages,
- slab-on-grade floors finished with brittle materials (e.g., ceramic tile, slate, marble, or brick pavers),
- slab-on-grade floors finished with semi-brittle materials (e.g., sheet vinyl, vinyl floor tile, and adhered wood flooring),
- the edge of the concrete slab, to the extent that it is visible from outside the house or from inside an attached garage, and
- the outside surfaces of concrete footings or stemwalls, to the extent that they are visible from outside the house or from inside an attached garage.

Outside the house, the edge of slab and face of footings or stemwalls may be bare concrete or masonry, painted, finished with a skim coat of stucco, or finished with stucco or other finishes continuous from the wall above.

4.7.1 Technical Consultant Assessment

If any of the following damage patterns are observed, consider retaining a structures specialist to perform a foundation and slab-on-grade inspection. In the absence of these conditions, earthquake damage to a foundation or slab-on-grade is unlikely, and further investigation is generally not warranted.

- fresh-appearing cracks wider than 1/2 inch or offset by more than 1/16 inch out of plane, as illustrated in Figure 4-20 (in all foundation and slab-on-grade elements except basement walls)
- fresh-appearing cracks wider than 1/8 inch in basement walls
- extensive or large cracks (with signs of recent movement) in the foundation far in excess of what would be expected from normal shrinkage and settlement (see Section 4.5)
- perceptible slopes in floors, slabs-on-grade (other than drainage slopes), or swimming pools that had not been noticed before the earthquake
- vertical or horizontal out-of-plane offsets exceeding 1/16 inch (the thickness of a nickel) across any earthquake-caused cracks
- indication of earthquake-induced permanent ground deformation

The structures specialist's assessment should include detailed visual inspection, measurement, and sometimes mapping of cracks. If the need is indicated by the initial structures specialist's assessment, the structures specialist may recommend selective pulling of carpets (for buildings with carpeting over slab-on-grade floors), a geotechnical investigation, or destructive investigation of the foundation or slab-on-grade floor.

Figure 4-20 Illustration of out-of-plane offset in a concrete slab-on-grade. Concrete slab on one side of the crack is higher than on the other side (photo credit: Exponent).

Destructive investigation should be necessary only in those instances when the structures specialist is unable to rule out, or reasonably assume, earthquake damage based on non-destructive means. If the building was constructed prior to 1980 and repair work will involve disturbance (e.g., demolition, removal, grinding, sanding) of any of the following types of floor finishes, a suitably qualified environmental consultant should be retained:

- vinyl tile or mastic,
- backing or underside of sheet vinyl, or
- enamel paint on concrete floors.

The consultant may test for the presence of regulated hazardous materials and, if the results of the tests are positive, recommend appropriate abatement and waste disposal measures.

4.7.2 Establishing the Cause of Cracks

The most reliable indicator of an earthquake contribution to an observed foundation crack is the presence of corresponding earthquake damage to adjacent slabs, soil, or superstructure. If corresponding damage is not present, in some cases it is possible to determine by visual examination of the crack surfaces whether the cracks are of recent origin or a long-term condition. Visible indicators are most reliable in the weeks immediately following the earthquake and become less so as time passes; cracks weather, repairs are made, and other events intervene to obscure fresh damage.

Characteristics of cracks that provide clues to their age include:

- Sharpness of the crack edge: Fresh cracks exhibit sharp edges free of weathering, rounding, or erosion. Cracks in protected locations, such as within a crawlspace or beneath a floor covering, will not “weather” and may look sharp and fresh for many years. Figure 4-21 shows a fresh crack in Portland cement concrete, whereas Figure 4-22 shows an older crack with worn and rounded edges.
- Relative color of crack surfaces and exposed surface of the element: A fresh crack will typically be a different shade than the exposed, weathered surface, as shown in Figure 4-23.
- Condition of crack surfaces: Fresh cracks exhibit clean fracture surfaces. Older cracks may exhibit contamination with paint (Figure 4-24), oil, grease, floor covering adhesive (Figure 4-25 and Figure 4-26), sawdust, drywall joint compound (Figure 4-27), or other foreign matter that may have accumulated since the crack initially developed.
- Grout, caulk, or other patching or repair material in the crack, as shown in Figure 4-28 through Figure 4-30.
- Leveling material adjacent to or spanning the crack, as shown in Figure 4-31.
- Dirt, dust, debris, or vegetation in the crack, as shown in Figure 4-32 through Figure 4-34.
- Where slabs are covered with an adhered floor finish, setting mortar or adhesive may extend into the crack (Figure 4-35), or the bottom side of finish material that spanned a pre-existing crack may show an impression of the crack in the pattern of adhesive trowel marks or setting mortar, as shown in Figure 4-36.

- Condition of carpet tack strips that cross the crack. Tack strips installed over old dormant cracks will span the crack without damage. Cracks that formed or widened since the tack strip was installed might break tack strips or pull the tack strip loose. Determining the age of breaks in tack strips is often difficult. Double tack strips or offset tack strips paralleling cracks indicate cracks were present when the tack strips were installed.
- Recent differential movement between adjacent elements is generally manifested by exposure of unpainted surfaces, torn caulk or expansion joint material, staining or debris remnants, gaps between trim and the abutting surface, and other discontinuities.
- Examination of the interface where two vintages of concrete meet can indicate the relative age of cracks. Recent cracks will extend through both vintages of concrete, while older cracks will be present only in the older vintage of concrete, as shown in Figure 4-37.
- If the pattern of a stain or efflorescence, which is a whitish stain on concrete or masonry caused by water seepage, is markedly different on two sides of a crack, then the crack was present before the stain developed, as shown in Figure 4-38.
- Typical shrinkage crack patterns for concrete slabs-on-grade were described previously. In addition, concealed control joints (formed with "zip strips"), as shown in Figure 4-39, and construction joints associated with additions or modifications, look like very straight shrinkage cracks. A very straight shrinkage crack can also indicate where slab reinforcing was not properly lapped or was intentionally separated.

Figure 4-21 Fresh crack in concrete exhibiting sharp edges, crack faces free of contamination and gap clear of debris (photo credit: Exponent).

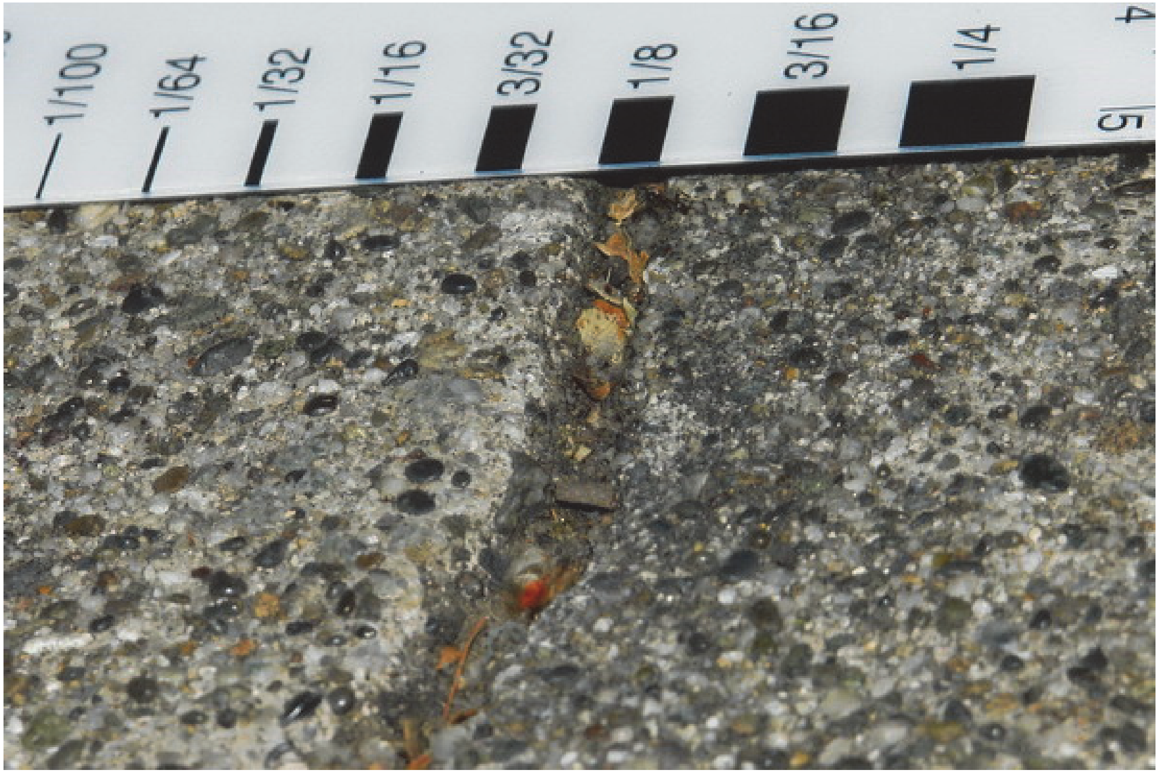


Figure 4-22 Older crack in concrete exhibiting worn and rounded edges (photo credit: Exponent).

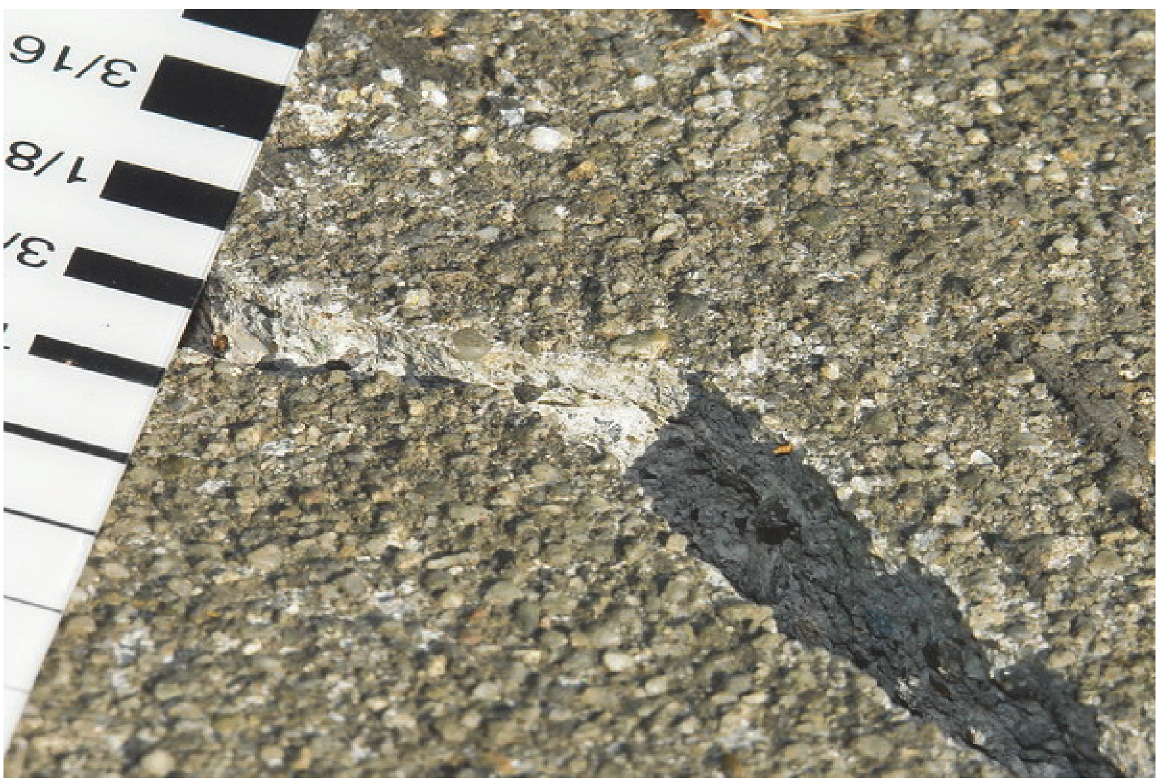


Figure 4-23 Fresh crack in concrete exhibiting lighter color on crack face relative to weathered surface (photo credit: Exponent).

Figure 4-24 Older crack in concrete exhibiting worn and rounded edges contaminated with paint (photo credit: Exponent).

Figure 4-25 Older crack in concrete floor slab contaminated with carpet pad adhesive (photo credit: Exponent).

Figure 4-26 Parquet flooring adhesive filling crack in concrete slab (photo credit: Exponent).

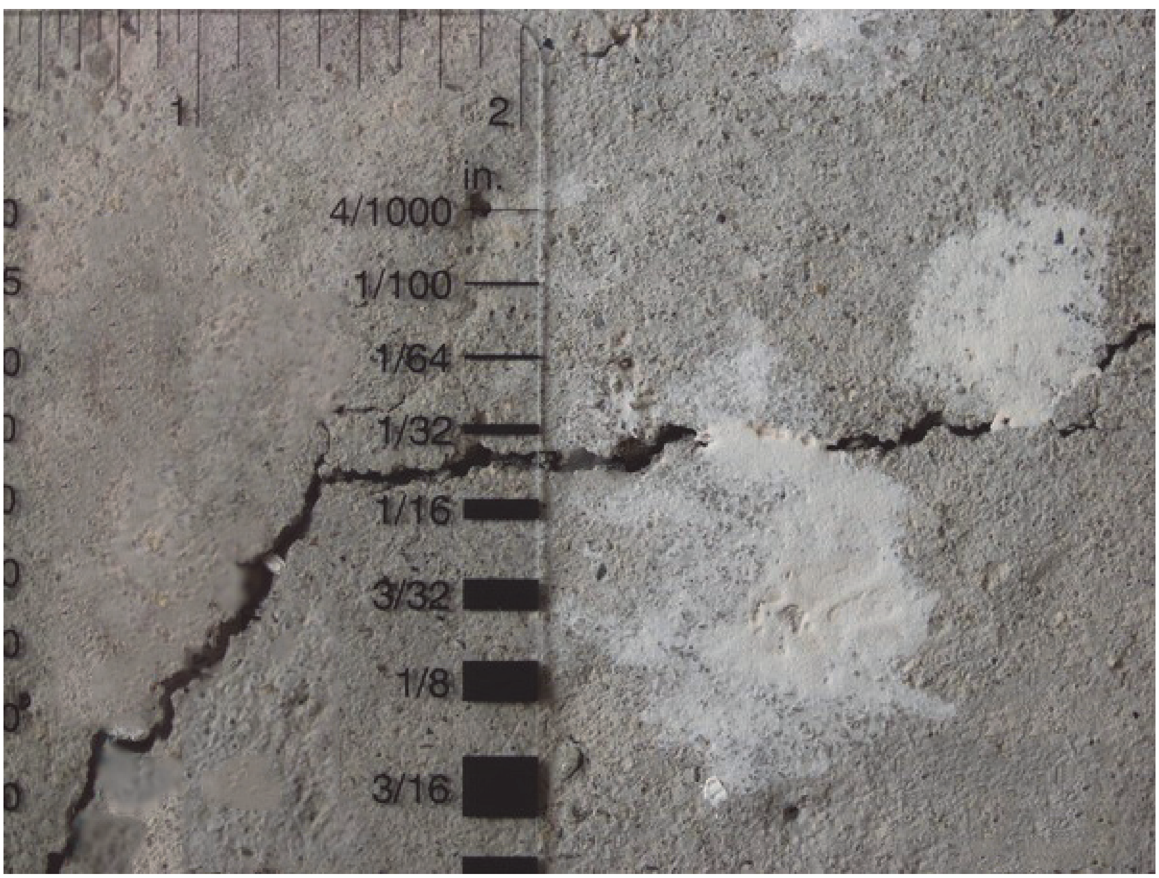


Figure 4-27 Dabs of drywall joint compound within shrinkage crack in concrete slab-on-grade floor (photo credit: Exponent).

Figure 4-28 Older crack in foundation stemwall exhibiting prior patching and painting (photo credit: Exponent).

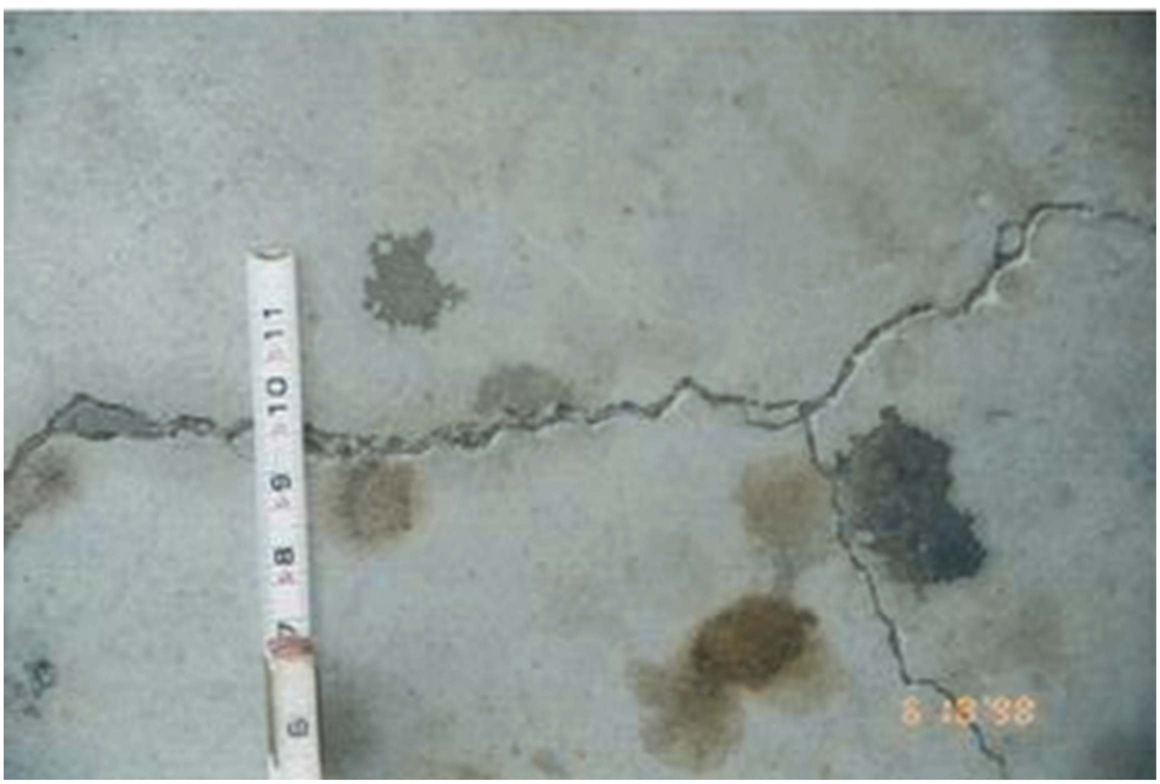


Figure 4-29 Mortar within garage slab-on-grade crack indicates previous patching of crack (photo credit: Exponent).

Figure 4-30 Crack in concrete slab-on-grade floor that exhibits two prior generations of patching, as well as opening since last patching (photo credit: Exponent).

Figure 4-31 White leveling compound spread across existing crack at time of carpet installation (photo credit: Exponent).

Figure 4-32 Debris (sawdust) from original construction indicates foundation crack is not recent (photo credit: Exponent).

Figure 4-33 Dirt and efflorescence indicates age of foundation wall crack is not recent (photo credit: Exponent).

Figure 4-34 Debris and vegetation in older crack (photo credit: Exponent).

Figure 4-35 Grout completely filling slab-on-grade crack indicates that slab crack was present at the time of the tile installation and has not experienced movement since tile installation (photo credit: Exponent).

Figure 4-36 Setting mortar that had flowed into an existing slab crack that remained bonded to the backside of a ceramic tile when the tile was removed, indicating that the concrete slab was cracked when the tile was installed (photo credit: Exponent).

Figure 4-37 Termination of crack in older concrete (upper left) where it abuts newer concrete (lower right) indicates that crack existed prior to the installation of the newer concrete (photo credit: Exponent).

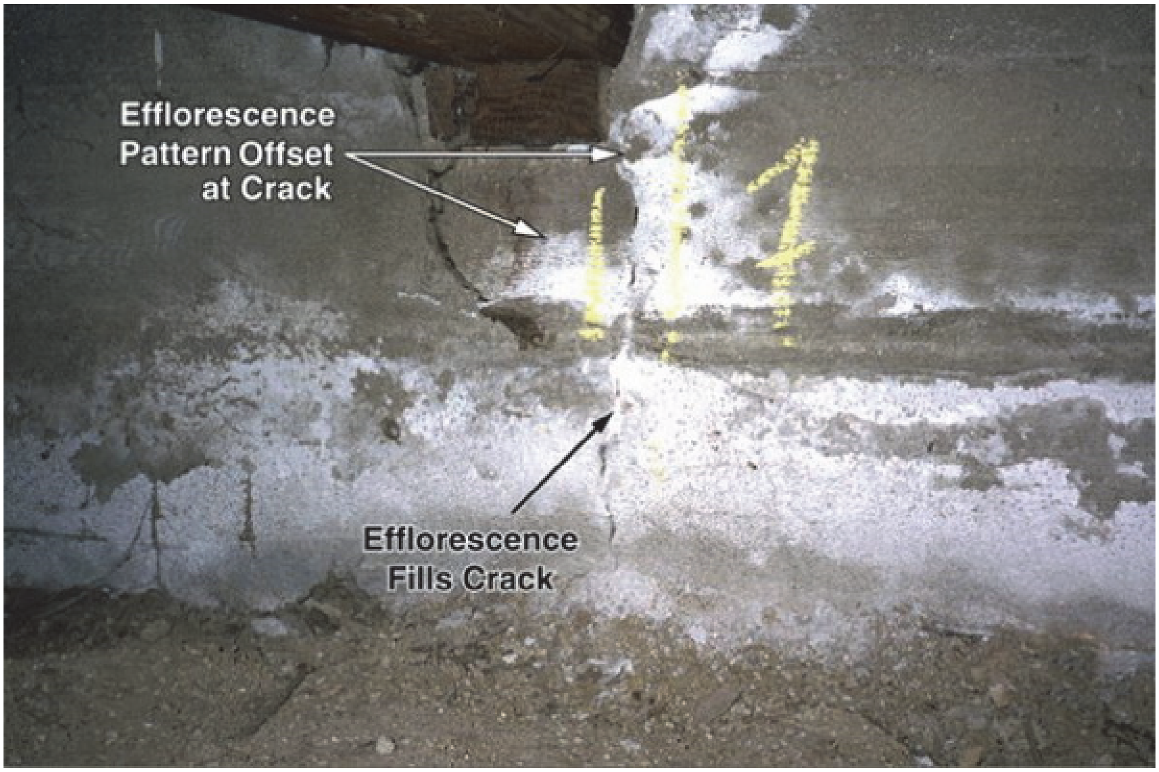


Figure 4-38 Pattern of efflorescence around crack in stemwall indicates that crack is not of recent origin (photo credit: Exponent).

Figure 4-39 Linear shrinkage crack in concrete floor slab at location of a concealed control joint created by a "zip strip" (photo credit: Exponent).

4.8 Repair Methodologies

The appropriate repair of foundations and slabs-on-grade must consider the nature, extent, cause, and significance of the damage. Where earthquake damage results from permanent ground deformation, stabilization of the site may need to be addressed as one component of the overall repair plan. Where the damage represents a loss of structural capacity a structural repair will be necessary. In all other cases, a nonstructural repair is appropriate.

Table 4-1 summarizes appropriate repair methods for those earthquake damage patterns that can be addressed without structures specialist assistance. If the cause of an observed damage pattern cannot be determined, or if the damage is outside the description given in the table, consider retaining a structures specialist to address the issue. The repair methods listed in the table are further discussed in the following sections. The methods in the table address the structural elements only; repair of any associated damage to nonstructural finishes should be done in accord with normal practices of the relevant trades. Some repair methods are included for structural materials other than concrete.

The repair methods presented in this chapter presume that the building materials are free of regulated levels of hazardous materials. If testing as recommended in Section 9.2.4 indicates the presence of regulated levels of asbestos or lead, the abatement and waste disposal recommendations of the environmental consultant should be incorporated into the overall scope of repair.

Table 4-1 Repair Methods Not Requiring Technical Consultant Assistance for Nominal Earthquake Damage to Foundations and Slabs-On-Grade[1, 2]

Element	*Earthquake Damage Pattern*	*Repair Method*
Slabs-on-grade	Earthquake damage to stucco finish along horizontal cold joint between bottom of slab and top of footing, no apparent footing damage, no evidence of sliding more than 1/8 inch	No structural repair of concrete warranted (see Chapter 5 for stucco repair recommendations)
	Opening of construction joint between edge of slab and adjacent wall footing caused by the earthquake	Seal gap with epoxy or grout
	Crack in slab Width: less than 1/8 inch Settlement, spreading, offset, or slope: slight to none	Seal cracks with epoxy if there is potential for water or pest intrusion, otherwise no repair
	Crack in slab Width: up to 1/2 inch Offset: up to 1/16 inch Settlement, spreading, or slope: slight to none	Seal crack with epoxy or epoxy and aggregate
	Local spall in concrete	Patch with repair mortar

Table 4-1 Repair Methods Not Requiring Technical Consultant Assistance for Nominal Earthquake Damage to Foundations and Slabs-On-Grade[1, 2] (continued)

Element	*Earthquake Damage Pattern*	*Repair Method*
Footings and stemwalls, concrete	Crack in footing or stemwall Width: less than 1/8 inch Settlement, spreading, offset, or slope: slight to none	Seal cracks if there is potential for water or pest intrusion, otherwise no repair
	Crack in footing or stemwall Width: up to 1/2 inch Offset: up to 1/16 inch Settlement, spreading, or slope: slight to none	Seal crack with epoxy or epoxy and aggregate
	Local spall in concrete	Patch with repair mortar
Footings and stemwalls, brick masonry	Crack in brick or mortar joint Width: less than 1/8 inch Settlement, spreading, offset or slope: slight to none	Seal cracks if there is evidence of water or pest intrusion, otherwise no repair
	Crack in brick or mortar joint Width: up to 1/2 inch Offset: up to 1/16 inch Settlement, spreading, or slope: slight to none	Repoint mortar joints. Remove and replace cracked bricks
	Local spall in masonry	Patch with repair mortar or remove and replace spalled bricks
Stemwalls, concrete masonry	Crack in masonry unit or mortar joint Width: less than 1/8 inch Settlement, spreading, offset, or slope: slight to none	Seal cracks if there is evidence of water or pest intrusion, otherwise no repair
	Local spall in masonry	Patch with repair mortar or remove and replace spalled units
Post and pier foundation systems	Post lean: up to 1/2 inch over the post height due to shifting of the house	No repair
	Post shifted on the footing due to shifting of the house Post is vertical Post falls in the center third of the footing horizontal dimension	Refasten post to the pier footing
Basement walls, concrete	Crack in basement wall Width: less than 1/8 inch Settlement, Spreading, offset, or slope: slight to none	Seal cracks if there is potential for water or pest intrusion, otherwise no repair
	Local spall in concrete	Patch with repair mortar

Table 4-1 Repair Methods Not Requiring Technical Consultant Assistance for Nominal Earthquake Damage to Foundations and Slabs-On-Grade[1, 2] (continued)

Element	*Earthquake Damage Pattern*	*Repair Method*
Basement walls, masonry	Crack in basement wall Width: less than 1/8 inch Settlement, spreading, offset, or slope: slight to none	Seal cracks if there is potential for water or pest intrusion, otherwise no repair
	Local spall in concrete	Patch with repair mortar or remove and replace spalled units
Wood sill plates	Sliding in any horizontal direction up to 1/4 inch with no other distress	No repair
	Local sill plate fracture at individual bolts, not more than one out of ten bolts	Add a replacement bolt or replacement retrofit plate in the vicinity of the fracture location for each affected bolt

(1) Repair methods presented in this table presume that the building materials are free of regulated levels of hazardous materials. If testing as recommended in Section 9.2.4 indicates the presence of regulated levels of asbestos or lead, the abatement and waste disposal recommendations of the environmental consultant should be incorporated into the overall scope of repair.

(2) Identify damage pattern and repair where damage has been identified during the damage investigation. Select damage pattern most representative of observed damage caused by or worsened by the earthquake. See Section 1.2.3 for discussion of worsened damage.

4.8.1 No Structural Repair Warranted

For many cracks in residential concrete, whether or not they are earthquake-related, the appropriate repair is to do nothing. These cracks are typically the result of shrinkage and have no practical effect on the function of the element. In the normal course of construction and maintenance of buildings, shrinkage cracks are ignored or cosmetically patched. Isolated cracks up to 1/2-inch wide with no more than 1/16-inch out-of-plane offset are structurally insignificant (except in basement walls, where cracks greater than 1/8 inch could indicate structurally significant damage). Nonstructural repair of a crack less than 1/8-inch wide with no more than slight settlement, spreading, offset, or slope may be appropriate for cosmetic reasons or to prevent moisture and pest intrusion. For cosmetic considerations of exposed concrete, see Section 4.8.6.

4.8.2 Seal Cracks or Gap

Larger cracks or gaps can provide an additional path of entry for insect pests or moisture and sealing of those cracks or cold joints may be desirable in some circumstances. Where no out-of-plane offset is present, cracks and gaps can be sealed by routing the crack and filling the space with an elastomeric joint sealant. Cracks and gaps can also be sealed with any of a number of commercially available cement-based patching materials, many of which have a latex additive to increase bond strength. For cosmetic considerations of exposed concrete, see Section 4.8.6.

4.8.3 Apply Leveling Compound

Where a vertical offset occurs across a crack in a floor slab, a leveling compound can be used to restore flatness as needed for installation of flooring. Floor covering installers routinely do minor leveling of slab surfaces to provide a smooth substrate beneath the floor finish.

4.8.4 Epoxy Injection

Epoxy injection consists of the injection, under controlled pressure, of epoxy resins formulated for structural repair of concrete into cracks in concrete elements. Epoxy injection is a widely used method for concrete crack repair because it solves several problems: it seals the crack against water and insect pest entry, it protects any reinforcing steel crossing the crack from corrosion, and it provides tensile and flexural strength comparable to or exceeding that of the uncracked concrete element. Cracks ranging in width from 0.002 inches to 0.25 inches can be satisfactorily repaired with epoxy injection. For cosmetic considerations of exposed concrete, see Section 4.8.6.

Epoxy injection is a specialized trade that utilizes specialized and often proprietary materials and methods. As such, specific materials, equipment, and procedures can vary by region or contractor. Quality assurance procedures are an essential aspect of epoxy injection repair work. In addition, some jurisdictions require an engineering report in support of epoxy repairs. For application to plain or lightly reinforced residential concrete, this requirement is typically waived, but regulations vary by jurisdiction. Recommendations regarding epoxy injection of residential concrete are presented in Appendix G.

4.8.5 Removal and Replacement

As discussed below, appearance is a consideration for some concrete repairs. Aesthetically acceptable repair of cracks in architecturally exposed concrete (e.g., driveways, walkways, patios, and pool decks) is generally impractical, although there are methods available for that purpose. Generally, however, for architecturally exposed residential concrete slabs-on-grade (e.g., walks, patios), removal of the damaged area and replacement in-kind is usually the most practical solution.

4.8.6 Cosmetic Considerations

Repair should also include cosmetic work that is necessary to assure a reasonably uniform appearance after the repairs are completed. Cosmetic considerations for foundations (stemwalls and footings) include:

- Unless the foundation is an exposed (i.e., visible) element in the building, cosmetic matching is not necessary.
- If the foundation in the area of the repair is an exposed element and the repair will detract from a reasonably uniform appearance, consideration of cosmetic matching should be included in the repair.

Cosmetic considerations for slabs-on-grade include:

- Unless the slab-on-grade is an exposed element in the building, cosmetic matching is not necessary.
- If the slab-on-grade in the area of the repair is an exposed element, repair should include consideration of cosmetic appearance.

4.8.7 Technical Consultant Repair Recommendations

For damage patterns not addressed in Table 4-1, or at sites with soil problems, a technical consultant may be asked to recommend repairs. Repairs that might be recommended by a technical consultant, in addition to those presented in Table 4-1, include:

- Grinding and leveling where a vertical offset across a crack in a slab-on-grade is greater than 1/16 inch.
- Epoxy or cementitious grout repair (possibly with prepacking with sand or aggregate) of cracks wider than 1/2 inch.
- Partial replacement of the slab, footing, or stemwall might be appropriate for sections with concentrations of damage or wide cracks with large offsets. Damaged or offset material is removed by saw cutting or jack hammering to create a gap at least 2-feet wide. New steel reinforcing is doweled into the edges of the existing concrete to ensure that the new and old concrete will be properly tied together. New concrete is then placed.
- External reinforcement consisting of leaving a cracked or damaged section of concrete (generally stemwalls) in place and attaching external reinforcement that restores the flexural and tensile capacity of the element. For conventional residential foundations, external reinforcement is appropriate when epoxy injection is not feasible. Typical external reinforcement approaches include:
    - steel plates bolted into intact concrete on both sides of the damaged area,
    - reinforced concrete grade beams constructed adjacent to the damaged area and doweled into intact concrete on both sides of the damaged area, and
    - fiberglass or carbon fiber composites that are bonded to the surface of the element and span across the crack.
- External post-tensioning consists of installing high-strength threaded steel rods along the inside face of a stemwall and pre-stressing the rods to provide a state of nominal compression in the stemwall. This method effectively strengthens or reinforces the stemwall and is effective in areas subject to slope creep or highly expansive clay. Otherwise, it is an excessively conservative method for residential foundation repair.
- Complete replacement of a slab or foundation is appropriate only when the foundation has been damaged beyond repair due to earthquake-induced permanent ground deformation.

4.8.8 Releveling

> **Releveling**
>
> No building is perfectly level. The objective of releveling is to return a building to its pre-earthquake condition. Care must be taken not to make the building more level than it was prior to the earthquake. Over releveling will likely cause significant cosmetic damage and may cause structural damage.

Earthquake-induced soil movement can cause differential settlement of the foundation, leaving the building in a noticeable out-of-level condition. Once the soil beneath the building is stabilized, there are several alternatives to relevel the building that may be recommended by the structures specialist, preferably with advice from a soils specialist:

- Releveling wood-frame floors over a raised foundation: wood-frame superstructures over a crawlspace are relatively straightforward to relevel on the existing foundation. Nuts on the mudsill anchor bolts are removed, the building is jacked level, the anchor bolts are extended using coupling nuts and reconnected, and the void beneath the mudsill is filled with grout. Wood support posts are shimmed or replaced with adjustable steel support posts. An experienced contractor can accomplish releveling with little disruption or damage to the building interior, but some allowance should be made for associated cosmetic refinishing.
- Releveling wood-frame buildings on slabs-on-grade: a wood-frame house on a slab-on-grade can also be releveled on the existing foundation, although all work must take place within the first-story living space and results in considerable disruption. Following releveling of the wood-frame building, the slab surface may be leveled with a leveling compound.
- Lift or compaction grouting, a type of pressure grouting that lifts the building and lifts and stabilizes the soil immediately beneath the foundation, is an alternative for releveling of buildings with slab-on-grade floors. Stiff, cementitious grout is injected into the soil beneath the slab through injection pipes around the building perimeter and distributed within the building interior. Grout is injected sequentially, gradually bringing the slab, foundation, and superstructure back up to level.
- Underpinning consists of installing concrete shafts or steel pipe piles into the ground beneath the foundation to support the building on deeper, more stable soil. Underpinning may be the recommended repair to address unstable soil conditions identified as part of the geotechnical investigation. In the absence of unstable soils, however, underpinning is not recommended for repair of earthquake-induced foundation damage. Underpinning may also include a helical pier.

4.8.9 Permits and Code-Triggered Upgrades

Depending upon the nature and scope of damage and proposed repair, building permits and other government agency approvals may be required by the local jurisdiction. In addition to normal changes in the building code over time, some jurisdictions have building code requirements that mandate varying degrees of upgrades if certain damage thresholds are exceeded. The repair guidelines presented herein are intended to represent prevailing best practices and do not include jurisdiction-specific requirements. The local building department should be contacted to determine the existence of any applicable local requirements. Where utilized, technical consultants should be asked to address any code-triggered upgrades that may be required to comply with applicable local building code requirements as part of the repair of earthquake damage.

CHAPTER 5

Walls

5.1 Quick Guide

This section provides a summary of where to look, what to look for, and when a technical consultant might be needed regarding a damage assessment of walls. A more detailed discussion begins at Section 5.2.

5.1.1 Where to Look: Exterior Walls

1. At the corners of door and window openings.
2. At building corners on the exterior near the base of the wall.
3. Along the plate line on the exterior, where the wood framing meets the concrete foundation.
4. If a weep screed is present along the bottom edge of the stucco, check for detachment by a hand pull at intervals around the building perimeter.
5. At the typical elevation (8 feet above the floor) of wall top plates in taller walls, such as gable end walls adjacent to cathedral ceilings.
6. At doors and windows, check for squareness and plumbness of opening.

5.1.2 What to Look For: Exterior Walls

If any of the following conditions exists, a technical consultant may be needed.

1. Fresh cracking (see Section 5.7.4), buckling, or detachment of exterior stucco or brick veneer.
2. Walls tilted out of plumb (either full-height walls or cripple walls).
3. Broken glass in windows or doors.
4. Collapse, partial collapse, or separation of masonry veneer.
5. Severe cracking, separation, or offsets at building irregularities.
6. The walls are racked visibly out of plumb, or doors or windows have been rendered inoperable by the earthquake due to their openings being racked out of square (excluding patio doors and closet doors that have come off their tracks or doors or windows rendered inoperable due to hardware failure or impact damage).
7. The stucco has developed cracks wider than 1/8 inch, particularly if they extend across the full width of a wall section between door or window openings.
8. Loose, bulging, or buckled stucco or fresh cracking along the sill plate line, as well as evidence indicating possible relative movement between framing and foundation.
9. Stucco cracks are greater than 1/8-inch wide or spalling that has exposed wire mesh reinforcing.

10. Evidence of detachment or delamination of stucco from the framing (as determined by visual observation or feel of looseness).
11. The house is taller than one story and has one or more open exterior wall lines in the first story with visible damage.

5.1.3 Where to Look: Interior Walls

1. At the corners of door and window openings.
2. At doors and windows, check for squareness and plumbness of opening.
3. Check for signs of sliding at the base of interior walls at door openings, archways, and the ends of walls.

5.1.4 What to Look For: Interior Walls

If any of the following conditions exists, a technical consultant may be needed.

1. Fresh cracking, buckling, or detachment of the interior plaster or drywall.
2. Signs of walls racked out of square (e.g., jammed doors, jammed or broken windows).
3. Walls tilted out of plumb (either full-height walls or cripple walls).
4. Signs of movement or sliding of interior partitions relative to the floor.
5. Pattern of cracking that extends from the floor slab through the wall.
6. Severe cracking, separations, or offsets at building irregularities.
7. The walls are racked visibly out of plumb, or doors or windows have been rendered inoperable by the earthquake due to their openings being racked out of square (excluding patio doors and closet doors that have come off their tracks or doors or windows rendered inoperable due to hardware failure or impact damage).
8. Gypsum wallboard or lath is bulging, loose, or has detached from the framing.
9. Nails have pulled through the edges of gypsum wallboard or there is a pattern of numerous nail pops.
10. Interior finish cracks are wider than 1/8 inch or occur at locations away from panel joints or the corners of door or window openings.
11. Fresh water damage to interior wall finishes due to rain or plumbing leakage within walls or ceilings.

5.1.5 Repair Guidelines

Structurally insignificant earthquake damage can be addressed as described in Section 5.8.

5.2 Overview

Wall surface materials or sheathing are among the first components of a wood-frame house to sustain damage in an earthquake. The severity of damage can range from cosmetic cracking, which is common and widespread, to structural damage, which is uncommon outside areas of intense ground shaking. Absent conspicuous visible damage, earthquake-induced damage to the underlying framing is highly unlikely. Because wall surface materials often have the structural role of laterally bracing the structure, careful inspection for indicators of possible structurally significant damage is essential. If indicators of possible structurally significant damage are found, a structures specialist should be retained to inspect the house. If indicators of potential structurally significant damage are not found, damage to wall surfaces should be considered cosmetic and repaired in accord with the guidelines presented in Section 5.8.

Cracking of wall surface materials due to non-earthquake causes is extremely common, especially in stucco. It is important to distinguish between earthquake-induced cracking and pre-existing cracking due to other factors, as discussed in Section 5.5.

In many situations, wall repair consists of patching and repainting the wall surface material. More severe damage may require installation of additional fasteners between the wall sheathing and the framing, localized removal and replacement of sheathing, removal and replacement of sheathing over the length of one or more walls, or installation of code-triggered upgrades to the seismic-force-resisting system of the building. Repairs other than those described in Section 5.8 should be done in accord with recommendations of a structures specialist's report.

5.3 Limitations

This chapter addresses only walls of conventional wood-frame construction covered on at least one side with stucco, lath and plaster, or drywall. It also applies to conventional wall elements with wood board sheathing, plywood, or oriented strand board (OSB) beneath the finishes. This chapter does not apply to the following:

- unconventional buildings characterized by unusual wall configurations, open plans with few room partitions, open exterior wall lines with little or no length of solid wall, or buildings containing steel frames,
- walls of brick, concrete block, or stone masonry (except for veneer over wood framing),
- adobe or log construction, or
- exterior wall finish materials other than conventional Portland cement stucco (such as exterior insulation and finish systems; wood, aluminum, or vinyl siding; or wood or cement-asbestos shingles)

5.4 Description of Typical Construction

The overwhelming majority of California houses have walls consisting of wood 2×4 vertical studs (which actually measure 1 1/2 inches by 3 1/2 inches in modern construction) spaced at 16 inches with structural sheathing or a nonstructural finish applied to each face, as illustrated in Figure 5-1 and Figure 5-2. The framing typically includes diagonal bracing or blocking beneath the sheathing. Newer houses, especially two-story houses, can be expected to have wood-structural-panel sheathing (plywood or OSB) beneath a finish of stucco, siding, or stone veneer. Where present, plywood or OSB provides the structural bracing to resist lateral loads and the stucco, drywall, and plaster serve only as nonstructural finishes. Accordingly, repairs to the finishes may be nonstructural. Typical exterior sheathing materials include stucco and panel siding (plywood or hardboard). Some houses have decorative areas of brick or stone masonry veneer. Less common (at least in California) exterior finish materials include cedar shingles, vinyl or aluminum siding, wood board-and-batten siding, and full-brick or stone-masonry veneer. In most cases, building paper is installed behind the exterior finish as a second line of defense against rainwater entry into the wall cavity.

Conventional stucco is typically a 7/8-inch thick layer of Portland cement plaster reinforced with wire mesh that is sprayed or troweled onto the wall in three layers and cures to a hard, durable finish, as illustrated in Figure 5-3. The three layers are termed scratch, brown, and finish or color coat. Stucco may be applied to open framing or over wood sheathing. Where applied to open framing, regularly spaced line wire is stretched across the framing to provide temporary support for the building paper during the application of the scratch coat of stucco. Wire mesh nailed or stapled to the wall framing or sheathing provides both reinforcement of the cement plaster and attachment of the stucco to the building.

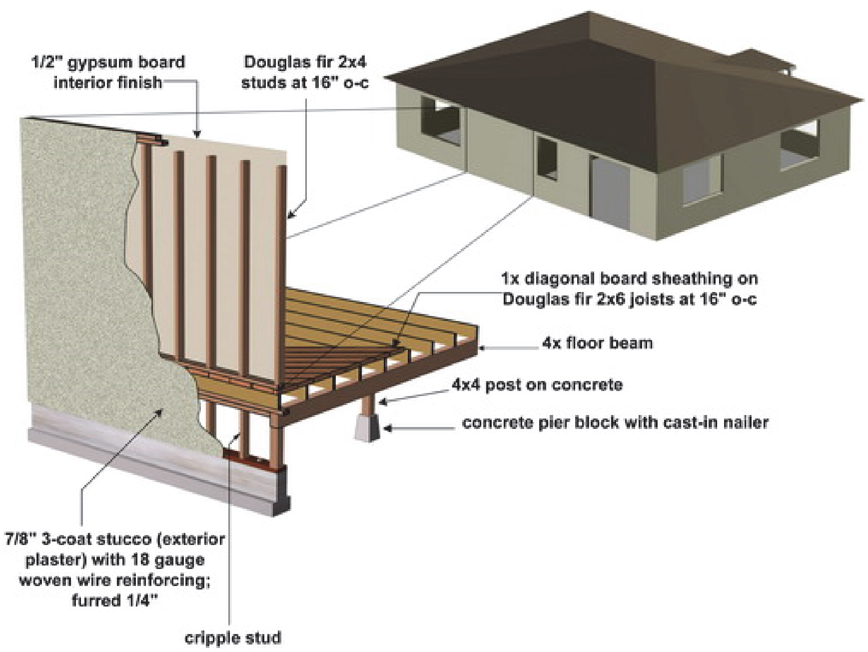


Figure 5-1 Typical wall construction for older single-story houses in California—sheathing materials may vary (image credit: CUREE).

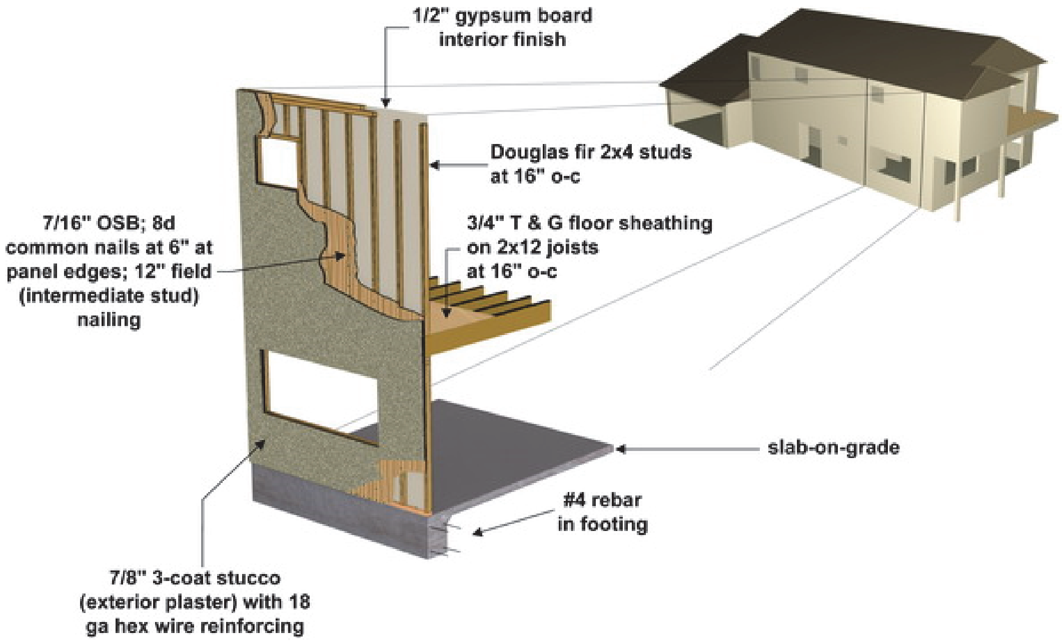


Figure 5-2 Typical wall construction for more modern two-story houses in California—sheathing materials may vary (image credit: CUREE).

Figure 5-3 Mock-up of typical three-coat stucco showing building paper, wire lath, scratch coat, brown coat, and finish or color coat (photo credti: Exponent).

Typical interior finishes are plaster in older homes and drywall in newer homes. Plaster in most houses built since the mid-1930s is applied over gypsum lath nailed to the studs (also called buttonboard); although in older houses (through the early twentieth century) wood lath was used. Ceramic or stone tile commonly found in bathtub and shower surrounds is typically applied over a lath and mortar base in older homes, whereas various panel substrates are used in newer construction. Decorative plywood, hardboard, or solid-wood paneling are used occasionally and are generally applied over drywall or plaster.

Walls serve several functions. As aesthetic elements, most walls are finished or decorated. As nonstructural elements, exterior walls protect the living space from the elements, and interior walls subdivide the living space. As structural elements, some walls support the weight of the roof or upper stories (bearing walls), and most walls serve to resist lateral forces from wind and earthquakes.

In addition to cosmetic effects, damage to a wall can affect its structural strength, stiffness, or stability and can also compromise its function as a weather-resisting building enclosure or as an architectural partition. As relatively stiff and brittle materials, drywall, plaster, and stucco are the wall components most susceptible to distress, even from causes other than earthquakes. By contrast, the underlying wood framing is quite flexible and is unlikely to sustain serious damage in the absence of significant conspicuous damage to wall finish materials. Accordingly, this chapter focuses on the brittle sheathing and finish materials.

5.5 Non-Earthquake Sources of Damage

Walls are subject to multiple types and sources of damage and distress during their service life, much of which goes unnoticed or is routinely repaired. This section describes conditions commonly found in stucco, plaster, and drywall, as well as in doors and windows, in the absence of earthquakes.

As discussed in Chapter 3, differential foundation movement is a common cause of wall cracks and operational problems in doors and windows. Due to their brittle nature, wall finish materials are sensitive to minor foundation movements, either settlement or heave. Soils in many areas of California are expansive, which results in swelling or shrinking with changes in soil moisture that can be related to seasonal rainfall, irrigation, plumbing leaks, improper drainage, or simple changes in drainage patterns. This soil movement causes distortion and cracking, generally in the form of diagonal cracks extending from the corners of door and window openings, and misalignment of doors and windows. These effects are often seasonal and cyclical (e.g., doors and windows may bind during one season but operate freely during other seasons). Fill settlement and creep of hillside soils have similar effects but do not exhibit cyclic seasonal variations. A common characteristic of cracking related to differential foundation movement is a unidirectional pattern of diagonal cracks in wall finishes, especially around openings (i.e., diagonal cracks only at one pair of diagonally opposite corners around a window), as illustrated in Figure 5-4. The cracking will be concentrated above the areas of greatest differential foundation movement.

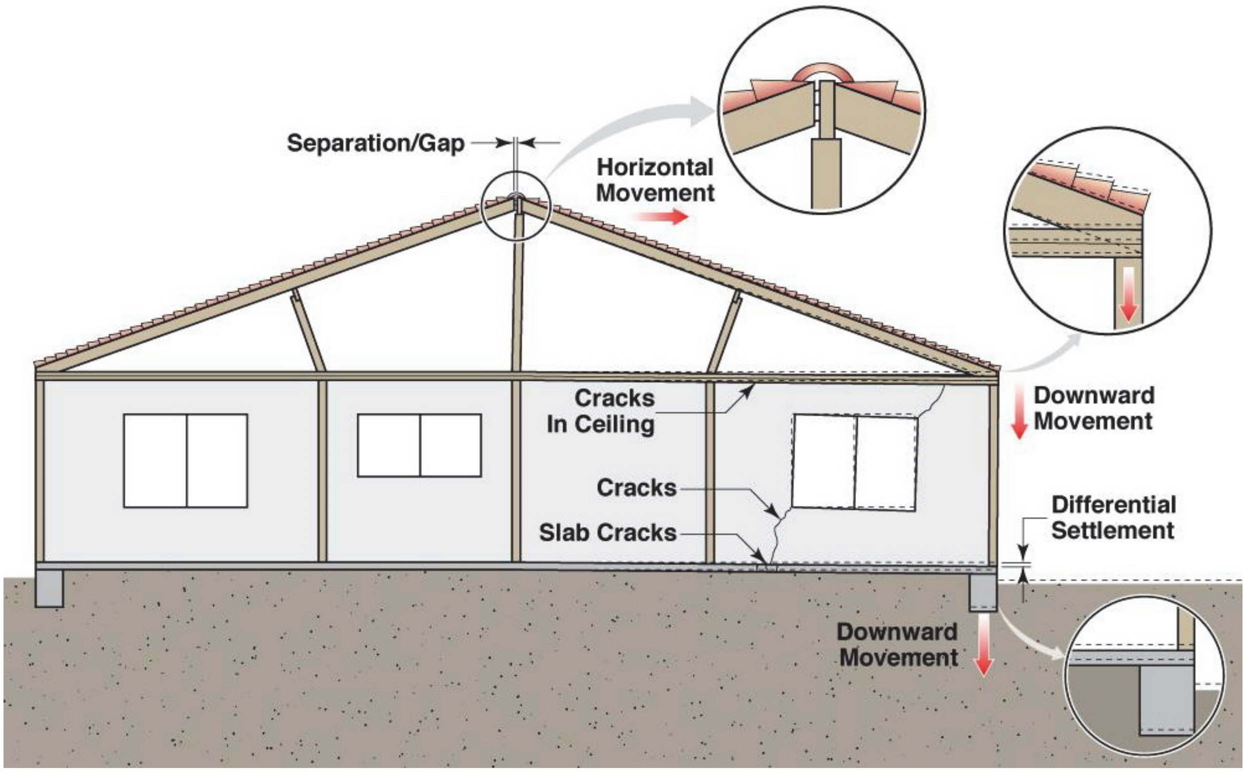


Figure 5-4 Illustration of common effects of differential settlement (image credit: Exponent).

5.5.1 Stucco

- Drying shrinkage: Like concrete, stucco shrinks slightly as it dries and invariably cracks to some degree. The degree of visible shrinkage cracking is largely dependent upon workmanship, the amount of water in the stucco mix, and the amount of time the first two layers are allowed to cure and dry prior to application of the finish layer. The thin finish layer, often called the "color coat," is typically pigmented with color so that painting is not required. There are four typical patterns of shrinkage cracks:
  - Diagonal cracks extending from the corners of door and window openings, as shown in Figure 5-5. Where openings are close together, cracks will tend to extend from the corner of one opening to the next, rather than extending diagonally.
  - Semi-random, semi-orthogonal pattern (i.e., a grid work) of cracks in portions of walls without openings, as shown in Figure 5-6. This pattern can often be seen when the thin finish coat is sandblasted during the course of a cosmetic renovation.
  - Roughly linear vertical cracks regularly spaced at about 16-inch intervals along the wall corresponding to the underlying studs, as shown in Figure 5-7. This pattern is due to uneven application of the stucco: thick between the studs but thin (and therefore prone to cracking) where the studs provided a rigid backing during application.
  - A pattern of thousands of very fine, interconnected cracks (known as crazing) that develops on the surface of the stucco and is most commonly visible on unpainted, smooth finished stucco, as shown in Figure 5-8.

Figure 5-5 Diagonal non-earthquake shrinkage cracks extending from the corners of a wall opening in stucco (photo credit: Exponent).

Figure 5-6 Semi-random, semi-orthogonal grid work of non-earthquake shrinkage cracks in stucco—the cracks are highlighted by patching material applied in the course of repainting the building (photo credit: Exponent).

Figure 5-7 Roughly linear vertical non-earthquake shrinkage cracks corresponding to the locations of underlying studs; crack locations have been highlighted with parallel lines of blue chalk (photo credit: Exponent).

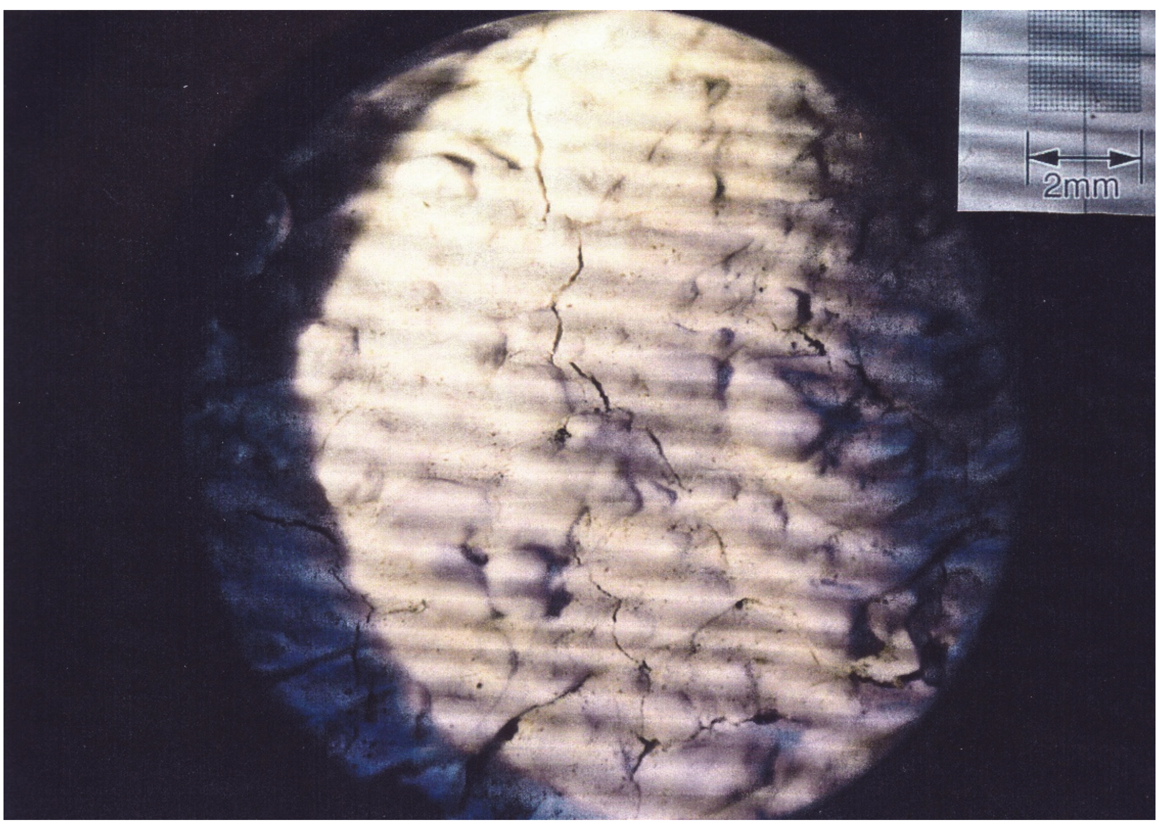


Figure 5-8 Magnified non-earthquake crazing cracking in stucco—circle is 5/8-inch across; bumps are grains of sand in stucco texture (photo credit: Exponent).

- Thermal expansion and contraction: Stucco also expands and contracts slightly with changes in temperature, which causes additional cracking and causes patched cracks to reappear. For this reason, in California, it is common to see more cracking in stucco located on south- and west-facing walls than in north- and east-facing walls.
- Seasonal shrinking and swelling: Houses with shallow foundations on expansive soils will experience stresses due to seasonal shrinking and swelling of the soil. These seasonal movements can cause preexisting stucco cracks to open and close and repaired cracks to reopen.
- Sill line cracking: For houses built in California prior to the early 1970s, it was common practice to extend the stucco seamlessly down over the concrete foundation to the ground surface (Figure 5-9). Due to a variety of factors, a horizontal crack often develops in the stucco along the line between the wood-frame superstructure and the concrete foundation—the sill line. In newer houses, a sheet-metal weep screed eliminates this crack because the stucco is not continuous over the wood-concrete interface.
- Construction and control joints: These are intentional discontinuities or planes of weakness built into the stucco, either as a result of additions to the building or attempts to control cracking. Well-defined linear cracks result. Sometimes, inattention to crack control will lead to a crack where a control or construction joint should have been installed. Control joints are uncommon in residential stucco.
- Framing movement: Wood-frame members used in residential construction are often “green” (i.e., wet), especially in California. If stucco is applied to the wood framing before it reaches a dry state, stresses will develop and cracks or bulges can develop in the stucco. Because wood shrinkage and warping are most pronounced in larger members, cracks are most likely in headers over wide doors and windows and beams that support walls in the story above.
- Construction sequence effects: Stucco manufacturers recommend that upper stories should be built and heavy roof tiles should be loaded into place before the stucco is applied to the first-story walls. Otherwise, the additional strains caused by the weight of the upper stories and roof can crack the brittle first-story stucco.
- Improper installation of wire lath: Proper embedment of continuous wire lath reinforces the stucco and is essential for satisfactory performance. If the wire lath is not properly furred out from the substrate or if adjacent pieces of lath are not properly lapped, excessive cracking will develop.

Figure 5-9 Stucco terminated at weep screed on mudsill of recent addition at the right side of the image juxtaposed with stucco extended down onto the original foundation at the left side of the image (photo credit: Exponent).

5.5.2 Plaster

- Seasonal shrinking and swelling: Plaster in houses constructed with shallow foundations placed upon expansive soils can be subjected to stresses due to differential distortion due to seasonal shrinking and swelling of the foundation soils. These seasonal movements can cause preexisting cracks to open and close and repaired cracks to reopen.
- Framing movement: Wood-frame members used in residential construction are often green, especially in California. If plaster is applied to the wood framing before it reaches a dry state, stresses will develop resulting in cracks or bulges developing in the plaster. Because wood shrinkage and warping is most pronounced in larger members, cracks are most likely in headers over wide doors and windows and beams that support walls in the story above.
- Construction and control joints: These are intentional discontinuities or planes of weakness built into the plaster, either as a result of additions to the building or attempts to control cracking. Well-defined linear cracks result. Sometimes, inattention to crack control will lead to a crack where a control or construction joint should have been installed.

5.5.3 Drywall

- Seasonal shrinking and swelling: Drywall in houses constructed with shallow foundations placed upon expansive soils can be subjected to stresses due to differential distortion due to seasonal shrinking and swelling of the foundation soils. These seasonal movements can cause preexisting cracks to open and close and repaired cracks to reopen.
- Framing movement: Wood-frame members used in residential construction are often green, especially in California. If drywall is applied to the wood framing before it reaches a dry state, stresses will develop and cracks or bulges can develop in the drywall. Corner bead cracks and separation often occur at the bottom of large beams or headers as a result of shrinkage of the beam relative to the non-shrinking drywall. Cracking due to framing movement and shrinkage is most common:
  - around window headers,
  - at drywall returns or jambs at windows,
  - at large headers over wide door and window openings,
  - at large beams or posts,
  - in stairwells,
  - at the juncture between interior partitions and ceilings attached to the bottom of prefabricated wood trusses, and
  - at the apex of cathedral ceilings.
- Gaps: Minor gaps are common where drywall abuts exposed framing, such as exposed wood beams. The source of the gaps is a combination of construction imperfections and shrinkage of the exposed framing members. At exposed large beams, twisting, splits, and checks running along the length of the beam are a natural phenomenon of the drying process of the beam and are generally not an indication of a structural problem. These conditions are not the result of an earthquake.
- Nail pops: If wood framing dries and shrinks after drywall installation, or if the drywall nails or screws are not drawn tight, the fastener head will, in time, cause a circular crack or a slight bump in the finish over the fastener, as shown in Figure 6-7. Nail pops generally occur in random locations (unless one part of the house was subject to the poor workmanship of a single drywaller during construction).

5.5.4 Ceramic and Stone Tile

- Cracking of isolated tile at reentrant corners, and cuts for plumbing are common.
- Cracking of grout lines at wall corners and at the juncture with tubs, shower pans, and floors is common due to minor shrinkage and thermal movements.
- Deterioration and decay of underlying framing from water leakage is common in walls and floors around showers and bathtubs.

5.5.5 Doors and Windows

Doors and windows require close alignment for proper operation. In addition to differential foundation movement discussed previously, poor construction quality, framing shrinkage, wood swelling, thermal expansion, and loose or deteriorated hardware can contribute to operability problems with doors and windows. Planed doors and heavily grouted windows are a good indication that a house has experienced pre-earthquake settlement.

5.5.6 Wood Trim

Gaps, separations, and openings in the joints of wood trim can result from poor workmanship, cracking of paint that once concealed a gap, or shrinkage of wood trim itself. It can also result from differential foundation movement or shrinkage of the wood framing.

5.6 Earthquake-Induced Damage

Stucco, plaster, and drywall are among the first components of a wood-frame house to sustain damage in an earthquake. The severity of damage can range from cosmetic cracking, which is common and widespread, to extensive cracking and delamination of the wall sheathing materials. Earthquakes generate lateral forces in buildings that cause walls to rack back and forth. Those forces can also cause walls to slide if they are not securely attached to the foundation. In the vast majority of cases, damage is confined to the wall finishes and sheathing, and damage to the underlying framing is uncommon. Wall surfaces can also be locally damaged by impact from contents, mechanical equipment, or collapsing fences or chimneys.

A key characteristic of earthquake-induced wall cracking is a symmetric pattern of diagonal cracks in wall finishes with similar diagonal cracks radiating from all four corners of window openings, as illustrated in Figure 5-10. Cracking will typically be present in similar locations on both faces of a wall, inside and outside in the case of perimeter walls, and for most multi-story residential buildings, larger and more concentrated in the lowest story, as shown in Figure 5-11.

A key indicator of the severity of damage to walls is the degree of racking in the wall. Little or no racking indicates, in most cases, an absence of structurally significant damage. Racking that results in broken window glass or impairs the operation of doors or windows indicates the possibility of structural damage and the need for evaluation by a structures specialist.

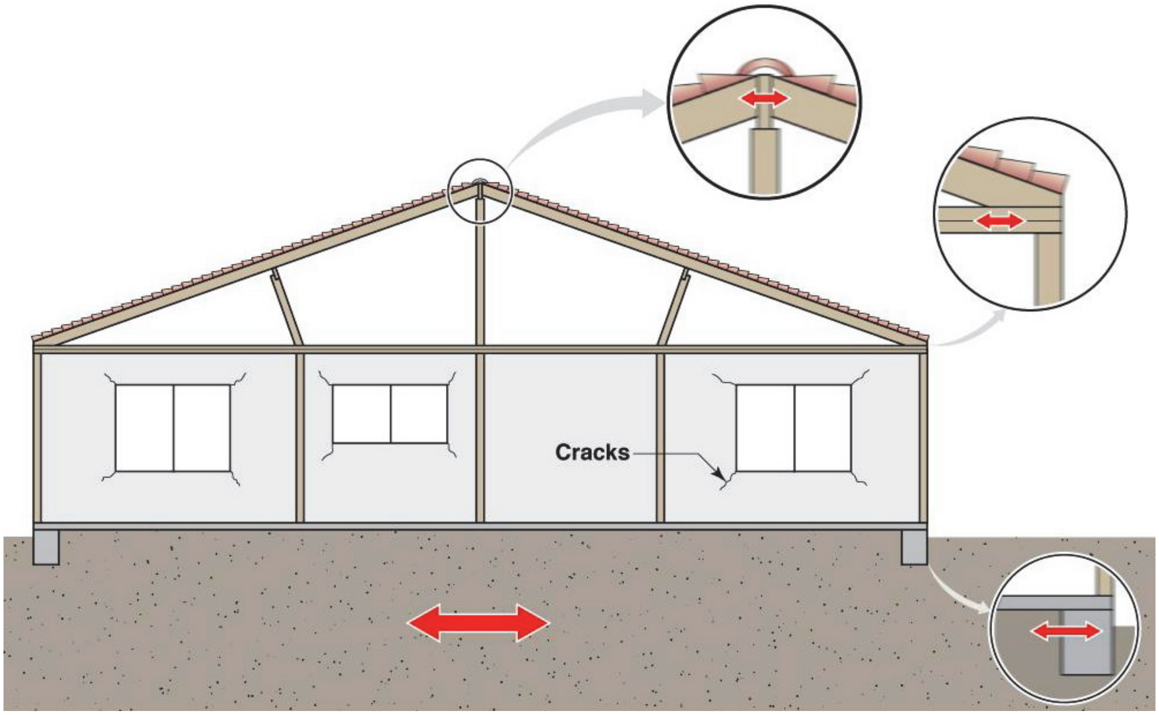


Figure 5-10 Typical crack pattern in wall finishes due to minor earthquake shaking (image credit: Exponent).

Figure 5-11 Severity of earthquake-induced cracking of wall finishes of multi-story buildings generally decreases at upper stories (photo credit: Exponent).

5.6.1 Stucco

Diagonal cracks at door, window, and vent openings are the first stucco cracks to form (assuming an absence of shrinkage cracks) in an earthquake. The extent of this cracking may be indistinguishable from normal temperature and shrinkage cracking. With stronger ground shaking, the diagonal cracks widen, spalling of stucco along cracks can occur (Figure 5-12), and “X” cracks (Figure 5-13) can form in stucco panels between window openings. Figure 5-14 illustrates the relationship between cracking and racking of a laboratory specimen of a wood-frame wall sheathed with stucco and drywall. If the shaking is strong enough, the stucco attachments can be damaged, and the stucco panels can detach in sheets from the wood framing. This failure mode, called delamination, is most likely in long stiff wall lines with few openings or in solid segments of walls between full-height openings, such as doors, as shown in Figure 5-15. It generally begins as detachment from the sill plate along the base of the wall. Walls where the stucco mesh was not fastened to the sill plate are especially vulnerable to this mode of failure.

Figure 5-12 Severe cracking and spalling of stucco wall test specimen after earthquake load testing (photo credit: Exponent).

Figure 5-13 Earthquake-induced "X" cracking between windows in stucco panels with a thin brick veneer (photo credit: Exponent).

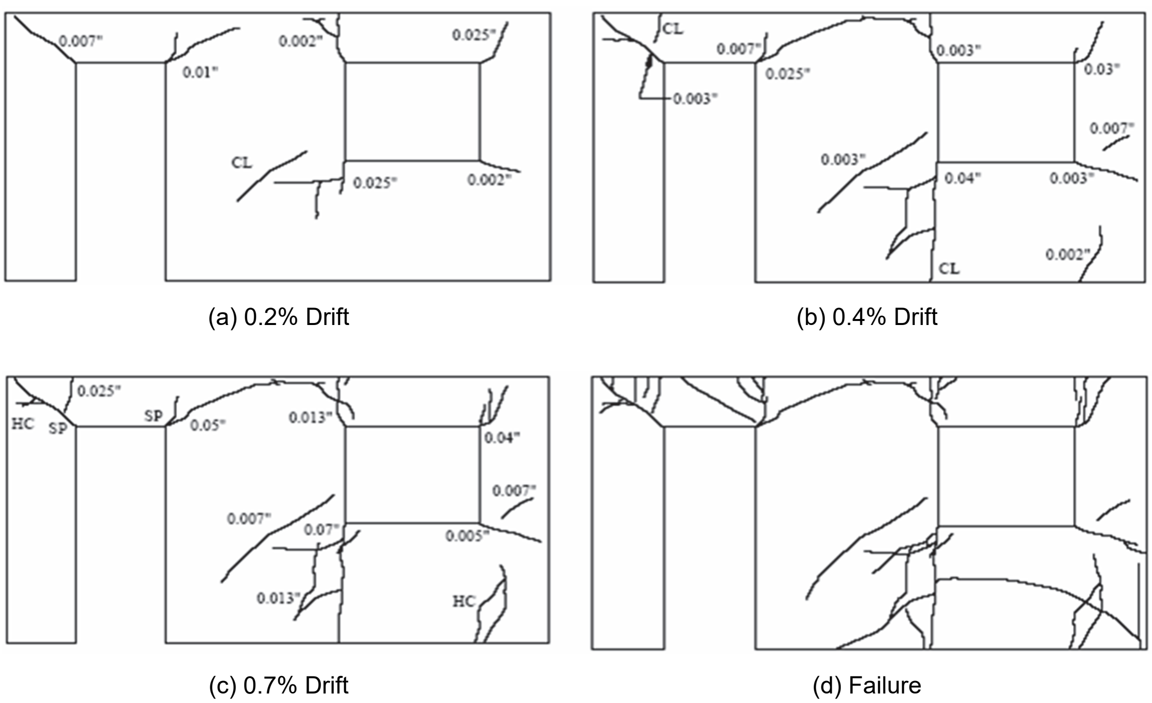


Figure 5-14 Relationship between seismic drift (racking) of wall and cracking of stucco finish of laboratory test specimen. Here, the "drift" is measured as the ratio of the lateral movement divided by the wall height (image credit: CUREE).

Figure 5-15 Earthquake-induced delamination of stucco from wood framing and associated damage to aluminum door frame (photo credit: Exponent).

The building paper beneath the stucco finish is more flexible and less brittle than stucco. Post-earthquake inspections of garages, crawlspaces, and other areas where the backside of the stucco wall is exposed have shown that the stucco can crack without affecting the building paper or the wood framing. Therefore, if the stucco itself is repairable and the repair is confined to treatment of the individual cracks, hidden damage to the building paper or studs is extremely unlikely, and removal of stucco for inspection is generally not necessary.

Stucco that extends down over the concrete foundation is susceptible to cracking along the sill plate line, as shown in Figure 5-16. Fresh cracking that is continuous around the building with signs of relative movement between the superstructure and the foundation is cause for assessment by a structures specialist. Care should be taken to differentiate between cracking caused by the earthquake and non-earthquake related cracking at this location as discussed above. Inspectors should look along the sill plate and at wall ends for consistent offsets exceeding 1/4 inch that would indicate sliding of the wall line on its foundation. In multi-story houses, especially those built over crawlspaces, buckling of the stucco will occasionally occur just above the sill plate line, as shown in Figure 5-17.

Figure 5-16 Earthquake-induced crack in stucco at sill line where stucco was extended down over the foundation (photo credit: Exponent).

Figure 5-17 Earthquake-induced cracking and buckling of stucco at the sill line where stucco was extended onto the perimeter concrete stemwall (photo credit: Exponent).

5.6.2 Drywall

The first earthquake-related cracks to form in drywall usually occur at the corners of door, window, and vent openings; along taped joints near those openings; and at locations of previously patched cracks. As the strength of shaking increases, these cracks will extend in length and width, and cracks can form along corner beads, interior wall corner joints, wall-to-ceiling joints, or tape joints between drywall sheets (Figure 5-18). Nail pops can form along the edges of a wall, especially near the ceiling. With stronger shaking, the diagonal cracks widen, and "X" cracks can form, particularly at panels between windows. In severe shaking, it is possible for drywall to detach from the framing.

Figure 5-18 Earthquake-induced cracking of drywall as a result of strong shaking (photo credit: Exponent).

5.6.3 Gypsum Lath and Plaster

Plaster is like weak stucco, while gypsum lath is panelized, similar to drywall. Earthquake damage patterns in a lath and plaster system are thus combinations of those typical of stucco and drywall. The first earthquake damage to appear usually includes diagonal cracks at the corners of door and window openings. With more intense shaking, the plaster will generally crack and spall along the lath panel joints, often in a stair step pattern, as shown in Figure 5-19. In severe shaking, detachment of the lath from the framing is possible.

Wood lath found in older houses is not panelized like gypsum lath. Typical damage patterns in plaster over wood lath are closer to those of weak stucco than those in panelized gypsum lath.

Figure 5-19 Earthquake-induced cracking and delamination of gypsum lath and plaster (photo credit: Exponent).

5.6.4 Ceramic and Stone Tile

Earthquake damage patterns in ceramic and stone tile wall finishes are similar to those of other wall finishes, as shown in Figure 5-20. Diagonal cracking of tile or stair step cracking of grout lines at reentrant corners around wall openings (if present) and cracking of grout lines at wall corners and wall-floor intersections are most common.

Figure 5-20 Earthquake-induced cracking of ceramic tile (photo credit: Exponent).

5.6.5 Doors and Windows

Earthquake damage to doors and windows occurs when their openings are racked out of square. Thus, the performance of doors and windows depends on the lateral resistance and overall performance of the building. Damage to doors and windows is typically accompanied by distress to the adjacent walls. Without typical cracking in adjacent wall elements, no damage to the doors or windows would be expected. In strong shaking, misalignment of door or window hardware or minor permanent racking of the openings could occur. Severe shaking can cause permanent racking of the openings, broken window glass, damage to hardware, and damage to the actual door or window unit, rendering it inoperable.

Doors and hinged windows (especially casement windows) are sensitive to permanent racking of their openings and can serve as good indicators of any permanent racking of the wall. A consistent pattern of impaired operation of doors or hinged windows, accompanied by damage to the adjacent or aligned walls, can be indicative of earthquake-induced racking of the building and warrants evaluation by a structures specialist.

5.7 Assessment Guidelines and Methodology

Initial inspection of wall elements consists primarily of visual examination of the patterns and details of visible cracks. In addition, checking for delamination is necessary to confirm that sheathing materials remain tightly attached to the wood-stud framing. The operation of doors and windows should also be checked, looking for damage consistent with observed wall cracks. The following subsections describe detailed observations that may be made. However, the most important aspect of the visual examination is assembling the *pattern* of damage from those details. For example:

- Are there diagonal cracks radiating from all four corners of all window openings in both the interior and exterior wall finishes of a wall?
- Is there conspicuous cracking of the wall finishes at the corners of visibly out-of-square openings?
- In multi-story buildings, is the cracking more severe on the lowest story?

5.7.1 Exterior

A thorough exterior inspection should include examination of all elevations of the building. Areas of cracking should be documented and photographed. If no cracking is observed, this also should be documented and photographed. Absent obvious signs of previous patching or paint within a crack, it is sometimes difficult to distinguish minor earthquake-related stucco cracks from non-earthquake cracks. If the plaster or drywall finishes on the interior face of the wall also exhibit a pattern of earthquake-induced cracking, it is reasonable to conclude that the earthquake caused much of the observed exterior stucco cracking. If the interior finishes are undamaged, earthquake shaking is likely not the predominant cause of the stucco cracking, even if it might have worsened pre-existing cracks enough to make them visible.

All exposed wall surfaces should be carefully observed through close visual inspection, where safely accessible (a pair of binoculars or a drone allows inspection of the upper portions of multi-story houses without ladder work). Check for the following damage patterns and document their location and severity:

- Racking or leaning of the building.
- Window or door openings racked out of square.
- Separation between different portions of buildings, such as where roofs or floors are discontinuous (e.g., in a split-level house), or where the main house attaches to a garage, addition, porch, or other building wing.
- Cracking, particularly adjacent to wall openings, at reentrant corners, along the sill line (Figure 5-21), and around the exterior of the fireplace or chimney.
- Bulging or buckling of the stucco or wall finishes, as shown in Figure 5-21.
- Detachment of the stucco from the framing, using visual inspection and checking for delamination where the studs are exposed (e.g., inside the garage, as shown in Figure 5-22) and along exposed edges of the wall surface materials or sheathing (e.g., along the sill line and at door openings). A mirror is useful for examining the bottom edge of the stucco. Hand pressure or hand pull along the bottom edge of the stucco can also be used to feel for any detachment from stud framing.

Figure 5-21 Earthquake-induced stucco cracking and buckling at a cripple wall (photo credit: Exponent).

Figure 5-22 Earthquake-induced racking and delamination of stucco as viewed from the interior of a wall within a garage. Arrows point to nails that have pulled through (photo credit: Exponent).

If all of the following conditions are true, then any earthquake damage may be judged structurally insignificant and may be repaired as discussed in the following subsection:

- The building is plumb.
- Stucco has not become detached from framing.
- All fresh cracks are located at corners of openings or wall discontinuities and are no more than 1/8-inch wide, and there is no spalling of stucco that exposes the wire mesh reinforcing.

If any of the following conditions exists, an evaluation by a structures specialist may be warranted:

- The walls are racked visibly out of plumb, or doors or windows have been rendered inoperable by the earthquake due to their openings being racked out of square (excluding patio doors and closet doors that have come off their tracks, or doors or windows rendered inoperable due to hardware failure or impact damage). Look for wear patterns on the floor as an indication of previous damage from an unlevel door.
- The stucco has developed cracks wider than 1/8 inch, particularly if they extend across the full width of a wall section between door or window openings.
- There is loose, bulging, or buckled stucco or fresh cracking along the sill plate line and evidence indicating possible relative movement between framing and foundation.
- Any cracks are greater than 1/8-inch wide or spalling has occurred that has exposed wire mesh reinforcing.
- There is evidence of detachment or delamination of stucco from the framing (as determined by manual inspection).
- The house is taller than one story and has one or more open exterior wall lines in the first story with visible earthquake damage.
- The building configuration, location, or damage state fall under criteria adopted by the local building department that require an assessment by a structures specialist.

Perfectly Plumb?

Neither structures nor components of structures are built perfectly plumb. Construction tolerances for wall plumbness can be on the order of 1/4 inch over an 8- or 10-foot wall height. Distinguishing between an out-of-plumb condition associated with earthquake damage to surrounding wall finish materials and normal construction imperfections is essential to proper evaluation of potential earthquake damage. Lack of plumbness in the absence of other earthquake damage is generally indicative of construction imperfection and does not generally warrant engineering assessment or repair.

5.7.2 Interior

The inspection should include a thorough interior inspection involving a room-by-room examination of wall and ceiling finishes. Areas of cracking should be documented and photographed. If no cracking is observed, this also should be documented and photographed. Absent obvious signs of previous patching or paint within a crack, it is sometimes difficult to distinguish minor earthquake-related plaster and drywall damage from non-earthquake cracks.

All exposed wall surfaces should be carefully observed, with manual inspection (hand pressure to feel for any sheathing detachment from stud framing) where safely accessible. Careful observation and attention to detail are essential. Wallpaper, paneling, and veneer can hide much of the minor cracking typical of both pre-earthquake and earthquake-related causes. Structurally significant damage can tear wallpaper and buckle or detach paneling. Still, where these finishes are present, the inspector should not rely on visual inspection alone, but should feel for loose paneling or bulging plaster beneath the wallpaper, especially at the corners of door and window openings. Check for the following damage patterns, and document their location and severity:

- Cracks or bulges in wall and ceiling finishes: If wall surfaces are finished with wallpaper, feel along the corners of openings for any bulges or tears in the underlying wall finish.
- Fresh separations between the wall and the floor (Figure 5-23) or between the wall and the ceiling.
- Differential movement or separation around the fireplace.
- Interior wall surface cracks aligned with cracks in the perimeter foundation or exterior stucco.
- Damage from falling or shifting contents or mechanical equipment.
- Window or door damage, including general condition and wear, squareness of opening, smoothness of operation, and evidence of pre-earthquake condition.
- Plumbness of doorjambs: Use a digital level to check plumbness and levelness of doorframes. If out of plumb, note direction of tilt and check for a pattern of tilts and associated cracking of surrounding wall finishes throughout the house.

If both of the following conditions are true, then any earthquake damage may be judged structurally insignificant and may be repaired as discussed in the following subsection:

- Where finish cracking is present, there is no pattern of racking of walls or wall openings of more than 0.2 degrees (i.e., 3/8 inch over 8 feet) from plumb.
- All interior finish cracks are no wider than 1/8 inch and are located in areas of expected earthquake damage (e.g., corners of openings, wall discontinuities, drywall joints).

If any of the following conditions exists, assessment by a structures specialist may be warranted:

- The walls are racked visibly out of plumb, or doors or windows have been rendered inoperable by the earthquake due to their openings being racked out of square (excluding patio doors and closet doors that have come off their tracks or doors or windows rendered inoperable due to hardware failure or impact damage). Look for wear patterns on the floor as an indication of previous damage from an unlevel door.
- Gypsum wallboard or lath is bulging, loose, or has detached from the framing.
- Interior finish cracks are wider than 1/8 inch and fall outside of the damage patterns listed in Table 5-1.
- The house is taller than one story and has one or more open exterior wall lines in the first story with visible earthquake damage.

Figure 5-23 Earthquake-induced displacement of an interior partition due to inadequate attachment to floor slab (photo credit: Exponent).

5.7.3 Technical Consultant Assessment

Assessment by a structures specialist should include detailed visual inspection of interior and exterior wall finishes, manual testing or probing, and measurement (and sometimes mapping) of cracks. Based on findings of that non-destructive assessment, the structures specialist may recommend destructive investigation. Destructive investigation may be necessary in those instances when the structures specialist is unable to rule out or reasonably assume the existence of concealed earthquake damage based on the non-destructive assessment.

If the building was constructed prior to 1980 and repair work will involve disturbance (e.g., demolition, removal, grinding, sanding) of any of the following types of wall finishes, a suitably qualified environmental consultant should be retained.

- Wall materials that may contain asbestos include:
    - gypsum joint compound (drywall "mud"),
    - interior plaster,
    - exterior stucco, and
    - asbestos-cement siding.
- Wall materials that may contain lead-based paint consist of enamel paint applied to:
    - doors, windows, and trim,
    - kitchen and bathroom walls and cabinets, and
    - exterior metals.

As discussed in Section 9.2.4, the consultant should test for the presence of regulated hazardous materials and, if the results of the tests are positive, recommend appropriate abatement and waste disposal measures.

5.7.4 Establishing the Cause of Cracks

In addition to details of individual cracks, the pattern of cracking provides an excellent indication of the source, cause, and age of cracks in wall sheathing. Shrinkage cracks occur at planes of weakness or emanate from openings or reentrant corners. Initial earthquake-induced cracking of wall finishes also occurs at these locations, so distinguishing between the two causes is not always easy. Where cracks appear consistently at corners of multiple openings in both the interior and exterior finishes of a given wall line, the cracks are, absent indicators to the contrary, most likely earthquake induced. More random cracking or cracking that occurs in only the exterior or interior finish is likely due to non-earthquake causes. Earthquake-induced cracking should be reasonably consistent over the length of any given wall line, as illustrated in Figure 5-10. Cracking confined to only a portion of the building may be due to non-earthquake causes. For example, cracking caused by differential settlement is associated with changes in floor slopes and generally occurs, or is much more pronounced, in one portion of the building, as illustrated in Figure 5-4. If there are signs of earthquake-induced permanent ground deformation at the site and a technical consultant concludes that the earthquake caused differential foundation movement, then the associated cracking of wall finishes is likely earthquake related. Otherwise, highly localized cracking of wall finishes is likely related to non-earthquake causes. Very straight vertical cracks indicate a construction joint, a control joint, or an addition to the building. Very straight horizontal cracks can indicate a location of poorly lapped wire mesh; such a location is likely to attract shrinkage cracking. Cracks in the shape of a "T" are generally not caused by earthquakes. These are commonly found in exterior stucco and are usually caused by shrinkage (Figure 5-24).

Figure 5-24 Photo of "T"-shaped cracks in stucco. Dark lines added for emphasis (photo credit: D. Dyce).

The most reliable indicator of an earthquake contribution to an observed wall crack is the presence of corresponding earthquake damage to doors, windows, and adjacent cosmetic finishes that would otherwise be operable and well maintained. Absent any corresponding damage, the age of cracks can often be determined by visual examination of the crack surfaces. Visible indicators are most reliable in the weeks immediately following the earthquake and become less so as time passes, cracks weather, repairs are made, and other events intervene to obscure fresh damage.

Characteristics of cracks that provide clues as to whether the cracks are fresh or caused by a long-term condition include:

- Contamination of crack surfaces: Fresh cracks exhibit clean fracture surfaces free of paint.
- Grout, caulk, or other patching or repair material in the crack, or other evidence of past repair, such as drywall tape.
- Dirt, dust, or other debris in the crack.
- Sharpness of the crack edge: Fresh cracks exhibit sharp edges free of weathering, rounding, or erosion. If the surface has been painted, the condition of the paint along the crack edge can be a very good indicator. A sharp fresh break in the paint indicates that it developed recently. A rounded edge on the paint indicates that the crack was present when the wall was last painted. Slight curling of the paint along the crack edge indicates that the crack is not recent but developed since the wall was painted. Cracks in protected locations, such as inside closets or behind furniture, will not "weather" and may look sharp and fresh for many years.
- Relative color of the crack surfaces and the exposed surface of the element.

- Recent differential movement between adjacent elements is generally manifested by exposure of unpainted surfaces, torn caulk or expansion joint material, staining or debris remnants, or gaps between trim and the abutting surface.

5.8 Repair Methodologies

The appropriate repair of walls must consider the nature, extent, cause, and significance of the damage. Where earthquake damage has occurred in other components of the house, wall repair should be considered as one component of a more general repair plan. For example, if the house has been racked out of plumb, it should be straightened prior to repairing wall finishes, doors, and windows. Where the damage is structurally significant, a structural repair will be necessary. In all other cases, a nonstructural repair is appropriate.

Table 5-1 gives appropriate repair methods for typical earthquake damage patterns. If the cause of an observed damage pattern cannot be determined, or if the damage is outside the description given in the table, consider retaining a structures specialist to specify appropriate repair. The repair methods listed in the table are further discussed below.

Table 5-1 Repair Methods Not Requiring Technical Consultant Assistance for Nominal Earthquake Damage to Wood-frame Wall Surface Materials[1, 2]

Element	*Earthquake Damage Pattern*	*Repair Method*
Stucco	Cracks up to 1/64-inch wide	No repair
	Crack in stucco Width: up to 1/8 inch Detachment from framing or spalling: slight to none	Rout, patch, and refinish
	Cracks in stucco Width: up to 1/8 inch Pattern: extensive Spalling or offsets: slight to none	Remove color coat, rout, patch, and refinish
Drywall	Short cracks up to 1/64-inch wide	Patch and refinish
	Cracks following taped joints or corner bead, puckering or buckling of tape at joint	Re-tape joints as required, rout, patch, and refinish
	Nail pops	Add drywall screw 1 inch from original fastener, set or remove original fastener, patch, and refinish
	Cracks up to 1/8-inch wide through the thickness of the board	Remove and replace drywall to nearest studs beyond crack (minimum 32 inches by 48 inches), refinish
	Crushing and puckering of drywall at panel edges	Remove and replace drywall to nearest studs beyond damage (minimum 32 inches by 48 inches), refinish
	Tear-out of fasteners at panel edges	Remove and replace drywall to nearest studs beyond damage (minimum 32 inches by 48 inches), refinish

Table 5-1 Repair Methods Not Requiring Technical Consultant Assistance for Nominal Earthquake Damage to Wood-frame Wall Surface Materials (continued)[1, 2]

Element	*Earthquake Damage Pattern*	*Repair Method*
Plaster on gypsum or wood lath	Limited cracks up to 1/64-inch wide	Patch and refinish
	Limited cracks up to 1/8-inch wide, no detachment of gypsum lath, no spalling	Rout, patch, and refinish
Construction joints	Minor movement	Caulk, patch, and refinish
Horizontal wood siding	Nail head withdrawal	Reset nails, patch and refinish
	Local splitting of siding at nails (particularly at end of siding board)	Renail siding at splits, patch, and refinish
Plywood panel siding	Nail head withdrawal without significant enlargement or tearing of the panel around the nail	Reset nails. If nail does not properly reset, add one new nail for each withdrawn nail. If originally painted, patch and refinish
	Nail head withdrawal with significant enlargement or tearing of hole around the nail	Renail siding, moving nails, patch, and refinish
	Disruption of flashing at horizontal joints	Refasten or replace flashing

(1) Repair methods presented in this table presume that the building materials are free of regulated levels of hazardous materials. If testing as recommended in Section 9.2.4 indicates the presence of regulated levels of asbestos or lead, the abatement and waste disposal recommendations of the environmental consultant should be incorporated into the overall scope of repair.

(2) Identify damage pattern and repair where damage has been identified during the damage investigation. Select damage pattern most representative of observed damage caused by or worsened by the earthquake. See Section 1.2.3 for discussion of worsened damage.

Some California jurisdictions have local building code provisions that impose additional repair requirements if the earthquake damage exceeds either a certain percentage of the wall line's strength or if the cost of repair exceeds a certain percentage of the wall line's replacement cost. Damage patterns described above as structurally insignificant represent less than a ten percent capacity loss. Repair cost as a percentage of replacement cost may be estimated by a contractor or insurance adjuster. If the structural significance of the damage or the application of building code provisions are in question, an assessment should be performed by a structures specialist.

Table 5-1 does not include any jurisdiction-specific upgrade requirements. Some insurance policies include coverage for these upgrades. If such requirements apply, then an engineered repair might be needed.

The repair methods presented in this chapter presume that the building materials are free of regulated levels of hazardous materials. If testing as recommended in Section 9.2.4 indicates the presence of regulated levels of asbestos or lead, the abatement and waste disposal recommendations of the environmental consultant should be incorporated into the overall scope of repair.

5.8.1 Crack Repair

Stucco

- Fine cracks (i.e., 1/64-inch wide or narrower) should not be patched, especially if the stucco is not painted. On painted stucco, cracks this fine will be sealed by a fresh coat of paint. When determining the area to be painted, consideration should be given to obtaining a reasonably uniform appearance.
- For cracks up to 1/8-inch wide, the crack should be opened to the brown coat by beveling the crack edges to accept patching material. Patch with flexible vinyl base patching compound. Stucco should be applied to match the existing surface texture, as necessary. The stucco should be refinished as necessary to match adjacent areas. When determining the area to be refinished, consideration should be given to obtaining a reasonably uniform appearance.
- When the number of cracks to be patched becomes extensive, it may be more economical to remove the existing finish coat with sandblasting and then apply a new finish coat. The process of sandblasting will accentuate cracks visible in the finish coat and expose cracks in the brown coat. A stucco finish coat, even if painted with latex paint, has no ability to conceal earthquake-induced cracking of stucco. When determining the area to be refinished, consideration should be given to obtaining a reasonably uniform appearance.

Drywall

- Where cracking follows panel joints or corner beads, existing tape and compound should be removed. The joint should then be re-taped, retextured, and repainted. When determining the area to be retextured and repainted, consideration should be given to obtaining a reasonably uniform appearance.
- Short (less than about 6-inches long) cracks less than about 1/64-inch wide extending from the corners of openings may be patched using drywall tape and joint compound, retextured and repainted. When determining the area to be retextured and repainted, consideration should be given to obtaining a reasonably uniform appearance.
- Where cracks are up to about 1/8-inch wide and extend through the drywall, the cracked piece should be removed to the nearest stud on either side of the crack (32-inch minimum width, 48-inch minimum height) and replaced, retextured, and repainted. When determining the area to be retextured and repainted, consideration should be given to obtaining a reasonably uniform appearance.
- Nail pops can be repaired by adding a drywall screw adjacent to the nail pop, resetting or removing the "popped" fastener, patching, retexturing to match the adjacent finish, and repainting. When determining the area to be retextured and repainted, consideration should be given to obtaining a reasonably uniform appearance.

Gypsum Lath and Plaster

Where the plaster is cracked but remains firmly attached to the lath, repairs can be accomplished by cleaning the crack and patching, texturing, and painting to match the existing surface texture and finish. When determining the area to be retextured and repainted, consideration should be given to obtaining a reasonably uniform appearance.

5.8.2 Construction Joints

Where minor movement has occurred at construction joints, only cosmetic repairs are necessary. Where these joints were simply painted, the appropriate repair is to clean and repaint the joint. Where caulking or grout along the joints has cracked or spalled (such as along shower enclosures), the appropriate repair is to remove the cracked material, clean the separation, and recaulk or regrout the joint where necessary. Even after the repairs are complete, cracks or separations may reappear due to the normal effects of material shrinkage, temperature changes, and minor differential movements of supporting elements (soil or structure). The reoccurrence of damage is unrelated to the earthquake. If damage occurred because there was no joint where there should have been one, then again, the damage is generally not structurally significant.

5.8.3 Technical Consultant Repair Recommendations

For damage patterns not addressed in Table 5-1, a technical consultant may be asked to recommend repairs. Repairs that might be recommended by a technical consultant, in addition to those presented in Table 5-1, include:

Stucco Repair

Where the stucco has buckled, delaminated, detached from the framing, or is severely cracked, the existing stucco should be removed back to intact, securely attached stucco. The underlying building paper should be repaired or replaced as necessary, and any new paper should be properly lapped with the existing paper. New wire mesh should be installed and nailed to the framing, and it should overlap existing mesh by at least 6 inches. Stucco should be applied, in three coats, to match the existing thickness and surface finish. The stucco should be refinished as necessary to match adjacent areas. When determining the area to be refinished, consideration should be given to obtaining a reasonably uniform appearance.

Drywall Repair

Fractured gypsum wallboard panels should be replaced in kind. Where the attachment of the drywall to the framing has loosened significantly, new fasteners should be installed around the wall perimeter and along panel joints showing signs of relative movement. The repaired areas should be refinished as necessary to match adjacent areas. When determining the area to be refinished, consideration should be given to obtaining a reasonably uniform appearance.

Plaster Repair

Where the lath has fractured (or where plaster damage suggests fracture of the gypsum lath), the damaged pieces should be removed to soundly attached plaster or lath, new lath installed and the area replastered. Where larger areas of repair are involved, and it is more economical to do so, lath and plaster should be removed to the limits of the wall panel and replaced with drywall.

When determining the area to be refinished, consideration should be given to obtaining a reasonably uniform appearance. If drywall is used, modification of trim at ceilings, floors, windows, and doors, may be necessary. If the plaster being replaced is 5/8-inch thick plaster reinforced with expanded metal lath over 3/8-inch gypsum lath, it may be necessary to install 1/2-inch plywood sheathing beneath the drywall to restore the strength of the wall assembly. Installation of 1/2-inch plywood will eliminate the need for modification of trim, in most cases.

Framing Repair

Severe damage to stucco or interior wall finishes indicates substantial wall racking and the possibility of damage to wood framing members, especially nailed connections at the sill or top plates. These conditions call for assessment by a structures specialist. If framing damage is found, replacement, renailing, or "sistering" of the affected members is usually the appropriate repair, but that judgment should be left to the structures specialist.

Building Realignment

When a building has been permanently racked out of plumb by more than 1/2 inch over the height of a story or the height of a cripple wall, as evidenced by a consistent pattern of damage to finishes, inoperable doors or windows, and out-of-plumb measurements of door and window jambs, it will generally be necessary to remove finishes from the racked walls, plumb the building, and reinstall finishes. It is essential to distinguish between overall earthquake-induced racking of the building and normal construction tolerances or other pre-existing conditions.

5.8.4 Permits and Code-Triggered Upgrades

Depending upon the nature and scope of damage and proposed repair, building permits and other government agency approvals may be required by the local jurisdiction. In addition to normal changes in the building code over time, some jurisdictions have building code requirements that mandate varying degrees of upgrades if certain damage thresholds are exceeded. The repair guidelines presented herein are intended to represent prevailing best practices and do not include jurisdiction-specific requirements. The local building department should be contacted to determine the existence of any applicable local requirements. Where utilized, technical consultants should be asked to address any code-triggered upgrades that may be required to comply with applicable local building code requirements as part of the repair of earthquake damage.

CHAPTER 6

Floors, Ceilings, and Roofs

6.1 Quick Guide

This section provides a summary of where to look, what to look for, and when a technical consultant might be needed regarding a damage assessment of floors, ceilings, and roofs. A more detailed discussion begins at Section 6.2.

6.1.1 Where to Look: Roof

1. While standing on the ground, look at the roof. You may need a pair of binoculars to be able to closely look at the roof. Pay particular attention to the ridge lines. Walk around the structure and look up at eves and rafter tails.

6.1.2 What to Look For: Roof

If any of the following conditions exists, a technical consultant may be needed.

1. Shifted or dislodged clay or concrete roof tile; impact damage to roof from falling chimneys, displaced rooftop heating, ventilation, and air conditioning (HVAC) units.
2. Significantly sagging roof ridgelines; signs of movement between rafter tails and wall finishes.
3. Buckled or dislodged flashing or tearing of roof membrane at roof-wall intersections in split-level buildings, additions, appendages, porches, or other building irregularities. Tearing of roof membrane or deck waterproofing at re-entrant corners.
4. Toppling, shifting, or damage or leakage at refrigerant and electrical line of rooftop mechanical equipment.
5. Shifting of or damage to solar panels.
6. Indications of relative movement, such as separations or cracks in roof at building irregularities including split levels, additions, or porches.

6.1.3 Where to Look: Ceilings

1. Look at ceilings inside the house or in a porch area. Pay particular attention to where the wall meets the ceiling and the corners. Look closely at unusual elevations, like coffered or vaulted ceilings.

6.1.4 What to Look For: Ceilings

If any of the following conditions exists, a technical consultant may be needed.

1. Collapse of ceiling finishes.
2. Damage to ceiling finishes and framing in vicinity of chimneys; damage to chimney flashing; gaps between masonry chimney and adjacent wall.

3. Separations or cracks in ceiling finishes at split levels, re-entrant corners, additions, appendages, or other building irregularities.
4. Fresh cracking of ceiling finishes, especially at re-entrant corners; cracks along corner bead at stairwell openings; cracking or tearing of finishes at ceiling-wall juncture; multiple nail pops.
5. Water damage or evidence of recent leakage from plumbing lines or roofing.
6. Indications of relative movement such as separations or cracks in ceiling finishes at building irregularities, including split levels, additions, or porches.

6.1.5 Where to Look: Interior Floors

1. Look for new cracks at the corners of where the floor meets the wall.
2. Look at hard surfaces, like ceramic tile.
3. Ask if there are any new lumps or bulges in the carpet. If so, look for wear patterns in the carpet which might help distinguish a new lump from an older lump.

6.1.6 What to Look For: Interior Floors

If any of the following conditions exists, a technical consultant may be needed.

1. Evidence of recent sloping, sagging, settlement or displacement of floors.
2. Impact damage to floor finishes from falling contents.
3. Indications of relative movement such as separations or cracks in floor finishes at split levels, re-entrant corners, additions, appendages, or other building irregularities.
4. Significantly sagging or bouncy floors consistent with loss of support.
5. A pattern of fresh cracks, gaps, or joint separations in floor finishes.

6.1.7 Where to Look: Exterior Floors

1. Look at porches and flatwork around the house. Look inside the garage at the edges of the garage slab.

6.1.8 What to Look For: Exterior Floors

If any of the following conditions exists, a technical consultant may be needed.

1. Evidence of recent sloping, sagging, settlement, or displacement of floors.
2. Indications of relative movement, such as separations or cracks in floor finishes at split levels, re-entrant corners, additions, appendages, or other building irregularities.
3. Cracking of stucco along the mudsill level accompanied by indications of relative permanent displacement (such as sliding) of the building relative to the foundation; cracking or splitting of mudsills.
4. Significantly sagging or bouncy floors consistent with loss of support.
5. Signs of movement between floor and exterior hardscape or retaining wall along the uphill side of houses on sloping sites.

6.1.9 Repair Guidelines

Structurally insignificant earthquake damage to floors, ceilings, and roofs can be addressed as described in Section 6.8.

6.2 Overview

Floor, ceilings, and roofs—the horizontal diaphragms in wood-framed buildings—are typically robust and do not generally sustain serious damage, even in areas of very strong ground shaking. Common damage patterns include shifting or falling of unsecured roof tile, damage to finishes and framing around masonry chimneys, minor cracking of ceiling finishes at re-entrant corners, and impact damage to floor finishes from falling objects. If indicators of structural damage are not found, such damage should be considered cosmetic and repaired in accordance with the guidelines presented in Section 6.8.

When subjected to strong shaking, floors, ceilings, and roofs in buildings with irregularities (e.g., split levels, one- to two-story transitions, hillside houses, additions, porches) are much more likely to sustain serious damage than are regular, conventional buildings. For those buildings without cripple walls, where floor joists bear directly on the mudsill, including the upslope edge of hillside houses, splitting of the mudsill can lead to sliding of the building on, or even off, its foundation. Floors, ceilings, and roofs can also sustain damage as a result of ground failure (see Chapter 3) when permanent ground deformation distorts the building's foundation, resulting in stretching or bending of floors, ceilings, and roofs. If any of these conditions are observed, a structures specialist should be engaged to inspect the house and provide repair recommendations.

There are numerous, long-term non-seismic conditions commonly found in floors, ceilings, and roofs, such as squeaky floors, loose nails, cracks and nail pops in ceiling finishes, or roof deterioration and leakage, that may have gone unnoticed prior to the earthquake. Distinguishing between earthquake-induced damage to these elements and pre-existing conditions due to other factors is essential to accurate assessment of earthquake damage.

6.3 Limitations

Only raised wood floors (second story or over crawlspace) of conventional wood-frame construction are addressed in this section. See Chapter 4 for discussion of concrete slab-on-grade floors. A structures specialist may be needed to evaluate damage in buildings of unconventional construction.

6.4 Description of Typical Construction

Floor, ceiling, and roof elements in typical wood-frame residential buildings in California are constructed of wood framing (joists and rafters) supporting sheathing (e.g., wood boards, plywood, plaster) and connected with nails (Figure 6-1). Roofs, ceilings, and floors serve several functions. As aesthetic elements, most are finished or decorated. As nonstructural elements, roofs protect the living space from the elements, and floors and ceilings subdivide the living space. As structural elements, roofs, ceilings, and floors support vertical loads that include their own weight, as well as the weight of people, contents, and occasionally snow. Floors, roofs, and ceilings also carry horizontal loads and tie the building together, thus playing a role in the earthquake resistance of houses. These elements are often referred to as horizontal diaphragms. Their function is similar to that of a beam loaded from the side—they collect the lateral inertial loads and distribute them to the walls and foundation (Figure 6-2).

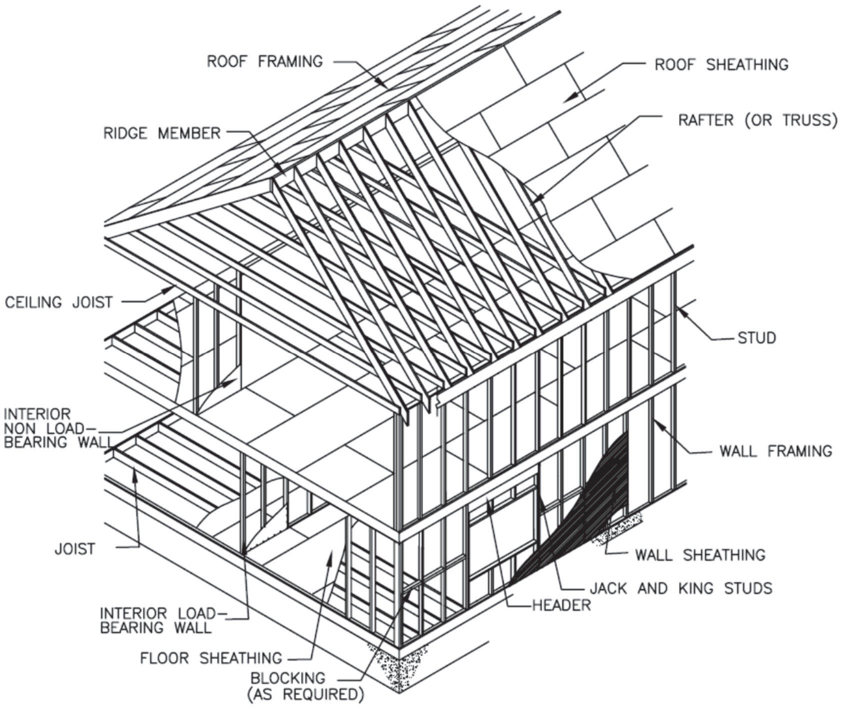


Figure 6-1 Elements of a typical wood-frame house (image credit: U.S. Department of Housing and Urban Development).

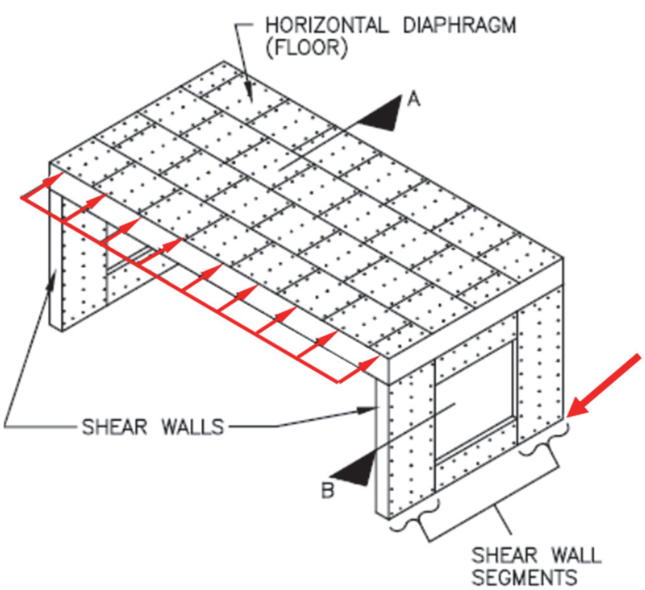


Figure 6-2 Schematic of the role of horizontal diaphragms (e.g., floors or roofs) as structural elements resisting earthquake forces, where the red arrows indicate the direction of forces (image credit: U.S. Department of Housing and Urban Development).

6.4.1 Typical Roof Construction

The two main components of a roof are the weatherproofing (e.g., shingles, felt) and the structure (e.g., framing).

There are two types of roof weatherproofing systems: those for steep or pitched roofs and those for low-pitched or flat roofs. There are a wide variety of materials available for pitched roofs, including asphalt shingles, wood shingles, wood shakes, clay tile, concrete tile, metal shingles, various fiber composite shingles, and metal panels. Asphalt saturated felt is typically installed beneath each of these systems as an added barrier to water infiltration. While shingles are securely attached to the roof deck with nails, concrete and clay tile may only be attached in certain areas, such as around the perimeter, while simply resting on wood cleats over the remainder of the roof. Waterproof membrane used on flat roofs generally consists of several alternating layers of building paper (or felt) and hot asphalt topped with gravel or a mineral cap sheet, technically referred to as built-up membrane but commonly referred to as tar and gravel roofing. More modern systems, consisting of sheets of plastic, rubber, or other composites, are rarely used on residential buildings in California. All roofing systems use flashing at penetrations and perimeters to provide a weather-tight transition to other materials.

Roof structures consist of numerous combinations of structural members (including conventional wood rafters, wood trusses, heavy timbers) and sheathing materials (including spaced or solid wood sheathing, plywood, OSB) depending upon the location and construction vintage. Buildings in snow country have much more substantial roof structures than buildings in warmer areas. Although 24-inch spacing is the most common for rafter and truss spacing, the spacing can range from 12 inches to 48 inches. Rafters and trusses are supported by exterior and some interior walls. Plywood and OSB are standard in more modern construction, while nominally 1-inch thick, spaced sheathing is common in older construction. Older buildings that have been more recently reroofed will often have plywood installed over spaced sheathing.

6.4.2 Typical Ceiling Construction

Typical ceiling finishes are plaster in older houses and drywall in newer houses. In most houses built since the mid-1930s, plaster is applied over gypsum lath (also called buttonboard); although in older houses (through the early twentieth century) wood lath was used. In all cases, the finishes are nailed (or screwed in the case of modern drywall installations) to ceiling joists (typically at 16-inch spacing) or the bottom chord of trusses (typically at 24-inch spacing). Drywall ceilings are often finished with a textured finish, commonly referred to as acoustical spray or “popcorn” texture. Where the roof structure consists of heavy timbers and solid-wood sheathing, the underside of the roof is often left exposed and finished with paint or stain.

Ceilings in buildings are often insulated, either with fiberglass batts or a variety of loose, blown-in insulation, such as fiberglass, cellulose, or rock wool. Exposed-beam ceilings are typically insulated with insulation board installed between the wood sheathing and the roofing materials.

6.4.3 *Typical Floor Construction*

There are two main components of floors: the finish materials (e.g., carpet, tile) and the structure (e.g., framing, concrete slab).

A wide variety of floor finish materials are in common usage, including hardwood, carpeting, sheet vinyl, vinyl tile, ceramic tile, stone, and loose-laid or floating-composite wood flooring. With the exception of the last, all are bonded or nailed to the floor sheathing. In some cases, an underlayment board may be installed over the floor sheathing to provide a smooth surface for the floor finish materials.

Two types of floor construction are commonly found in California: conventional and heavy timber. Conventional framing consists of wood floor joists spaced at 16 inches and supporting board, plywood, or OSB sheathing. Heavy timber framing consists of 4× beams spaced 48 inches apart and supporting 1 1/2-inch-thick wood sheathing or 1 1/8-inch-thick plywood. Floor joists are supported directly on perimeter foundations or perimeter walls and interior walls and beams. In crawlspaces, the beams are typically supported on wood or steel posts.

In California, the ground floor is often a thin, lightly reinforced, or unreinforced concrete slab cast directly on the ground. These floors are finished with tile, carpet, or sheet vinyl in living areas and left exposed in garages and sometime utility rooms or porches. See Chapter 4 for further detail.

6.5 Non-Earthquake Sources of Damage

Buildings are subject to multiple types and sources of damage, distress, and deterioration during their service life, much of which goes unnoticed or is routinely repaired. This section describes conditions commonly found in roofs, ceilings, and floors in the absence of earthquakes.

Non-earthquake damage to roofs, floors, or ceilings—such as water, decay, or insect damage—can weaken the structural members and their connections.

6.5.1 *Non-Earthquake Roof Damage*

Common non-seismic roof conditions include leakage at flashing and penetrations, deterioration, deflection and sag, workmanship and material defects, and withdrawal of nails.

Flashing at penetrations, transitions, and roof perimeters is a common source of water leakage, as a result of poor design or poor installation. In many cases, defective installations will be patched with mastic, which provides a short-term fix but not a long-term solution.

Deterioration from exposure to the elements is the most common problem associated with roofs. All roofing materials have a finite service lives, the length of which is governed by the composition of the roofing material, the quality of its installation, and environmental exposure. Typical service lives may be as short as 10 years to 15 years for wood shingles or low-quality built-up membrane, and in excess of 50 years for high-quality clay tile installations. Deterioration occurs gradually and may not result in leakage to the interior of the building until it reaches advanced stages.

In non-snow areas, roof structures are typically designed to be as light as possible with little or no consideration of deflection. As a result, many roofs will exhibit some degree of sag, which will increase with time. Without reinforcing the roof structure, installation of multiple layers of roofing or replacement of wood shakes with concrete tile will exacerbate the visible sag. Sag will often be most noticeable in areas where support conditions of the roof change, such as where a wall intersects the roof framing (Figure 6-3). Sag in the roof is generally not an indication of a serious structural defect.

Figure 6-3 Heavy tile roof sagging between wall supports, indicated by arrows (photo credit: Exponent).

Some houses in California, especially older houses, are built on unstable soils, which, over time, can lead to differential movement of the foundation and superstructure. Depending upon the structural configuration and the nature of the differential movement, separations may develop in the roof structure, typically at the ridge, eaves, and irregularities (e.g., at additions or porch attachments).

Neither great craftsmanship nor the finest materials are generally employed in the construction of roofs. Thus, it is common to find nails that have missed their target, poorly made joints, and misaligned framing in attics (Figure 6-4). In addition, framing lumber will shrink, twist, and split as it dries. Due to the fact that wood shrinks much more across the grain than it does along the grain, miter cuts made in wood will change angle as the wood dries, becoming more acute and giving the visual impression that the rafters have splayed outward.

In the course of reroofing, it is common to find withdrawn nails that originally had been driven flush (Figure 6-5). This condition can result from shrinkage of the framing lumber but more commonly results from thermal cycling of the roof, which causes nails to back out of the framing over time.

Figure 6-4 Poor fit-up of roof framing at rafter-to-ridge board junction (photo credit: Exponent).

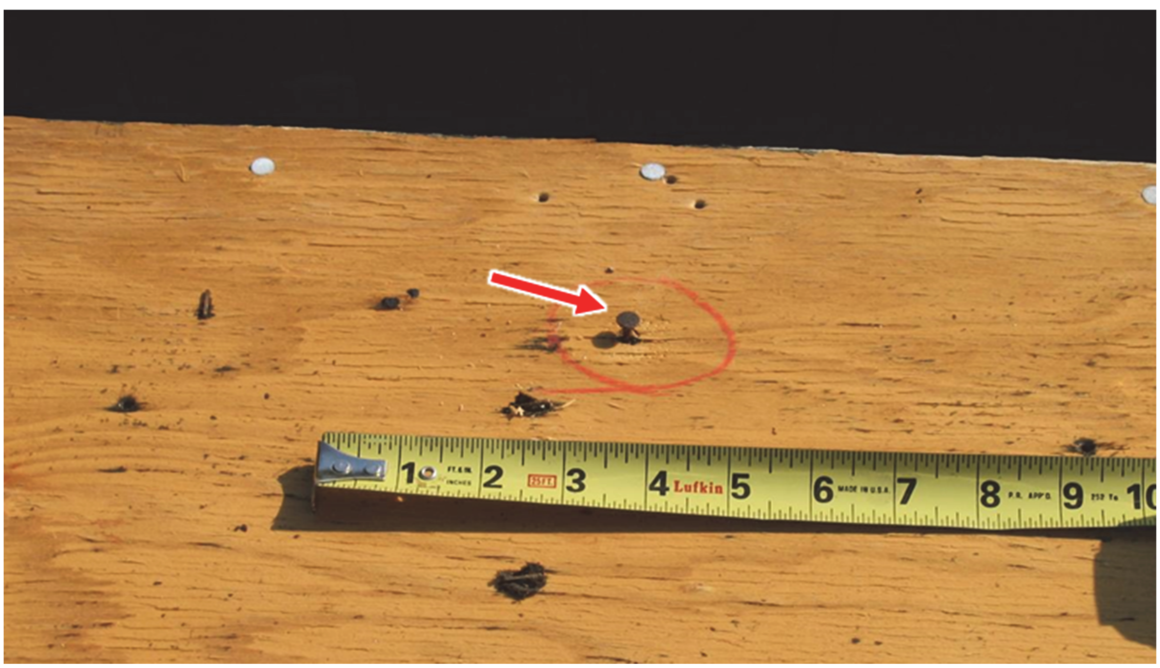


Figure 6-5 Nail withdrawal from plywood roof sheathing due to long-term moisture cycling (photo credit: Exponent).

Cracking of mastic used for roofing repairs or penetration seals is very common, often due to large thermal strains at irregularities or long-term deterioration, such as photo-degradation or embrittlement (Figure 6-6).

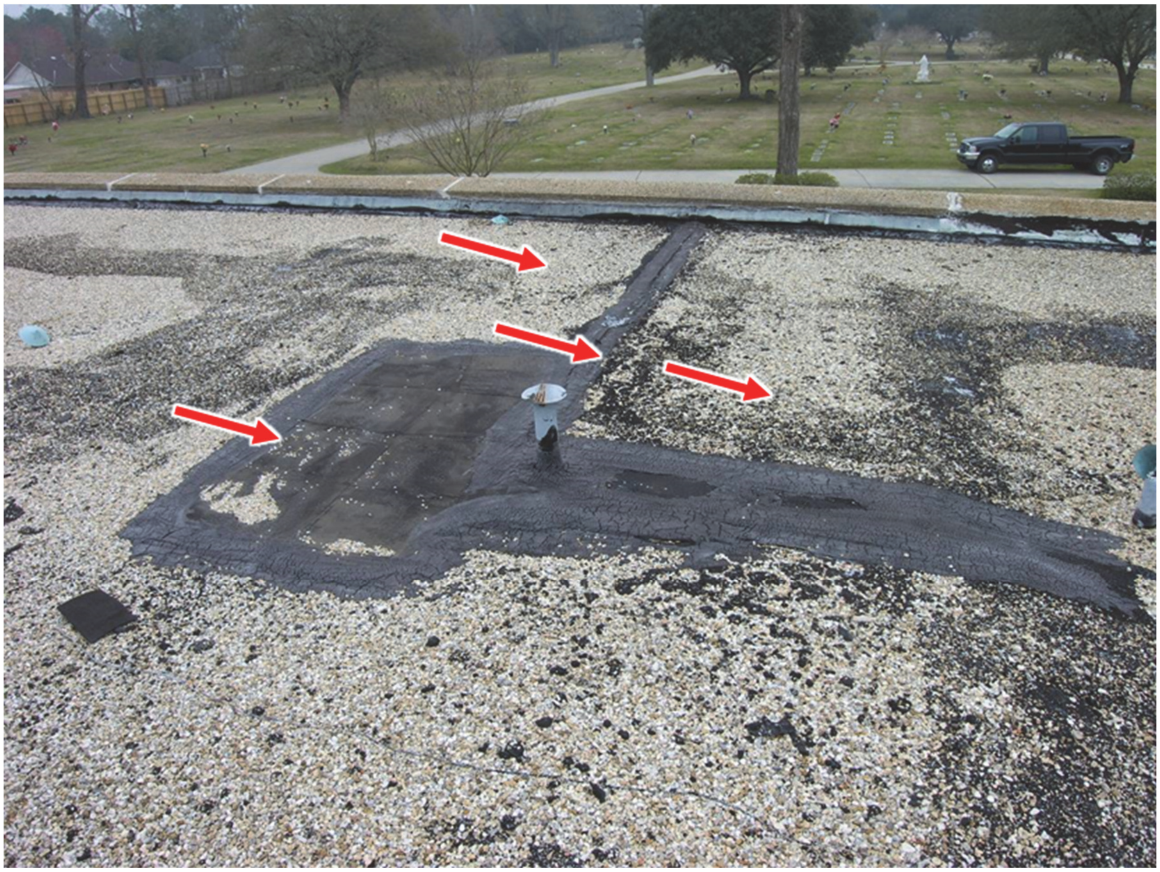


Figure 6-6 Deteriorated mastic at repair of built-up roof (photo credit: Exponent).

6.5.2 Non-Earthquake Ceiling Damage

Common non-earthquake problems with ceilings are generally limited to cosmetic concerns, including surface irregularities, cracks, and nail pops.

The most common imperfection with drywall ceilings is tape joints that are visible under low light angles on ceilings with smooth finish. Joints will be spaced at 4 feet in one direction and at 8 feet to 12 feet in the other direction. Related is the problem of nail pops (or dimpling) at fasteners, which develop over time and are generally associated with changes in moisture content in the wood framing (Figure 6-7). The difficulty of preventing nail pops and making inconspicuous tape joints over large ceiling areas is one of the reasons that heavy texture finishes are so widely used for ceilings. A related problem is irregularity of ceiling framing, which shows up as surface irregularities in the drywall finish.

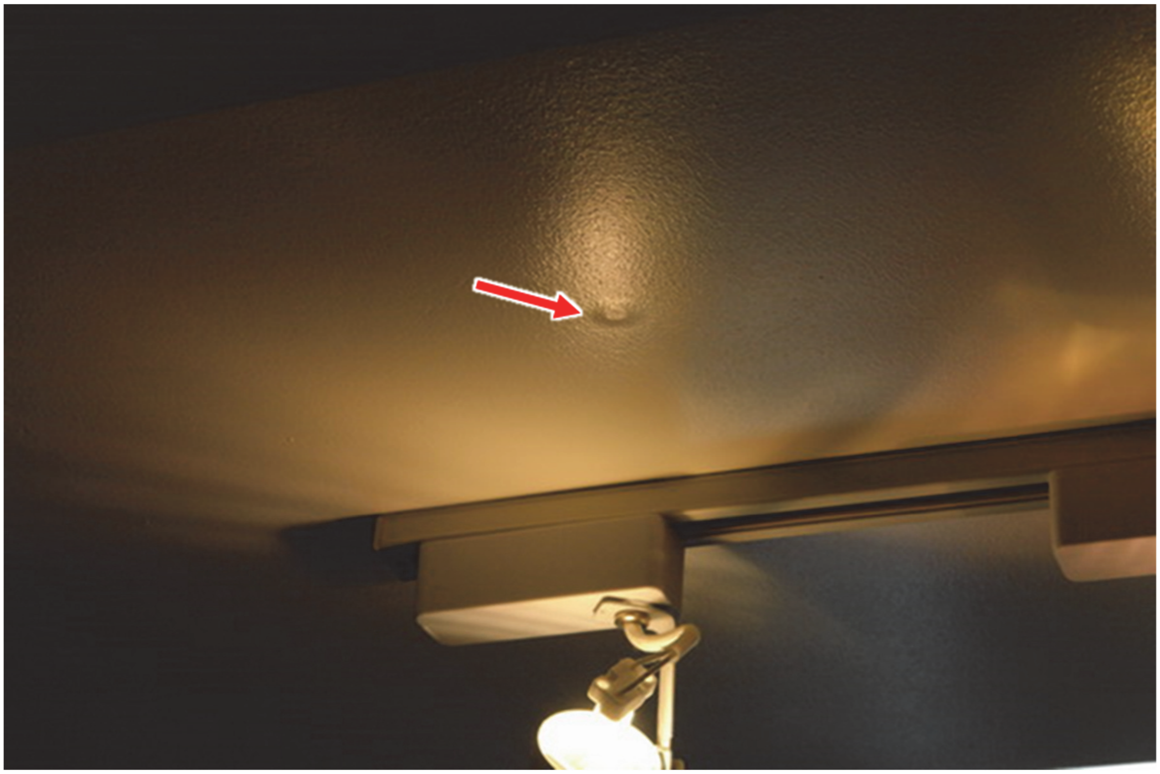


Figure 6-7 Nail pop visible in ceiling (photo credit: Exponent).

Fine cracking of ceiling finishes, especially adjacent to re-entrant corners, is common in both drywall and plaster ceiling finishes. Due to shrinkage of the plaster, linear cracks extending the width or length of the room will often develop in larger rooms near the centerline of the ceiling. A linear crack will often develop in cathedral ceilings as a result of non-uniform shrinkage of the roof rafters (as discussed in the preceding subsection), resulting in opening of the framing at the interior side of the roof apex.

Where ceilings include exposed wood (either paneling, decking, or heavy timbers), the wood members will typically exhibit various benign natural imperfections that generally go unnoticed, including shrinkage, checking, twisting, and warping. Intersections between exposed wood and drywall generally consist of one material butted against the other, in many cases forming an irregular gap.

Depending upon their structural configuration, long-term differential movement of houses founded on unstable soil can cause cracks in the ceiling finishes, typically at re-entrant corners and along ceiling-wall junctures.

6.5.3 Non-Earthquake Floor Damage

Common non-earthquake problems with floors include sloping or out-of-level conditions, construction imperfections, bounciness, squeaks and loose nails, deterioration of finishes, and cracking of lightweight fill.

Many houses in California, especially older houses, are built on unstable soils, which over time can lead to differential movement of the foundation and superstructure. The result will often be floors that are out of level with noticeable slope (i.e., greater than 1 inch in 20 feet). Differential foundation movement can also result in gaps between posts and beams in the crawlspace (Figure 6-8). These gaps leave the beams unsupported, resulting in a sag and bounce in the floor in the vicinity. Soils on or near the tops of slopes can creep or move laterally over time, stretching the foundation and raised wood floor, resulting in tilted support posts (Figure 6-9), cracked mudsills (Figure 6-10), and gaps or cracks in floor finish materials (Figure 6-11).

As with roofs, neither great craftsmanship nor the finest materials are generally employed in the construction of the floor structure. Thus, when examining floor framing, it is common to find nails that have missed their target, poorly made joints, and misaligned framing. In addition, framing lumber will shrink, twist, and split as it dries. Due to the vagaries of construction, it is not unusual to find misalignment between posts and footings or posts installed at an angle to accommodate the misalignment (Figure 6-12). Most wood-frame floors are designed to satisfy minimum building code requirements. As a result, many floors are rather flexible and will exhibit some bounce, even in the absence of any defect or damage in the framing. This condition is especially noticeable in the vicinity of floor lamps, china cabinets, and other vibration-sensitive furnishings.

Figure 6-8 Gap between post and pier foundation in crawlspace (photo credit: Exponent).

Figure 6-9 Tilted support posts in crawlspace (photo credit: Exponent).

Figure 6-10 Cracked mudsill and missed nails (photo credit: Exponent).

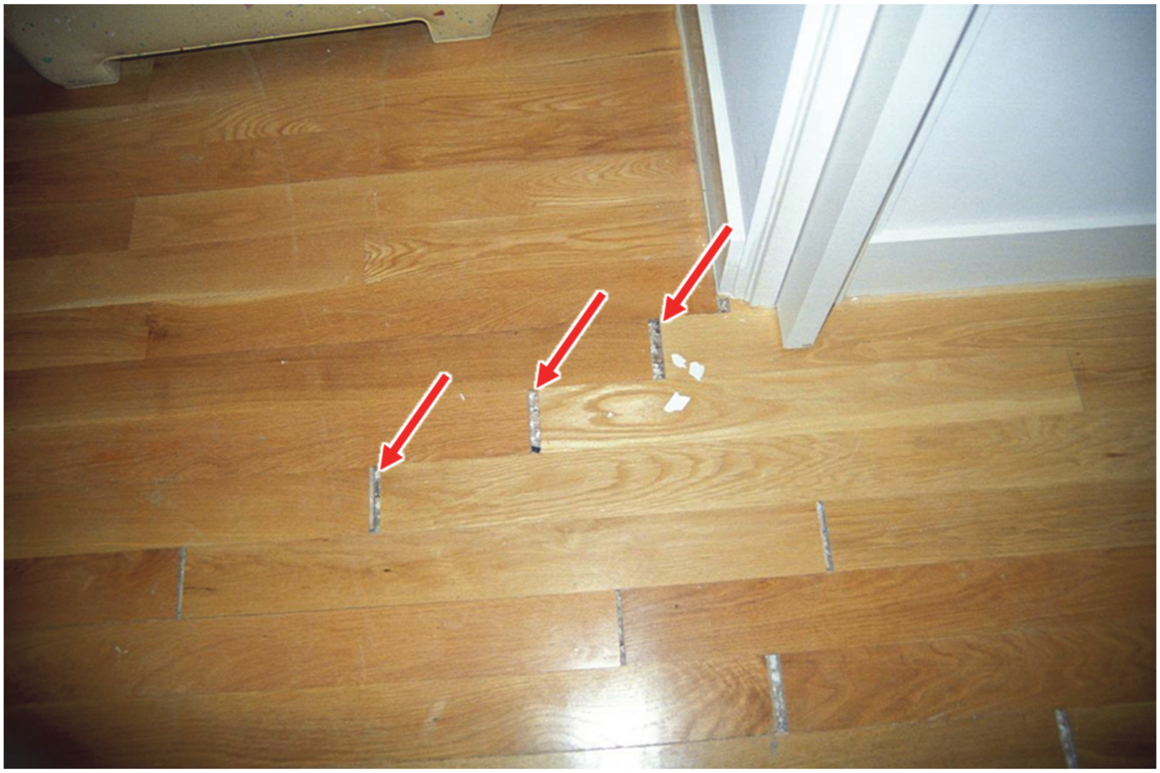


Figure 6-11 Gaps in flooring due to elongation of floor diaphragm caused by non-earthquake-induced slope movement (photo credit: Exponent).

Figure 6-12 As-built misalignment between girder and footing accommodated with offset post (photo credit: Exponent).

Floor squeaks under foot traffic are a common problem in wood-frame floors. Recognized causes of floor squeaks are:

- use of “green” (i.e., wet) lumber,
- improper spacing of sheathing panels,
- improper glued floor construction practice,
- improperly driven nails,
- loose blocking or rubbing bridging,
- loose wall-floor connections,
- improperly installed joist hangers,
- loose connections between subfloors and underlayment or between subfloors and hardwood flooring,
- use of cement coated nails,
- movement between ductwork and floors,
- variation in joist depths or straightness, and
- loose tongue and groove joints in subfloors.

Floor squeaks are most common in older buildings where floor construction consists of board sheathing and hardwood flooring. Floor squeaks are generally concentrated in those areas that receive the greatest foot traffic. Improvements in construction materials and techniques over the past several decades have greatly reduced, but not eliminated, the problem of floor squeaks. In the course of replacing carpet, it is common to find some withdrawn nails that originally had been driven flush. This condition results primarily from shrinkage of the framing lumber.

As a result of both the flexibility of floor structures and moisture-related movement of wood, brittle floor finishes (e.g., ceramic tile, stone) installed over wood flooring will often develop cracks, generally over points of support (such as beams or posts). Where the subfloor is flexible, deterioration of grout joints in brittle floor finishes is also a problem. Over time, joints in the underlayment may also telegraph through flexible floor finishes, such as sheet vinyl and vinyl tile.

While not common in single-family houses, a 1 1/2-inch-thick layer of lightweight concrete is often used in place of underlayment for sound control in multi-family wood-frame buildings. That fill is unreinforced, placed with a high-water content, and of low strength, resulting in the development of cracks from shrinkage or traffic loads and deterioration (Figure 6-13).

Figure 6-13 Shrinkage cracks in lightweight concrete fill (photo credit: Exponent).

6.6 Earthquake-Induced Damage

The most common earthquake damage patterns in floors, ceilings, and roofs are all essentially nonstructural and include shifting or falling of unsecured roof tile, damage to finishes and framing around masonry chimneys, minor cracking of ceiling finishes at re-entrant corners, and impact damage to floor finishes from falling objects. In conventional residential wood-frame construction, diaphragms are lightly loaded and will typically experience relatively little distortion during an earthquake. Accordingly, damage to finishes is common, while structural damage is not.

The most common type of roof framing damage occurs due to failure of an adjacent chimney. Many masonry chimneys, some dating back to the 1930s, are attached to the house with steel straps, where one end is embedded in the chimney mortar and the other is nailed to the framing (e.g., roof, ceiling, or second floor). During an earthquake, when the chimney shifts away from the house, the framing connected to the strap can be damaged. If it appears that the chimney has shifted more than 1/4 inch from the house, an attic inspection should be conducted to inspect the adjacent framing.

In areas of strong shaking, structural damage to floor, ceiling, and roof framing can occur at building irregularities. There are two types of building irregularities that can lead to damage: (1) vertical irregularities, where the plane of the floor, ceiling, or roof is discontinuous (e.g., split levels, one-story to two-story transitions, additions, porches); and (2) plan irregularities that create re-entrant corners (L-, T-, and U-shaped floor plans), as shown in Figure 6-14.

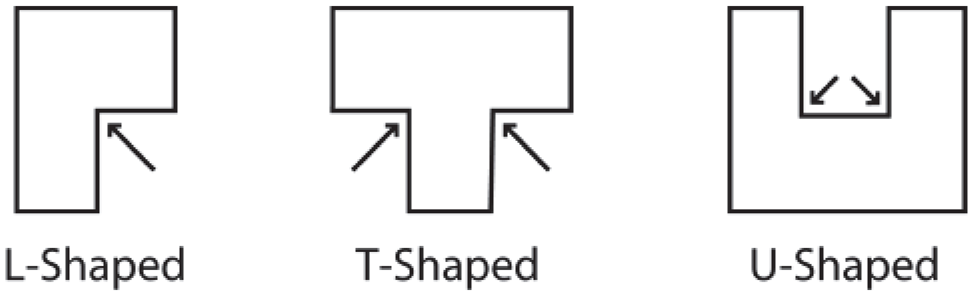


Figure 6-14 Re-entrant corners of plan irregularities are often locations of damage in horizontal diaphragms during strong shaking.

Damage at vertical irregularities occurs when the portions of the building on either side of the irregularity move in opposing directions. If the structural tie across the irregularity is not sufficiently strong (a common situation, especially in older buildings), separation will occur at the discontinuity of the structural diaphragms, with damage ranging from minor finish damage to complete structural separation. Split-level houses represent vertical irregularities in the lateral load path that can lead to separation in discontinuous floor and roof framing (i.e., the horizontal diaphragms). In the past, split-level houses have suffered serious damage due to this discontinuity, as shown in Figure 6-15. Modern seismic design principles discourage this condition or provide special detailing to accommodate it. Discontinuities in horizontal diaphragms should be inspected carefully for indications of framing separation.

Figure 6-15 Stemwall anchorage failure and earthquake-induced separation across discontinuous floor and roof diaphragms of a split-level house (photo credit: R. Kachadoorian, USGS Denver Library Photographic Collection).

In larger wood-frame buildings, damage can also occur at the re-entrant corners in the floor plan when the intersecting wings move in slightly different directions during the earthquake, resulting in tension or tearing at the re-entrant corner. Damage associated with both vertical and plan irregularities tend to increase with the height of the building. If there are indications of earthquake damage associated with a building irregularity, a structures specialist should be engaged to inspect the building and provide repair recommendations.

Floors, ceilings, and roofs can also sustain structural damage as a result of ground failure (see Chapter 3). Houses that have been subjected to significant differential ground movement can sometimes suffer loss of support of floor joists. This will result in observable floor detachment from the supporting walls and noticeable bounce in the floor. If there are indications of ground failure at a site, as discussed in Chapter 3, a technical consultant should be engaged to inspect the building, evaluate soil conditions, and provide repair recommendations.

6.6.1 Earthquake-Induced Roof Damage

With few exceptions, earthquake-induced damage to roofs is limited to nonstructural or isolated minor structural damage. The most common earthquake-induced damage is shifting or falling of unsecured roof tile and damage to flashing, and in some cases, framing around chimneys. Less common are structural damage at discontinuities, damage due to earthquake-induced ground failure, and deformation or collapse of structurally deficient roofs.

Figure 6-16 Clay roof tile and mortar joints shifted by earthquake shaking (photo credit: Exponent).

Many of the indicators of earthquake damage discussed below have other potential non-earthquake causes, as discussed in Section 6.5. Accordingly, it is necessary to evaluate the patterns of indicators to determine which are consistent with earthquake-induced distortions and which are consistent with other causes.

Roofs can be damaged by masonry chimneys by three means: flashing damage due to relative motion between the chimney and building (Figure 6-17), impact damage from toppling chimneys (Figure 6-18), and damage to framing where steel strap ties from the chimney are attached to roof framing (Figure 6-19). Flashing damage will typically only be discoverable by a rooftop inspection. The other two modes of damage should be readily observable from the ground. If either of the latter two conditions exists, framing in the vicinity of the chimney should be inspected from within the attic.

Figure 6-17 Buckled chimney flashing due to earthquake shaking (photo credit: Exponent).

Figure 6-18 Earthquake damage from impact of falling masonry chimney (photo credit: USGS).

Figure 6-19 Masonry chimney and fireplace that have tilted away from the house. The chimney tore loose the wood framing to which steel tie straps from the chimney were attached (photo credit: L. S. Cluff, NISEE e-Library).

Roof damage at vertical irregularities can range from minor flashing damage to complete structural separation. Damage at the re-entrant corners of a building plan (e.g., the inside corner of an L-shape building) typically only occurs in taller (i.e., three-story), flat-roofed buildings and is generally limited to tearing of the membrane and possibly tear out of nails in the roof sheathing at the re-entrant corner.

The potential for damage to roof framing depends upon the roof geometry, sheathing type, and weight of roofing. Gable roofs with spaced board sheathing (in lieu of plywood or OSB panels) that have had wood shingles replaced with concrete tile without adequate reinforcing are the most vulnerable to racking, or in extreme cases, collapse. Conventionally framed roofs are typically braced in the direction of the ridge with diagonal 2×4 braces from the ridge down to a ceiling joist or top plate. These braces are typically the weakest link in the roof structure. Because the spaced sheathing has relatively little stiffness to resist earthquake forces, the diagonal ridge braces can be subject to significant load in the longitudinal direction, which could cause them to buckle (Figure 6-20) or fail at their connections (Figure 6-21). Thus, the braces and their end connections should be a key inspection point if an attic inspection is performed. Roofs sheathed with plywood or OSB and hip roofs are especially resistant to earthquake damage and, in the absence of irregularities, structural damage during earthquakes is unlikely.

Figure 6-20 Diagonal ridge brace buckled due to earthquake; this brace is in line with the brace shown in Figure 6-21 (photo credit: Exponent).

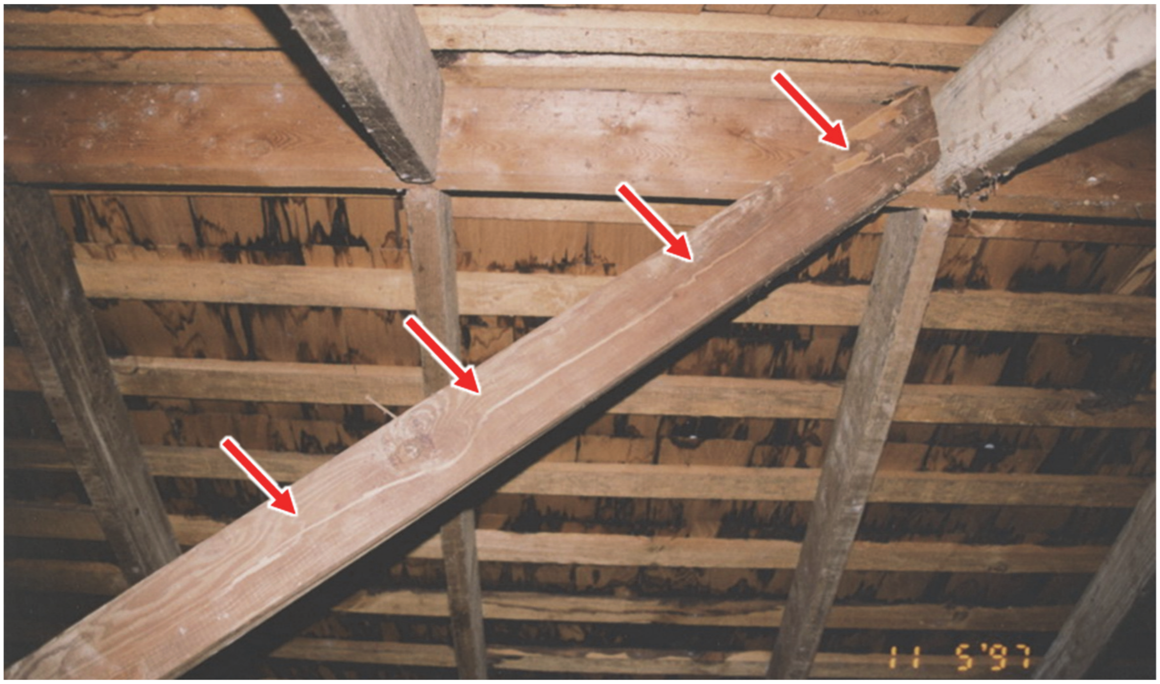


Figure 6-21 Diagonal ridge brace cracked during earthquake; this brace is in line with the brace shown in Figure 6-20 (photo credit: Exponent).

Earthquake damage to pre-fabricated roof trusses is not common. Any observed earthquake-induced damage, including splitting or tearing of the metal connector plates, may warrant evaluation by a structures specialist.

6.6.2 Earthquake-Induced Ceiling Damage

The most common type of earthquake-induced ceiling damage is minor cracking of ceiling finishes at re-entrant corners and cracking along corner beads at the intersection between the ceiling and an opening, conditions commonly found at stairwell openings (Figure 6-22). Ceilings can also sustain damage in areas adjacent to chimneys, where tie straps from the chimney damage framing as the chimney pulls away from the building. Where there are irregularities in the lateral load path, such as building plans where the second story is set back to mid-length of the garage, cracking of drywall finishes can occur along tape joints (Figure 6-23).

Where ceilings include exposed wood framing, or where there is significant finish damage, framing should be inspected carefully for signs of earthquake-induced movement or shifting (Figure 6-24). It is important to recognize that natural imperfections in wood, including shrinkage, cracks, twisting, and warping, as well as irregular gaps where other finish materials abut the wood, are quite common and often mistaken for earthquake damage.

Figure 6-22 Earthquake damage to ceiling corner bead at stairwell (photo credit: Exponent).

Figure 6-23 Earthquake damage to tape joints at vertical load path irregularity (photo credit: Exponent).

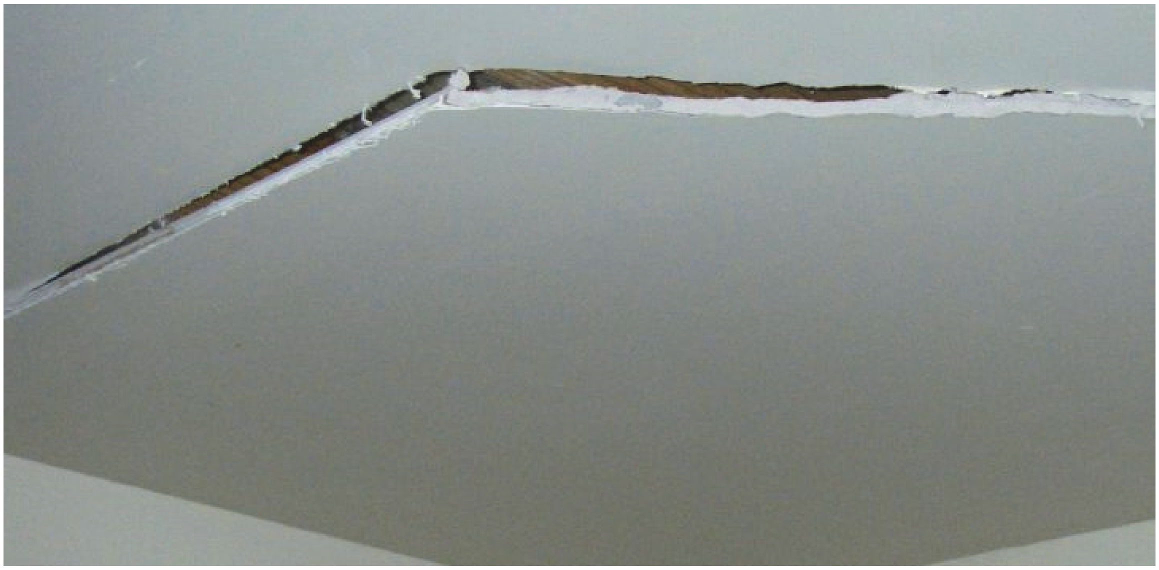


Figure 6-24 Earthquake damage to ceiling finish (photo credit: M. Heller, EERI Library).

6.6.3 Earthquake-Induced Floor Damage

The most common and serious failure modes for floors are lateral movement and loss of vertical support. Floors are restrained from lateral movement either by direct attachment to the foundation or through walls that are anchored to the foundation. Failure of a supporting wall, as discussed in Chapter 5, will cause failure of the floor (Figure 6-25). As a result of the strength required to support building occupants and contents, floors generally have sufficient strength to resist the lateral forces imposed by earthquakes, and structural damage associated with the direct effects of earthquake shaking is uncommon.

Figure 6-25 Sagging floor due to earthquake-induced shifting and loss of support (photo credit: Exponent).

For floors attached directly to the foundation, the weak link in the lateral load path is the mudsill attachment—either bolting to the foundation or nails between the joists and the mudsill. The mudsill is typically a 2×4 or 2×6 pressure treated plate (new construction utilizes 3× plates) that attaches the floor to the foundation. In older construction, the mudsill may be redwood.

Sills that are inadequately attached to the footing with anchor bolts can split and slide on (or off) the foundation. Sometimes the mudsill is well bolted, but the joists are not adequately nailed to the mudsill, a condition that also leads to a sliding failure (Figure 6-26) or bulging. Sliding of sill plates or sliding (or bulging) of the framing on the sill plate can typically be seen by the damage to exterior finishes. Another indication of sliding or failure of the mudsill is uniform leaning of post supports in the crawlspace consistent with the direction of movement of the floor.

Figure 6-26 Sliding of joists on mudsill due to earthquake (photo credit: NISEE).

Hillside houses, especially those supported by columns on the downhill side, are particularly vulnerable to failure at the floor-foundation connection. In many cases, the lateral load from the earthquake is concentrated in the uphill mudsill. Failure of that connection can result in complete collapse of the building. A gap between the upslope edge of the floor and any adjacent construction, such as concrete hardscape, indicates possible damage to this connection (Figure 6-27). Damage that suggests lateral movement of the floor should prompt investigation by a structures specialist.

In areas of strong shaking, with extensive disruption of contents, floor finishes can be damaged by the impact of falling debris.

Figure 6-27 Earthquake-induced gap between floor and wall supported on retaining wall on uphill side of house on sloped lot (photo credit: Exponent).

Occupants may report an increase in the number of floor squeaks after an earthquake due to heightened sensitivity to pre-earthquake conditions at the house. However, as discussed in Section 6.5.3, floor squeaks are common in houses that have never experienced severe ground shaking. It has been suggested that earthquake-induced racking of the floor diaphragm loosens nails that then squeak under foot traffic. However, racking distortion of a magnitude that could loosen floor sheathing or framing connections is highly unlikely for any wood-frame residential building that remains habitable.

6.7 Assessment Guidelines and Methodology

Initial inspection of floors, ceilings, and roofs consists of visual examination and documentation of nonstructural damage, as well as indicators of possible structurally significant damage that would trigger a more detailed inspection. Careful observation and attention to detail are essential, but it is also important to look for patterns of damage—isolated finish cracks are not cause for concern, but finish cracking near a discontinuity indicates possible concealed damage that requires further investigation.

The initial inspection should include interior living space and exterior inspection from the ground, as discussed in the following subsections. Absent indications of concealed damage, roof, attic, and crawlspace inspections are not recommended; entry to these spaces presents its own set of hazards that outweigh the potential benefits. If there are indications that the house may have sustained damage that would be revealed via roof, attic, or crawlspace inspection, an appropriately qualified inspector should conduct that inspection. In some cases, a structures specialist will need to be retained to ascertain structural damage and specify appropriate repairs. If there is evidence of ground failure at the site, a technical consultant should be retained to investigate both the geotechnical as well as structural condition of the property.

The following subsections enumerate specific inspection points and observations that are relevant to assessing potential damage to floor, ceilings, and roofs.

6.7.1 Exterior

Exterior inspection points and observations relevant to assessing conditions that may indicate potential damage to floor, ceilings, and roofs include:

- Foundation and floor system: Is there a raised wood floor? Is the raised wood floor resting directly on the mudsill or is it supported on cripple walls? Are the cripple walls of uniform height or do they vary in height to accommodate a sloping site? Any signs of racking of the cripple walls? Are there any indications of movement or sliding of the floor at the sill plate level? Evidence of sliding is generally most obvious at building corners at the foundation level. Any gaps between the building and upslope hardscape? Is the hillside building partially supported on columns or posts?
- The presence of vertical irregularities: Are the roof and floor lines continuous or are there changes in elevations, such as split levels, one- to two-story transitions, porches, or attached garages? Any signs of damage at the irregularities? Are there additions, which may be at the same level, but not well tied to the original building? Any signs of damage at the interface between the original building and the addition?
- The presence of plan irregularities: Is the footprint of the building basically rectangular or is it composed of one or more wings in an L-, T-, or U-shaped floor plan? Any signs of damage at the re-entrant corners?
- The presence of masonry chimneys: Are there (or were there) any masonry chimneys in the building? Have they fallen and impacted the roof? Have chimneys on exterior walls collapsed or pulled away from the building?
- Rooftop HVAC units: Have any rooftop HVAC units fallen from their supports and damaged the roof?
- Roofing: Does the building have a clay or concrete tile roof? Have any tile fallen or shifted? Rake tile, tile just below the ridge, and tile just below penetrations or walls, such as chimneys, skylights, dormers, and upper story walls are particularly vulnerable. Are the tile lines straight?
- Rooflines: Is the shape hip, gable, or flat? Any unusual sagging, racking, or distortion of rooflines? Any signs of movement of rafter tails at eave-wall intersection?

6.7.2 Interior

- Floor finishes: Any fresh impact damage? Any patterns of cracks, gaps, or separations in flooring to suggest movement of the underlying structure? Any signs of cracking at re-entrant corners of plan irregularities? Any signs of cracking at vertical irregularities?
- Floor structure: Any noticeable sag or excessive bounciness in the floor?
- Ceiling finishes: Any cracks emanating from the corners of openings? Any cracks along corner beads around openings? Any signs of cracking at re-entrant corners of plan irregularities? Any signs of cracking at vertical irregularities?

6.7.3 Roof

A rooftop inspection may be performed to check the following items:

- shifting of roof tile,
- damage to flashing at chimneys or at building irregularities, and
- damage to membrane roofing at building plan irregularities.

6.7.4 Attic

If concrete or clay tile are present on a gabled roof, a visual survey of the attic should be made from the scuttle opening, without entering the attic, to determine whether the roof is sheathed only with spaced sheathing or whether plywood or OSB sheathing has been installed, either as part of the original construction or over the spaced sheathing as part of reroofing.

A more detailed attic inspection should be conducted if any of the following are found during the initial inspection:

- damage or distress to finishes in the vicinity of building irregularities that suggest movement, separation, or damage to concealed framing,
- toppling of a chimney onto the roof,
- pulling of chimney away from building, or
- clay or concrete tile is installed on a gabled roof sheathed only with spaced sheathing.

The detailed attic inspection should focus on:

- the condition of framing and connections at building irregularities,
- the condition of framing and tie straps in the vicinity of any masonry chimneys and the condition of framing in the vicinity of any areas where falling masonry may have impacted the roof, and
- for tiled gabled roofs with only spaced sheathing, the condition of longitudinal braces (braces aligned parallel to the ridge board) and their end connections.

6.7.5 Crawlspace

A crawlspace inspection should be conducted if any of the following are observed in the course of the initial inspection:

- signs of sliding or movement at the mudsill level,
- signs of racking of cripple walls, or
- any noticeable sag or excessive bounciness in the floor.

The detailed crawlspace inspection should focus on:

- condition of the mudsill and its attachment to both the foundation and the floor joists (especially, check for cracks in the mudsill at anchor bolts), and
- condition of support post connections to beams and footings, including gaps, distress, or tilting.

6.7.6 Technical Consultant Assessment

Assessment by a structures specialist should include detailed exterior and interior visual inspection, and, if warranted, rooftop, attic, and crawlspace inspections. Based on findings of that non-destructive assessment, the structures specialist may recommend destructive investigation. Destructive investigation may be necessary in those instances when the structures specialist is unable to rule out or reasonably assume the existence of concealed earthquake damage based on the non-destructive assessment. This might mean localized removal of finishes to see the framing.

If the building was constructed prior to 1980 and repair work will involve disturbance (e.g., demolition, removal, grinding, sanding) of any of the following types of ceiling or floor finishes, a suitably qualified environmental consultant should be retained:

- Material in floors, ceilings, or roofs that may contain asbestos include:
    - sprayed acoustic (“popcorn”) ceiling finishes,
    - gypsum joint compound (drywall “mud”),
    - interior plaster,
    - ceiling tile,
    - vinyl floor tile or mastic,
    - backing or underside of sheet vinyl,
    - roofing felt, and
    - roofing mastic.
- Material in floors, ceilings, or roofs that may contain lead consists of enamel paint applied to:
    - kitchen and bathroom ceilings, and
    - enamel paint on concrete floors.

As discussed in Section 9.2.4, the consultant should test for the presence of regulated hazardous materials and, if the results of the tests are positive, recommend appropriate abatement and waste disposal measures.

6.8 Repair Methodologies

The appropriate repair of damaged floors, ceilings, and roofs must consider the nature, extent, cause, and significance of the damage. Where earthquake damage has occurred in other components of the building, floor, ceiling, or roof repair should be considered as one component of a more general repair plan. For example, if the mudsill has been split and cripple walls racked out of plumb, a repair plan that includes moving the building back into position, repairing the cripple wall, and replacing the mudsill should be developed. Where the damage represents a loss of structural capacity, broadly defined, a structural repair will be necessary. In all other cases, a nonstructural repair is appropriate.

Table 6-1 and the following subsections present appropriate repair methods for typical nonstructural earthquake damage patterns. If the cause of an observed damage pattern cannot be determined, or if the damage is outside the description given in the following subsections, consider retaining a structures specialist to address the issue. The repair methods listed in the table are further discussed below.

Table 6-1 Repair Methods Not Requiring Technical Consultant Assistance for Nominal Earthquake Damage to Wood-frame Ceiling Surface Materials[1, 2]

Element	*Earthquake Damage Pattern*	*Repair Method*
Drywall	Cracks up to 1/64-inch wide	Patch and refinish
	Cracks following taped joints or corner bead, puckering or buckling of tape at joint	Re-tape joints as required, rout, patch, and refinish
	Nail pops	Add drywall screw 1 inch from original fastener, set or remove original fastener, patch, and refinish
	Cracks up to 1/8-inch wide through drywall	Remove and replace drywall to nearest joists beyond crack (minimum 32 inches by 48 inches), refinish
	Crushing and puckering of drywall at panel edges	Remove and replace drywall to nearest joists beyond damage (minimum 32 inches by 48 inches), refinish
	Tear-out of fasteners at panel edges	Remove and replace drywall to nearest joists beyond damage (minimum 32 inches by 48 inches), refinish
Plaster on gypsum or wood lath	Cracks up to 1/64-inch wide	Patch and refinish
	Cracks up to 1/8-inch wide	Rout, patch, and refinish
Construction joints	Minor movement	Caulk, patch, and refinish

(1) Repair methods presented in this table presume that the building materials are free of regulated levels of hazardous materials. If testing as recommended in Section 9.2.4 indicates the presence of regulated levels of asbestos or lead, the abatement and waste disposal recommendations of the environmental consultant should be incorporated into the overall scope of repair.

(2) Identify damage pattern and repair where damage has been identified during the damage investigation. Select damage pattern most representative of observed damage caused by or worsened by the earthquake. See Section 1.2.3 for discussion of worsened damage.

The repair methods presented in this chapter presume that the building materials are free of regulated levels of hazardous materials. If testing as recommended in Section 9.2.4 indicates the presence of regulated levels of asbestos or lead, the abatement and waste disposal recommendations of the environmental consultant should be incorporated into the overall scope of repair.

6.8.1 Roofs

Repair of roofing is generally straightforward:

- Clay or concrete tiles that have shifted should be reset. Where tile have fallen and broken or been broken by impact from falling masonry or HVAC units, tile may be replaced in-kind, if the color and pattern of material is still available. In the absence of structural repair work to the roof, removal and replacement of the underlayment is generally not necessary.
- Shingle and shake damage by impact from falling masonry or HVAC units may be replaced in-kind, if the color and pattern of material is still available.
- Damaged flashing at chimneys should be repaired in conjunction with repair or replacement of the chimney. Damaged flashing at other locations should be repaired once the underlying structural movement has been evaluated.
- Impact damage and tearing of roof membrane at re-entrant corners on low-pitched (i.e., flat or nearly flat) roofs can be repaired by an experienced roofing contractor.

6.8.2 Ceilings

Table 6-1 gives appropriate repair methods for typical nonstructural earthquake damage patterns in ceilings. If the nature or extent of damage are outside the description given in Table 6-1, a structures specialist may be asked to recommend repairs. The repair methods listed in the table are further discussed below.

Drywall

- Where cracking follows panel joints or corner beads, existing tape and compound should be removed. The joint should then be re-taped, retextured, and repainted. When determining the area to be retextured and repainted, consideration should be given to obtaining a reasonably uniform appearance.
- Short (less than 6-inches long), fine cracks (less than about 1/64-inch wide) extending from the corners of openings may be patched using drywall tape and joint compound, retextured, and repainted. When determining the area to be retextured and repainted, consideration should be given to obtaining a reasonably uniform appearance.
- Where cracks are up to 1/8-inch long and extend through the drywall, the cracked piece should be removed to the nearest joist on either side of the crack (32-inch minimum width, 48-inch minimum length) and replaced, retextured, and repainted. When determining the area to be retextured and repainted, consideration should be given to obtaining a reasonably uniform appearance.
- Nail pops may be repaired by adding a drywall screw adjacent to the nail pop, resetting or removing the “popped” fastener, patching, retexturing to match the adjacent finish and repainting. When determining the area to be retextured and repainted, consideration should be given to obtaining a reasonably uniform appearance.

Gypsum Lath and Plaster

- Where the plaster is cracked but remains firmly attached to the lath, repairs can be accomplished by cleaning the crack and patching, texturing, and painting to match the existing surface texture and finish. When determining the area to be retextured and repainted, consideration should be given to obtaining a reasonably uniform appearance.

Construction Joints

- Where minor movement has occurred at joints between wood and drywall or between wood members, only cosmetic repairs are necessary. Where these joints were simply painted or stained, the appropriate repair is to clean and repaint or restain the joint. Where caulking or joint compound along the joints has cracked or spalled, the appropriate repair is to remove the cracked material, clean the separation, and recaulk or remud the joint where necessary. Even after the repairs are complete, cracks or separations may reappear due to the normal effects of material shrinkage, temperature changes, and minor differential movements of supporting elements (soil or structure). The reoccurrence of damage is unrelated to the earthquake. If damage occurred because there was no joint where there should have been one, then again, the damage is generally not structurally significant.

6.8.3 Floors

Repair of impact damage to floor finishes is a nonstructural repair that can be performed by an experienced tradesperson.

- Most damage to wood floors can be addressed with isolated repairs; complete refinishing of the floor is not typically necessary.
- Damage to tile (e.g., vinyl, ceramic, or stone) can be addressed with isolated replacement of damaged pieces, provided matching colors and patterns are available.
- Damage to sheet vinyl will generally require complete replacement.

6.8.4 Permits and Code-Triggered Upgrades

Depending upon the nature and scope of damage and proposed repair, building permits and other government agency approvals may be required by the local jurisdiction. In addition to normal changes in the building code over time, some jurisdictions have building code requirements that mandate varying degrees of upgrades if certain damage thresholds are exceeded. The repair guidelines presented herein are intended to represent prevailing best practices and do not include jurisdiction-specific requirements. The local building department should be contacted to determine the existence of any applicable local requirements. Where utilized, technical consultants should be asked to address any code-triggered upgrades that may be required to comply with applicable local building code requirements as part of the repair of earthquake damage.

CHAPTER 7

Fireplaces and Chimneys

7.1 Quick Guide

This section provides a summary of where to look, what to look for, and when a technical consultant might be needed regarding a damage assessment of fireplaces and chimneys. A more detailed discussion begins at Section 7.2.

7.1.1 Where to Look: Exterior Chimney

1. Examine exterior portions of the fireplace and chimney for collapse, cracking, tilting, or displacement relative to the building. Binoculars may be useful, especially for taller chimneys.

7.1.2 What to Look For: Exterior Chimney

If any of the following conditions exists, a technical consultant may be needed.

1. Collapse, visible cracking, tilting, or displacement of the chimney relative to the building.
2. Deterioration of exposed mortar.
3. Displaced connection of appliance flues connected to chimneys.
4. Concealed damage: If the condition of the chimney cannot be determined based on visual inspection or if there is concern regarding concealed damage to the flue or masonry, a professional chimney inspector (chimney sweep) should be engaged.
5. Leaning chimney, where the cause of the leaning is unclear or damage to building framing is suspected.

7.1.3 Where to Look: Fireplace

1. Interior: Examine the fireplace facing for signs of relative movement or separation from the surrounding wall and firebox. Examine the firebox for fresh cracking. Where exposed, examine the masonry finishes that wrap around the flue for signs of distress and cracking.
2. Rooftop: Examine the flashing for evidence of recent movement between the chimney and building. Inspect the flue lining for displacement or damage. Check for cracking by attempting to rock the chimney.

7.1.4 What to Look For: Fireplace

If any of the following conditions exists, a technical consultant may be needed.

1. Damage to flashing and counter flashing between the masonry chimney and the roof.
2. Shifted or loose clay flue tile segments and displaced joint mortar.
3. Deterioration of exposed mortar.

4. Separation of interior fireplace facing from, or movement relative to, the adjacent wall or firebox.
5. Displacement of poorly secured metal flue pipe of factory-built fireplaces.
6. Differential movement between fireplace inserts and the firebox.
7. Damage that may allow smoke and sparks to enter walls or attic spaces.
8. Displaced connection of appliance flues connected to chimneys.
9. Concealed damage: If the condition of the chimney cannot be determined based on visual inspection or if there is concern regarding concealed damage to the flue or masonry, a professional chimney inspector (chimney sweep) should be engaged.

7.1.5 Where to Look: Interior Chimney

1. Inspect the chimney for evidence of cracking or shifting. Inspect steel straps (if present) at the connections to the framing for signs of distress and movement. Check metal flues for displacement or damage.

7.1.6 What to Look For: Interior Chimney

If any of the following conditions exists, a technical consultant may be needed.

1. Visible cracks or offsets.
2. Damage to framing adjacent to chimney or where metal tie straps from masonry attach to framing.
3. Damage to flashing and counter flashing between the masonry chimney and the roof.
4. Shifted or loose clay flue tile segments and displaced joint mortar.
5. Deterioration of exposed mortar.
6. Damage that may allow smoke and sparks to enter walls or attic spaces.
7. Open or offset joints in metal flues.
8. Displaced connection of appliance flues connected to chimneys.
9. Concealed damage: If the condition of the chimney cannot be determined based on visual inspection or if there is concern regarding concealed damage to the flue or masonry, a professional chimney inspector (chimney sweep) should be engaged.
10. Leaning chimney, where the cause of the leaning is unclear or damage to building framing is suspected.

7.1.7 Repair Guidelines

Structurally insignificant earthquake damage can be addressed as described in Section 7.8.

7.2 Overview

Masonry fireplaces and chimneys are essentially independent, self-supporting structures often constructed on their own foundations, although connected to or abutting walls and upper floors, ceilings, and roofs. Due to their heavy mass, relatively high stiffness, and generally low strength, masonry chimneys are one of the elements most vulnerable to earthquake damage in a house and historically have performed very poorly during earthquakes. Because the masonry chimney and wood-frame house respond differently to earthquake shaking, relative movements can occur between the two and cause pounding damage between the chimney and building, particularly at the ceiling and roof. Unreinforced chimneys have a tendency to either crack or overturn at the roofline during strong ground shaking. Reinforced chimneys (i.e., chimneys with steel reinforcing bars embedded in the masonry) typically do not suffer as much serious damage. Chimneys constructed along an exterior wall have a tendency to pull away from the building, either creating a gap between the chimney and building or completely overturning. The firebox of masonry fireplaces will typically not be damaged during earthquakes but will generally exhibit cracks that formed from thermal stresses during normal use. Clay tile chimney flue liners can be damaged during an earthquake, particularly if the chimney is unreinforced and there are voids between the flue and surrounding masonry.

Most California houses with fireplaces built after 1980 use factory-built fireplaces with insulated metal flue pipes. The factory-built fireplace is constructed of a light-gauge metal. The flue pipes may be concealed by a wood-frame chase finished with such materials as stucco, wood siding, or stone veneer. Given their light weight, flexibility, and relative strength, factory-built fireplaces and metal flues are much less vulnerable to earthquake damage.

Some masonry fireplaces have been retrofit with fireplace inserts that should not be confused with factory-built fireplaces.

A thorough inspection of masonry chimneys and fireplaces typically requires assessments from the ground level, building interior, attic, and roof.

Seriously damaged masonry chimneys are generally not repaired with the same materials; rather they are replaced either in whole or in part with metal flues. The interior facings applied around both masonry and factory-built fireplaces sometimes separate and fall if they are poorly secured to the underlying framing. Such finishes can be replaced with the same material when proper masonry veneer connections are used, provided the fireboxes are repairable or undamaged.

7.3 Limitations

This section addresses the most common types of conventional fireplace and chimney construction. Damage to chimneys and fireplaces of unconventional construction, such as cast-in-place concrete, or construction that is structurally integrated with the building may warrant evaluation by a technical consultant.

7.4 Description of Typical Construction

The overwhelming majority of California residential masonry chimneys are associated with fireplaces. Masonry chimneys can also be used to vent mechanical appliances, such as furnaces and water heaters, but this is uncommon in California and will generally be found only in houses older than about 50 years.

The following are common general types of chimney structures:

- Unreinforced brick masonry chimneys constructed with lime-based mortars. Such chimneys were typically constructed before 1930 and are the most susceptible to earthquake damage as lime mortars exhibit very low strength properties including low bond strengths with the brick masonry. Lime mortars are so soft that the mortar can be easily removed or scraped away with an object, such as the tip of a screwdriver.

- Unreinforced brick masonry chimneys constructed with Portland cement-based mortars. These mortars exhibit greater strength properties than lime-based mortars and have resulted in chimneys exhibiting somewhat better performance during earthquakes (Figure 7-1).
- Reinforced brick masonry chimneys constructed with Portland cement-based mortars. Masonry chimneys and fireplaces in California are typically reinforced if constructed after provisions of the 1967 Uniform Building Code (or more recent versions) were adopted and enforced by the governing municipality. If constructed on an exterior wall, the code also required strapping the chimney at each floor and ceiling level more than 6 feet above grade.
- Monolithic precast or cast-in-place concrete fireplace and chimney units. Although not common, these have been used in some housing developments in California.
- Non-masonry chimneys consisting of metal flue pipe (either double or triple wall) attached to a factory-built fireplace. The metal flue pipe associated with a factory-built fireplace is typically concealed by a much larger wood-frame chase covered with wood siding, stucco, or stone veneer intended to architecturally mimic the size of a masonry chimney. The top of the chase is capped with a metal cap flashing. Due to their light weight, these fireplaces and flues typically suffer little to no damage during an earthquake.

Figure 7-1 Damage to masonry chimney at shoulder (photo credit: K. V. Steinbrugge, NISEE e-Library).

As illustrated in Figure 7-2 through Figure 7-4, the main components of a masonry fireplace and chimney structure are:

- Foundation: Typically consists of a poured concrete footing.
- Hearth: Consists of the floor of the firebox and outer hearth, which extends beyond the front of the fireplace.
- Firebox: Consists of an open chamber lined with refractory brick.
- Face or facing: A decorative finish of brick or stone masonry applied over the front edge of the firebox and surrounding wall.
- Chimney: Extends from the top of the fireplace up through the roof.
- Flue liner: Constructed of clay tile that are resistant to the detrimental effects of combustion products.
- Crown or cap: Tops the masonry chimney.
- Steel straps: Anchors the chimney to the building at the ceiling or roof level (Figure 7-4).
- Flashing: Seals the intersection between the chimney and the roofing.
- Spark arrester: A metal screen covering the flue to prevent the escape of burning embers.

Unlined or Lined Chimneys

Masonry chimneys can be either unlined or lined. Unlined chimneys are uncommon and are typically found in houses built before adoption of the first Uniform Building Code, in 1927. A typical liner consists of refractory clay flue tile segments that are stacked and mortared at the joints with a refractory mortar. If the chimney is unreinforced, the flue lining typically has a void space between the flue tile and surrounding brick masonry. In a reinforced masonry chimney, this space is more likely reinforced and grouted.

As illustrated in Figure 7-5 through Figure 7-9, the main components of a factory-built fireplace and chimney are:

- Factory-built fireplace: A sheet-metal unit with the hearth and firebox lined with refractory panels.
- Face or facing: An optional decorative finish of brick or stone masonry applied over the front edge of the firebox and surrounding wall.
- Metal flue: Consists of interlocking sections of stainless steel and galvanized double wall pipe.
- Fire stops: Consist of flat sheet metal that encircles the flue, laterally stabilizing the flue as well as closing off the space between the flue and surrounding framing.
- Chimney chase: A common but optional wood-frame decorative enclosure of the metal flue that may be finished with wood siding, stucco or stone, or masonry veneer.
- Cap flashing: A sheet metal assembly covering the top of the chimney chase.
- Spark arrester: A metal screen covering the flue to prevent the escape of burning embers.

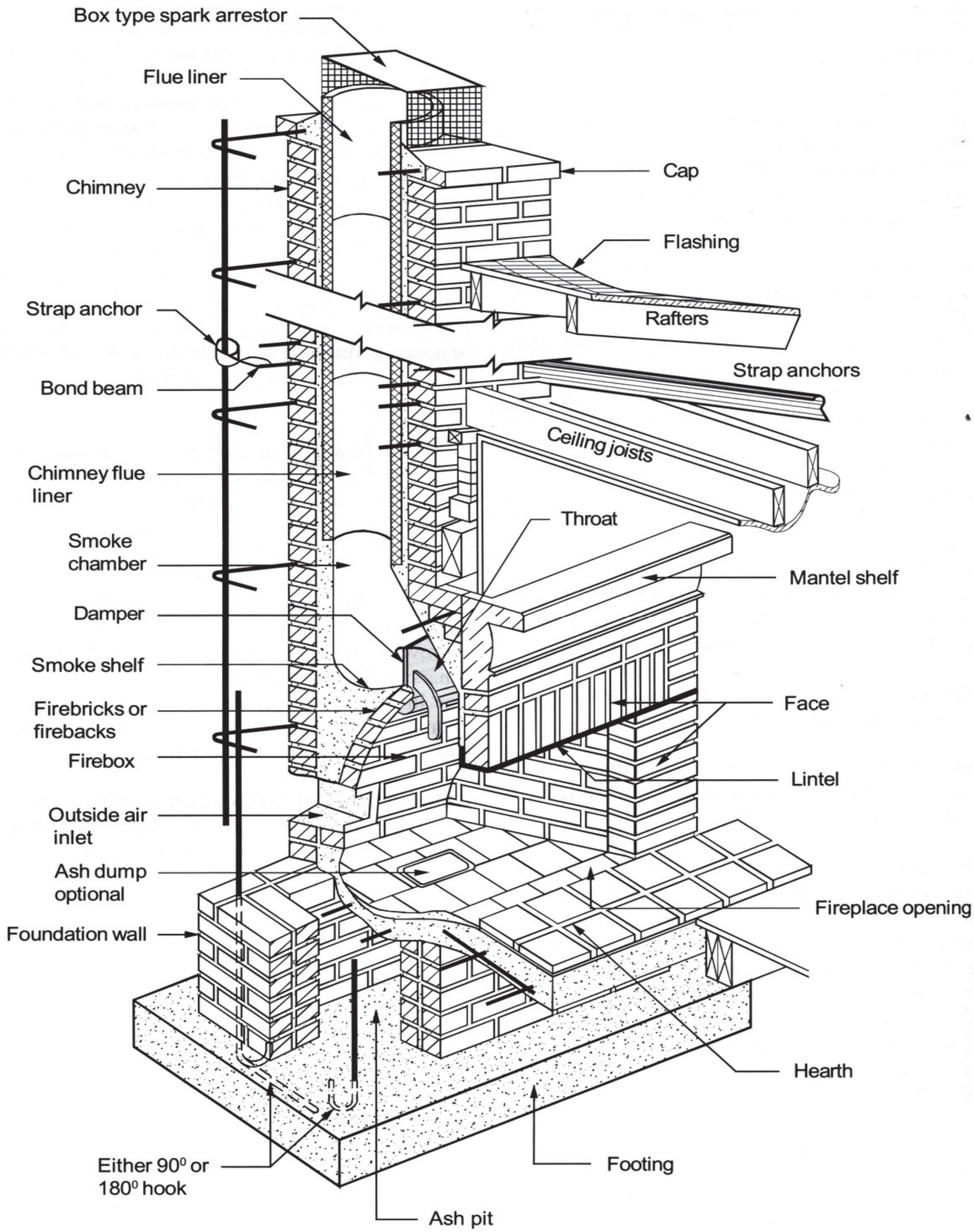


Figure 7-2 Schematic diagram of masonry fireplace and chimney structure (MIA, 2004).

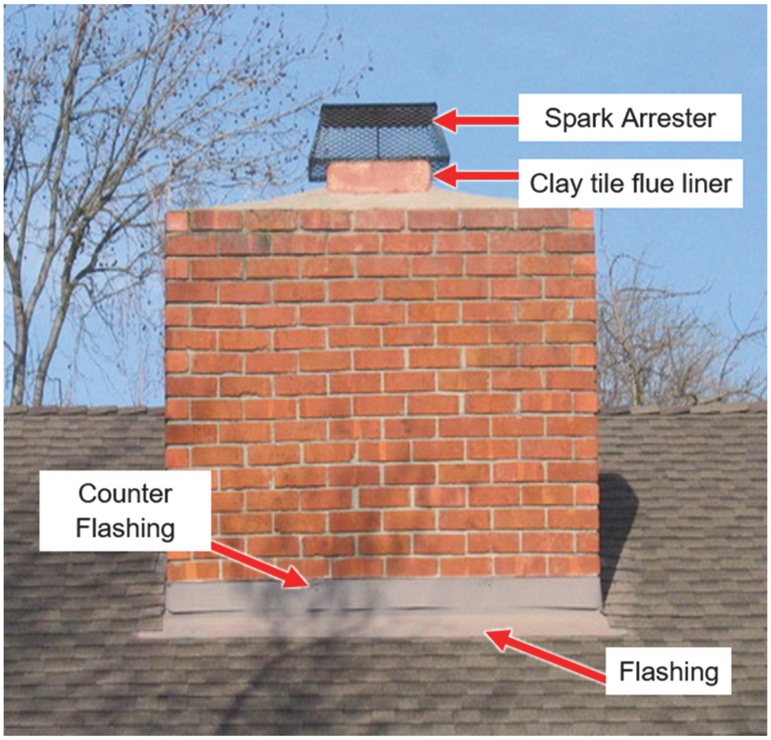


Figure 7-3 Undamaged masonry chimney above the roof (photo credit: Exponent).

Figure 7-4 Chimney visible in attic with undamaged steel tie strap between chimney and framing (photo credit: Exponent).

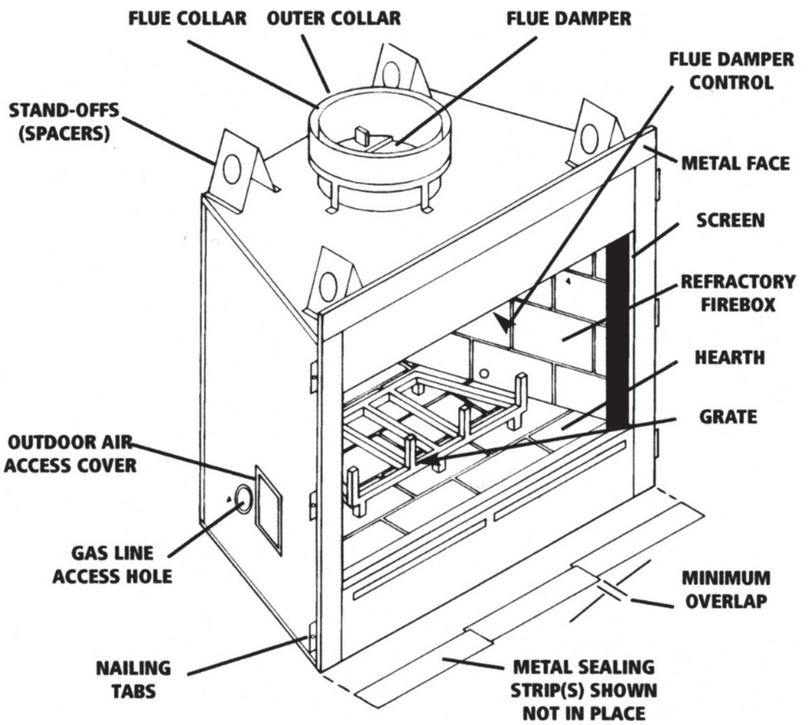


Figure 7-5 Schematic diagram of a factory-built fireplace (HEF, 2003).

Figure 7-6 Undamaged factory-built fireplace and metal flue in wood-frame chase during construction (photo credit: Exponent).

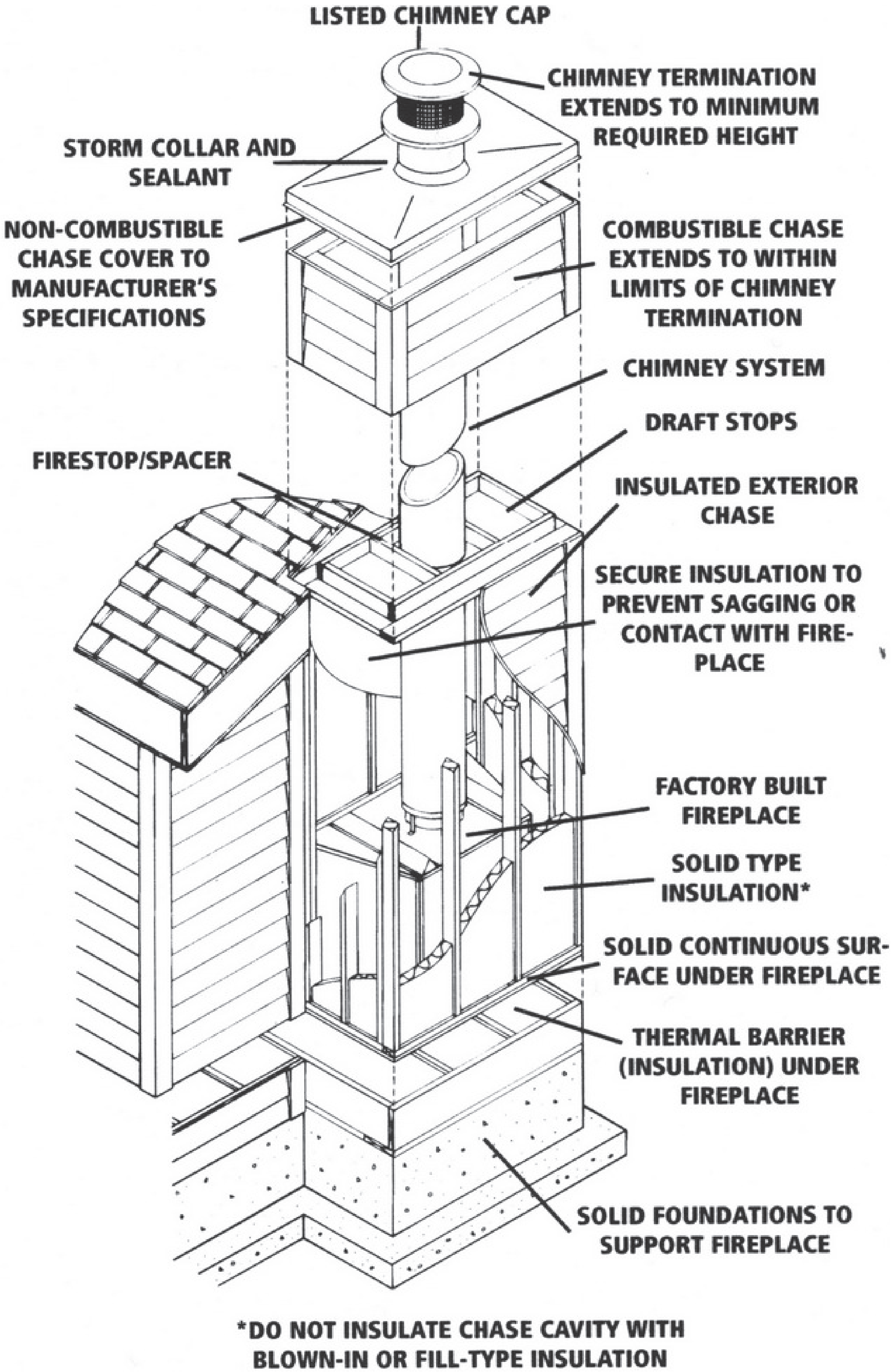


Figure 7-7 Schematic diagram of a factory-built fireplace and chimney assembly (HEF, 2003).

Figure 7-8 Undamaged stucco-clad, wood-frame chimney chase (photo credit: Exponent).

Figure 7-9 Undamaged firebox of factory-built fireplace with brick patterned refractory panels (photo credit: Exponent).

7.5 Non-Earthquake Sources of Damage

7.5.1 *Firebox*

It is extremely common to observe cracked masonry firebrick in the hearth and firebox from thermal-related stresses. This cracking can occur along mortar joints and through the firebrick (Figure 7-10). Such cracking generally has rounded edges and is limited in size and extent. Most of the thermal cracks are less than 1/16-inch wide.

Figure 7-10 Typical thermal cracking of firebrick and mortar lining firebox of a masonry fireplace (Source: Exponent).

7.5.2 *Chimney*

It is not unusual for masonry chimneys to exhibit distress and deterioration due to their weight, the quality of materials, and their environmental exposure. The following are common conditions observed in chimneys in the absence of earthquake damage:

- Hairline crack between masonry and exterior wall: A cold joint or discontinuity exists between masonry fireplaces and chimneys and the surrounding wall finishes. Hairline cracking at the joint is normal (Figure 7-11).
- Long-term settlement: Compared to the adjacent wood-frame building, masonry fireplaces and chimneys are relatively heavy structures and are often supported on independent, shallow concrete foundations. Differential settlement can occur between the chimney and the house, resulting in distress to the roof flashing and exterior siding or finishes at their interface with the chimney. For a

chimney located on an exterior wall, the differential settlement of a chimney foundation can result in gaps (Figure 7-12) between the chimney and house that gradually increase in width towards the top of the chimney (Figure 7-13).

- Isolated cracks: Random cracking of individual bricks (Figure 7-14) and random, isolated cracking of mortar joints are commonly found on most chimneys.
- Combustion products: Combustion products cool and condense as they rise through the chimney flue. The condensation products are acidic in nature and will cause deterioration of the mortar in unlined chimneys or deterioration of the mortar used at joints between flue tile elements in lined chimneys. Even with lined chimneys, flue gases can leak between the flue tile and masonry at deteriorated joints between the tiles. This type of deterioration is usually located near the top of the chimney where the formation of condensation products from combustion is the greatest.
- Natural weathering: Erosion and deterioration of mortar is expected on any brick masonry over the long term. Loose and disintegrated mortar is typically most prevalent above the roofline, because this area is subjected to the heaviest weathering from precipitation.
- Shrinkage cracking of crown or cap: The crown of the masonry chimney is constructed of an unreinforced Portland cement mortar mix. This mix will shrink after mortar placement with the potential for shrinkage cracking.
- Thermal expansion and contraction: The heat from combustion will cause the flue tile to expand. If the flue tiles are free to expand and contract, this movement should not result in any distress. However, if the crown of the chimney is bonded to the tile, this expansion can cause cracking of the crown or, if the crown mortar is well bonded to the brick masonry, lifting of the top few courses of brick.

Figure 7-11 Normal crack between masonry fireplace and chimney and exterior stucco wall (photo credit: Exponent).

Figure 7-12 Gap between chimney and house, where mortar filler was used to fill the previous gap. Since the repair, the gap has widened, evidenced by paint in the gap and the cobweb spanning the gap (photo credit: Exponent).

Figure 7-13 Tapered gap between chimney and house that has resulted from long-term differential settlement of fireplace foundation. Mortar filler was used to fill the previous gap (photo credit: Exponent).

Figure 7-14 Random isolated cracking of brick and mortar joints commonly found on masonry fireplaces and chimneys (photo credit: Exponent).

7.5.3 Interior Facings

Interior masonry facings are generally not well secured to either the wall or firebox. As a consequence, hairline cracks are commonly found at the mortar joint between the facing and the firebox (Figure 7-15) and at the intersection or mortar joint between the facing and wall finishes. Isolated random cracking of the brick or stone and mortar joints of the facing is also common.

Figure 7-15 Mortar joint between firebox and masonry facing where hairline cracks are frequently found (photo credit: Exponent).

7.6 Earthquake-Induced Damage

7.6.1 Fireplace

The firebox of masonry fireplaces typically will not be damaged during an earthquake but will, in general, exhibit cracking as a result of thermal stresses that develop during normal usage. Earthquake-related cracking of the firebrick generally is a result of significant and obvious damage to the surrounding masonry structure (Figure 7-16).

Figure 7-16 Earthquake-induced failure of masonry fireplace at firebox level (photo credit: R. Reitherman).

Because of their light weight, factory-built fireplaces have generally not suffered damage during earthquakes. Isolated random cracking of the firebox in either site-built or factory-built fireplaces is not earthquake related.

7.6.2 Chimney

Due to their heavy mass, generally low strength, and high stiffness, masonry chimneys are one of the most vulnerable elements to earthquake damage in a house and historically have performed very poorly during earthquakes. Predominant earthquake related failure modes of masonry chimneys are:

- "Bending" failures where horizontal cracks develop (generally at the roof line or shoulder at the top of the fireplace), and the upper portion of the chimney may shift or topple (Figure 7-17 through Figure 7-22).

- Failures at and below the firebox (Figure 7-16 and Figure 7-23) are less common and often associated with movement of the entire building relative to the foundation.
- Relative movement between the chimney and the wood-frame building that can create a gap between the chimney and wall (Figure 7-24 and Figure 7-25), damage flashings (Figure 7-26 and Figure 7-27), and possibly damage framing where straps from the chimney are attached (Figure 7-24).
- Separations of outer masonry layers (also called wythes) from inner layers of the chimney masonry.

Figure 7-17 Earthquake-induced damage to masonry chimney above roofline (photo credit: Exponent).

Figure 7-18 Earthquake-induced failure of masonry chimney at roofline (photo credit: Exponent).

Figure 7-19 Earthquake-induced damage to masonry chimney in attic (photo credit: Exponent).

Figure 7-20 Earthquake-induced failure of masonry chimney at gable (photo credit: Exponent).

Figure 7-21 Earthquake-induced damage to masonry chimney at mid-story (photo credit: Exponent).

Figure 7-22 Earthquake-induced damage to masonry chimney at shoulder (photo credit: F. Lewis, NISEE e-Library).

Figure 7-23 Earthquake-induced damage to masonry fireplace at foundation level (photo credit: Exponent).

Figure 7-24 Earthquake-induced masonry chimney and fireplace that have tilted away from the house. The chimney tore loose the wood framing to which steel tie straps from the chimney were attached (photo credit: L. S. Cluff, NISEE e-Library).

Figure 7-25 Earthquake-induced tapered separation between masonry chimney and exterior wall. There is also damage to the top of the chimney due to deterioration of mortar (photo credit: Exponent).

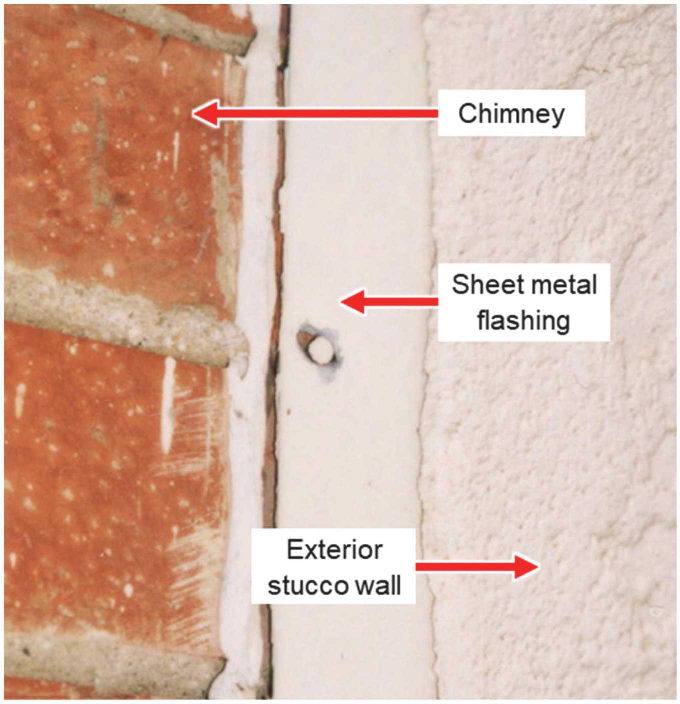


Figure 7-26 Relative cyclic movement between chimney and building caused by earthquake, indicated by elongated hole in metal flashing and gap between caulking and flashing (photo credit: Exponent).

Figure 7-27 Tearing of flashing between chimney and roof caused by relative movement between chimney and building during earthquake (photo credit: Exponent).

When surrounded by the building, the most common location for earthquake damage to masonry chimneys is at the roofline. Unreinforced chimneys have a tendency to either crack or overturn at the roofline during strong ground shaking. Chimneys constructed of lime mortars have a tendency to break apart into smaller units of masonry due to the weak strength properties of this mortar (Figure 7-28). Chimneys constructed with Portland-cement mortars, although exhibiting higher bond strengths than lime mortars, break apart into larger elements. Reinforced chimneys typically do not suffer serious damage when confined by the building.

Chimneys constructed along an exterior wall have a tendency to pull away from the building, either creating a gap between the chimney and building or completely overturning. Unreinforced chimneys tend to break into smaller sections (Figure 7-29), whereas reinforced chimneys generally hold together and move or overturn about the base as a single unit (Figure 7-24).

Damage to the clay tile chimney flue is uncommon in reinforced masonry chimneys, where the flue is well supported by grout. The clay tile chimney flue liner can, however, be damaged during an earthquake if the chimney is unreinforced and there is a void space between the flue and surrounding masonry, leaving the flue liner laterally unsupported. A damaged flue is a safety risk when the chimney is in use.

Figure 7-28 Rooftop debris from collapse of masonry chimney during earthquake (photo credit: D. Dyce).

Figure 7-29 Collapsed unreinforced stone chimney caused by earthquake (photo credit: M. G. Hopper, USGS Denver Library Photographic Collection).

Metal flues, if properly installed, perform well during earthquakes. Those flues installed without proper intermediate fire stops are vulnerable to shifting or misalignment, which can cause joints between pipe sections to open. Also, poorly attached metal flue chimneys have been observed to separate from houses in past earthquakes. Generally, wood-frame chases behave as wall panels and should be evaluated as such in accord with Chapter 5. A unique problem with wood-frame or light steel-frame chases that extend above the roof is that some may not be properly framed or attached to the roof structure and can break loose during strong ground shaking.

7.6.3 Interior Facings

Interior masonry facings (e.g., hearth, mantel) are often not well secured. Consequently, they can pull away from the wall (Figure 7-30) or collapse (Figure 7-31). Hairline cracks at the intersection between the facing and wall finishes, or the intersection between the facing and the firebox, should not be mistaken for earthquake-related damage.

Figure 7-30 Masonry mantle that separated slightly from the wall finish during earthquake (photo credit: Exponent).

Figure 7-31 Collapsed masonry facing caused by earthquake (photo credit: Exponent).

7.7 Assessment Guidelines and Methodology

The condition of the chimney and fireplace structure should be assessed from the exterior at ground level and from the interior, attic, and roof level. The first step should be determination of the type of fireplace and chimney (See Section 7.4). Factory-built fireplaces and flues can be distinguished from other types of fireplaces and chimneys by one or more of the following elements: metal firebox; a metal flue pipe extending above the roof; a wood-frame chimney chase covered with finishes, such as stucco, wood siding, or masonry veneer; and a metal cap on the chimney chase.

7.7.1 Ground Level

From the exterior or ground level look for evidence of collapse (debris may have been cleaned up), visible cracking, tilting, or displacement relative to the building. A pair of binoculars may be useful to inspect the chimney, particularly if a roof is too steep for safe mounting without special fall protection.

A masonry chimney located on an exterior wall may exhibit a separation along the vertical joint between the chimney and building, which grows in width towards the top of the chimney (Figure 7-25). This separation may be earthquake-induced because masonry chimneys are essentially independent structures and are constructed on their own foundations. This separation can also be caused by long-term differential settlement of the chimney foundation relative to the building's foundation. If a separation is observed, close examination of the joint between the chimney and building is required to better assess the cause. If there are one or more generations of intact sealant between these two elements, it is clear that the earthquake was not the cause. If this gap is open or a failed sealant is observed, additional investigation is necessary to determine the nature and extent of any damage to the chimney or attached framing. A fresh, unweathered appearance to this gap may indicate that the separation resulted from the earthquake. This conclusion should, if possible, be verified at the chimney flashing. By contrast, the accumulation of dust, debris, cobwebs, or paint in an open joint indicates that long-term foundation settlement is the more likely cause.

The shoulder area of any masonry fireplace and chimney on an exterior wall should be carefully inspected for cracking or damage. The transition between the chimney and firebox is a natural location for cracking if the chimney separates from the building. For reinforced chimneys, minor cracking at this location (less than 1/16 inch) is probably not serious; however, the integrity of the flue should be checked with a smoke test by a qualified chimney inspector. If the chimney is unreinforced, cracking at the shoulder will likely require removal of the chimney, at least down to the shoulder.

To determine the type and condition of the mortar, perform a screwdriver test by probing mortar head and bed joints between masonry at random locations on the chimney, particularly in areas most exposed to weathering. Mortar that is impervious to a screwdriver indicates higher strength and greater earthquake resistance than mortar that crumbles or chips, which can be an indication of weak mortar with lime content or deterioration due to long-term weathering.

Some masonry chimneys are covered with a stucco finish. It is common to see some shrinkage cracking in the stucco finish; random, weathered cracking is indicative of shrinkage cracking. Earthquake-induced cracking of the masonry will telegraph through the stucco finish; look for fresh horizontal stucco cracking at roofline and chimney shoulder.

7.7.2 Interior

Examine fireplace facings for signs of recent separation from, or movement relative to, the adjacent wall and relative to the firebox.

Masonry fireboxes should be inspected for fresh, conspicuous cracking. Thermal-related cracking of the firebrick from burning fires is common and often mistaken for earthquake damage. If a fireplace insert is installed, check for signs of differential movement, such as fresh cracking, between the insert and fireplace.

Where chimneys are exposed on the interior, inspect the finishes that wrap around the masonry flue for signs of distress and cracking.

7.7.3 Roof

Masonry chimneys should be inspected from the roof level whenever it is possible to safely do so. Some roofs are too steep to safely inspect the chimney without fall protection. Occupational Safety and Health Administration's (OSHA's) steep-slope fall-protection regulations apply to roofs that have slopes greater than 4-in-12 (18 degrees) with unprotected sides and work surfaces that are at least 6 feet above a lower work level or the ground. If the roof is too steep, some inspection can often be accomplished from a strategically placed ladder and binoculars, or with a telephoto lens or drone.

Inspect the chimney for evidence of recent movement between the chimney and building. Most chimneys have metal flashing and counter flashing to weatherproof the roof at this penetration. Relative movement between the chimney and surrounding building can distort the flashing or pull the flashing from under the counter flashing. In some cases, roof mastics or sealants have been used to seal problematic flashing details. Such methods have little flexibility and are easily torn by minor relative movements. On chimneys located on exterior walls, multiple layers of mastic/sealant can indicate historic, long-term problems with chimney movement due to differential foundation settlement.

Inspect the crown of a masonry chimney. Cracking of the mortar cap or crown is common but is generally not caused by earthquakes. However, crown mortar in poor condition could allow shifting of the flue liner at the top of the chimney.

Remove the spark arrestor and use a flashlight or mirror (on sunny days) to illuminate and inspect the clay flue lining (or metal flue pipe in non-masonry chimneys) for displacement and damage. Look for significantly shifted or loose clay flue tile segments and displaced joint mortar. Be careful to distinguish between recent shifting of flue tile segments and mere imperfections in the original manufacture or installation of the flue tile. Recent fractures or offsets often are conspicuous by the lack of creosote build-up.

Note whether there is creosote build-up in the flue, which can indicate heavy use of wood fuels. The condensate of combustion gases is acidic and can cause deterioration of exposed mortars. Natural weathering of the chimney mortar is also most severe above the roofline. It is common to see deteriorated and eroded mortars on older chimneys.

Tap the clay flue liner lightly with a hard object. A hollow sound will indicate a void space between the liner and brick masonry, a possible indicator that the chimney is unreinforced. A solid sound indicates that there is no void and that the masonry is grouted and likely reinforced.

For unreinforced masonry chimneys that do not exhibit visible damage from the roof, attempt to rock the top of the chimney (from all four sides, if possible) by firmly pushing it, as shown in Figure 7-32. This task should be performed with extreme caution. Ensure that no harm from any falling masonry will occur before commencing. This inspection may require another person to look for a separation that opens during pushing; although, an experienced inspector can detect cracking by the "feel" of the chimney's response to rocking. There is a distinctly different feel when pushing a cracked chimney—the chimney will rock slightly if damaged, but a chimney that is not cracked will feel quite solid and will not rock. This procedure should not be performed on any chimneys with lime mortars or severe weathering due to their extremely poor bond strength. Perform a screwdriver test to check for weak lime mortar or deterioration of Portland-cement mortar.

Figure 7-32 Illustration of rocking procedure for checking chimney for earthquake-induced cracking (photo credit: Exponent).

7.7.4 *Attic*

Chimneys should be inspected from the attic whenever possible. Care should be taken when entering attic spaces, including use of appropriate eye protection and a respirator as required. Disposable coveralls and kneepads are also advised. Step or place your weight only on the attic framing and not the ceiling finishes. See Appendix F for attic inspection safety guidelines.

Chimneys that are internal to the building should be inspected for evidence of cracking or shifting. In particular, focus on the portions of the chimney near roof and ceiling lines. Examine the framing surrounding the chimney for signs of pounding (i.e., impact between masonry and wood framing) between the chimney and the house or other types of damage. Check the condition of attachment of any steel straps between the chimney and framing, either at the ceiling or roof level.

Chimneys located on the exterior wall may be exposed in the attic area. Wall sheathing may conceal a chimney located on the gable end. Chimneys located along a roof eave will not be visible in the attic; however, if exposed, check for signs of cracking. If constructed in accordance with the 1967 UBC or later edition, the chimney should be secured to the attic framing. Inspect the strap at the connections to the framing for signs of distress and movement.

7.7.5 *Consultant Assessment*

Additional inspections by one or more technical consultants may be necessary to refine initial assessments if any of the following conditions are noted:

- Damage to flue lining: If it is uncertain whether or not the flue lining was damaged by the earthquake, a camera scan of the flue pipe should be performed by a professional chimney inspector.
- Cracking of chimney: If there is concern regarding cracking of the chimney in inaccessible locations, a smoke test can be performed by a professional chimney inspector.
- Minor differential movement between fireplace and chimney and building: A gap between the building and the fireplace and chimney can represent a long-term condition resulting from differential settlement of the chimney foundation, or it can represent earthquake-induced damage. If the cause is uncertain, a technical consultant should be retained.
- Chimney repair: A design professional may be required by local building officials if a masonry chimney is to be repaired or rebuilt using masonry.

7.8 Repair Methodologies

Appropriate repairs are a function of the nature and extent of earthquake damage, original construction details, and local building code requirements. Once damage to the fireplace and chimney has been assessed, the local building official should be consulted for guidance as to damage level triggers and corresponding repair requirements, if any.

Damage from minor relative movement, such as damage to flashings, mastic, or caulking, that does not extend to cracking of a masonry chimney can be repaired with like kind and quality materials. Damaged or collapsed interior masonry facings can also generally be replaced with materials of like kind and quality if the chimney and the rest of the fireplace are undamaged or repairable.

In reinforced chimneys, cracking without significant offset can be repaired by routing out and tuck-pointing the cracked mortar joints. For more serious damage to a properly reinforced chimney, it will generally be necessary to demolish that portion of the chimney above the level of damage (assuming it has not collapsed) and rebuild the upper portion or replace just the upper portion with a metal flue pipe tied into the remaining portion of the undamaged chimney flue.

For damaged unreinforced masonry chimneys or damaged flue liners, the local building official may allow use of the undamaged firebox but require replacement of the entire chimney with an insulated metal flue pipe (similar to that installed with factory-built fireplaces) enclosed in a wood-frame chase.

Even well-designed and -constructed masonry fireplaces and chimneys are vulnerable to damage under ground shaking of moderate intensity. Given this poor seismic performance, it is recommended that damaged fireplaces and chimneys not be replaced with in-kind materials. Rather, it is recommended that they be replaced with a factory-built fireplace and metal flue, which will provide much better performance in future earthquakes.

Table 7-1 gives appropriate repair methods for typical earthquake damage patterns. If the cause of an observed damage pattern cannot be determined, or if the damage is outside the description given in the table, consider retaining a technical specialist to specify appropriate repair.

Table 7-1 Repair Methods Not Requiring Technical Consultant Assistance for Nominal Earthquake Damage to Chimneys[1, 2]

Element	*Earthquake Damage Pattern*	*Repair Method*
Chimney	Cracks in individual bricks less than 1/16-inch wide, no offset, slope or settlement	No repair
	Crack in bricks less than 1/8-inch wide, no offset or spall	Remove and replace bricks
	Spall in chimney bricks or mortar, extending only partially through width of bricks	Remove and replace bricks
	Crack in mortar joint less than 1/8-inch wide, no offset, slope, or settlement	Repoint mortar joints

(1) Repair methods presented in this table presume that the building materials are free of regulated levels of hazardous materials. If testing as recommended in Section 9.2.4 indicates the presence of regulated levels of asbestos or lead, the abatement and waste disposal recommendations of the environmental consultant should be incorporated into the overall scope of repair.

(2) Identify damage pattern and repair where damage has been identified during the damage investigation. Select damage pattern most representative of observed damage caused by or worsened by the earthquake. See Section 1.2.3 for discussion of worsened damage.

7.8.1 Permits and Code-Triggered Upgrades

Depending upon the nature and scope of damage and proposed repair, building permits and other government agency approvals may be required by the local jurisdiction. In addition to normal changes in the building code over time, some jurisdictions have building code requirements that mandate varying degrees of upgrades if certain damage thresholds are exceeded. The repair guidelines presented herein are intended to represent prevailing best practices and do not include jurisdiction-specific requirements. The local building department should be contacted to determine the existence of any applicable local requirements. Where utilized, technical consultants should be asked to address any code-triggered upgrades that may be required to comply with applicable local building code requirements as part of the repair of earthquake damage.

CHAPTER 8

Mechanical, Electrical, and Plumbing Systems

8.1 Quick Guide

This section provides a summary of where to look, what to look for, and when a technical consultant might be needed regarding a damage assessment of mechanical, electrical, and plumbing systems. A more detailed discussion begins at Section 8.2.

8.1.1 Where to Look

1. Water heaters can typically be found in garages, basements, or closets.
2. Condenser units for air conditioning systems are located outside the building, either at grade or on the roof.
3. Evaporative cooling units are typically found on the roof or in attics, garages, basements, or closets.
4. Furnace and air conditioning units can be found in garages, basements, attics, or closets or on rooftops.
5. Fuel oil tanks are typically found in the basement, near the furnace unit.
6. Propane tanks are typically found in rural locations away from the house on a concrete slab.
7. Check water flow and pressure at all sinks.
8. Check water flow in clothes washers, built-in dishwashers, and water dispensers.

8.1.2 What to Look For

If any of the following conditions exists, a technical consultant may be needed.

1. Loose overhead electrical service wires, excessive sag, or exposed conductors.
2. Water heater(s) toppling or shifting; leakage from tanks, leakage from water connections, or displaced flue connections; or damage or leakage at gas lines or electrical connections.
3. Toppling, shifting, damage, or leakage at refrigerant and electrical lines of the air conditioning condenser unit(s).
4. Toppling, shifting, damage, or leakage at power and water connections of the evaporative cooling unit(s).
5. Shifting, damage, or leakage at gas lines, flue connections, electrical connections, and condensate drain connections of the furnace(s).
6. Damage or leakage at the gas lines of gas clothes dryers and gas stoves.
7. Rocking or broken closet collar bolts of toilets.

8. Toppling, shifting of the stove or flue of freestanding wood stoves.
9. Toppling, shifting, damage, or leakage at fuel connections of fuel oil and propane tanks.
10. Shifting and leakage at water connections of roof-mounted solar panels.
11. Other signs of water damage or evidence of leakage from water supply lines or sprinkler systems.
12. Shifting, connection failures, or broken piping of pool and spa equipment.
13. Consider contacting a plumber if any of the following are observed:
    a. reduced water flow to appliances or faucets (inline screens, filters, and bubble strainers may need to be cleaned), or
    b. ground cracking or failure at the property or in the vicinity (a plumber should leak test the sewer lateral and pressure test the underground water piping).
14. Consider contacting a qualified heating, ventilation and air conditioning (HVAC) repair person or contractor if any of the following are observed:
    a. misaligned flues or exhaust vents from any gas, oil, or wood-fired appliances (in this event, proper ventilation must be verified), or
    b. leakage from refrigerant lines at condenser or evaporator coils.
15. Consider contacting a leak detection service if any of the following conditions are observed:
    a. sliding or shifting of the building or concrete slab-on-grade floor relative to the foundation,
    b. ground cracking or failure at the property or in the vicinity,
    c. seepage or leakage in the basement, crawlspace, utility closets, or at the baseboard in the basement or on the ground floor of the structure, or
    d. saturated zones of soil adjacent to the perimeter of the structure.
16. Wiring pulled loose as a result of shifting of equipment or structural damage.

8.1.3 Repair Guidelines

Earthquake damage can be addressed as described in Section 8.8. Repair of typical earthquake damage to mechanical, electrical, and plumbing (MEP) systems generally consists of component repair or replacement in kind.

8.2 Overview

If there are conditions observed that call into question the integrity of gas lines, furnace or water heater flues, or electrical connections, contact appropriate utility companies or service personnel before restoring utility services to the house.

Typical residential MEP systems consist of one or more heating and air conditioning systems (Figure 8-1); electrical service and branch circuits to which plumbing or mechanical equipment may be hard wired; low voltage wiring for phones and alarm systems; coaxial cable TV wiring; built-in appliances; plumbing fixtures; water and gas supply lines; and sewer lines.

Figure 8-1 Undamaged rooftop HVAC unit (photo credit: Exponent).

Earthquake damage to MEP systems and equipment typically occurs where:

- large, heavy pieces of equipment (e.g., water heaters, propane tanks, fuel tanks) are not properly restrained, as shown in Figure 8-2 and Figure 8-3,
- rigid water, gas, refrigerant, electrical, or other connections to equipment do not allow relative motion between the equipment and the building,
- significant displacement occurs at penetrations of partitions or slabs resulting in breakage of pipes or conduits, or
- permanent earthquake-induced ground displacement ruptures buried utility lines.

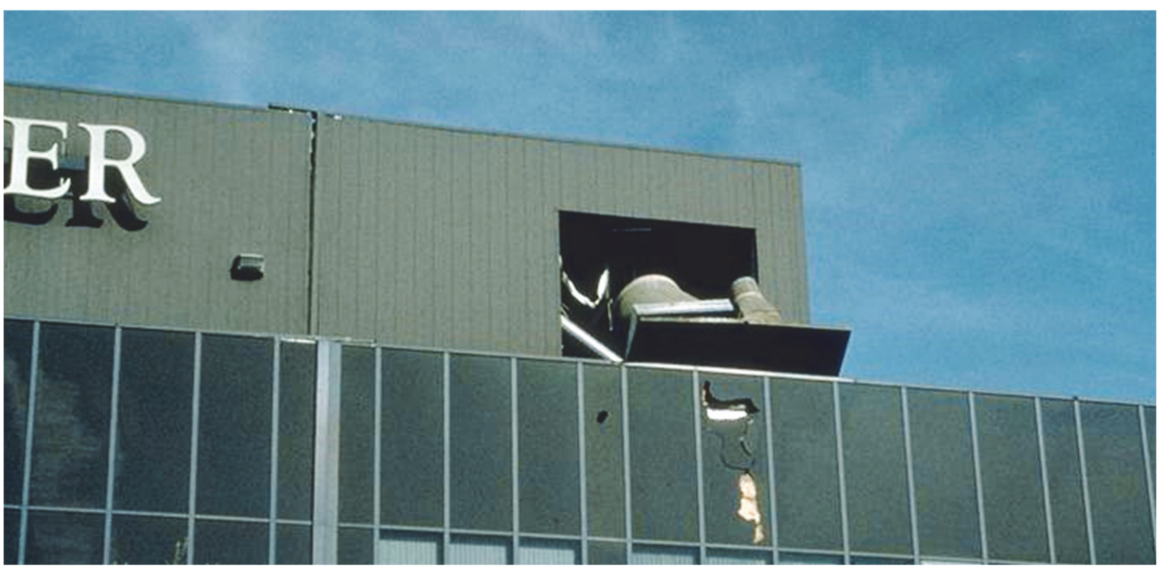


Figure 8-2 Earthquake-casued damage to rooftop HVAC unit (photo credit: R. K. Reitherman, NISEE e-Library).

Figure 8-3 Earthquake-caused displacement of unsecured water heater (photo credit: Exponent).

An inspection of these systems should include a review of all large or heavy pieces of equipment in the house. This will include water heaters, air conditioning condenser units, furnaces, toilets, and any type of liquid storage tanks. If an inspector sees there is no bracing of a water heater, it should be mentioned to the property owner, and when a water heater is installed, it should be braced per local codes.

Ductwork, flues, wiring, and piping concealed within walls or floors are generally more robust than the surrounding framing and wall finishes. Thus, destructive investigation of concealed systems is generally not recommended.

Damage to water lines inside the house will most likely be in the form of pipe breakage (as opposed to pin holes) and is usually readily apparent via the resultant water damage or unusual accumulation of water in crawlspaces or elsewhere on the property. If there is evidence of ground separation (see Chapter 3), there is also the possibility of damage to underground water, sewer, and gas lines. Damage to underground sewer lines is more difficult to detect from a visual inspection. However, because sewer lines run underground in a similar manner to water supply pipes, damage to sewer lines is possible when other utility lines on the property have been damaged or evidence of earthquake-induced permanent ground deformation is present on the property. If there is evidence of utility line damage, ground separation on the property, or shifting or sliding of a concrete slab-on-grade floor relative to the foundation, contact a leak detection service to verify the integrity of the underground sewer line.

Commonly, the shaking inherent in earthquakes can result in dislodging of corrosion, scale, or other debris in water lines, which can, in turn, result in plugging of filters, aerators, or other constrictions in water supply lines. Reduced water pressure at a particular fixture reported by an owner or occupant after an earthquake can be an indicator of this condition. This problem is usually easily remedied by removing and cleaning or replacing the affected filters or aerators.

8.3 Limitations

This document addresses only the MEP systems that are typically found in single-family houses. It also applies to small, multi-family dwellings that use similar systems. This document does not apply to the following conditions.

- High-rise buildings with large mechanical systems, such as chillers, boilers, roof-top water tanks, elevators, fire pumps, or cooling towers. Such building systems tend to be more complex and customized than residential systems, and a proper assessment will usually involve the use of mechanical engineering consultants.
- Commercial buildings with a significant amount of roof-mounted mechanical equipment, metal ducting, drop ceilings, and large diameter piping. Again, proper assessment of such buildings may require the use of mechanical engineering consultants.

8.4 Description of Typical MEP Systems

The MEP systems in typical single-family and small multi-family dwellings are fairly simple. This section provides a brief overview of the most common systems and their major components.

8.4.1 Plumbing

The water supply for a house generally comes from a service tap off of a water main near the street. The service tap will usually have a meter for measuring water usage and a shutoff valve that defines the end of the municipal utility's property. The remainder of the line is the property owner's property and usually passes underground from the street to a location near the house where it comes above ground to a second shutoff valve. The water line then splits in various directions to supply cold water to various appliances and fixtures throughout the house, including the water heater, sinks, bathtubs, showers, toilets, refrigerators, dishwashers, clothes washers, and water softeners, as well as in ground irrigation systems, pools and spas, and, in some cases, a fire suppression sprinkler system. There are a variety of materials used for water distribution piping in the house, including copper, galvanized steel, and polymeric (plastic) materials (e.g., PVC, CPVC).

Drain or sewer lines generally feed via gravity back to a sewer main on the street (if in an area with municipal sewers) or to a septic system. In cases where the house is below the street (or septic tank) level, there will also be pumps to lift the wastewater up to the appropriate level. Common sewer piping materials used above and below grade include cast iron, galvanized steel, copper, and plastic. Archaic below-grade-only materials include clay tile and various asphalt composites.

8.4.2 Mechanical

Most houses of recent construction include mechanical systems used for heating and cooling. The most common system is forced air heating and cooling, which uses a blower and a series of ducts to distribute conditioned air throughout the house. Heating is generally provided via an electric, fuel oil, or gas-fired furnace that is co-located with a blower and cooling coil. This unit is generally found in a basement, garage, attic, or closet. For gas or fuel oil-fired systems, a flue will be present to direct combustion gases outside the house via a vent on the roof. Natural gas is generally supplied via a connection to a gas main that has a meter and shutoff valve (Figure 8-4). In areas of the country where earthquakes are common, the gas meter may have an automatic valve that shuts off the gas supply in the event of an earthquake (Figure 8-5). In rural areas where there is no gas service, propane tanks are sometimes used to supply fuel for the property. In certain areas of the country (e.g., New England), fuel oil is commonly used for heating. This fuel oil is similar in composition to automotive diesel fuel and is generally stored in a large tank in the basement near the furnace. Radiant heating systems, which circulate hot water or steam through piping embedded in the floor or are connected to radiators, may also be used.

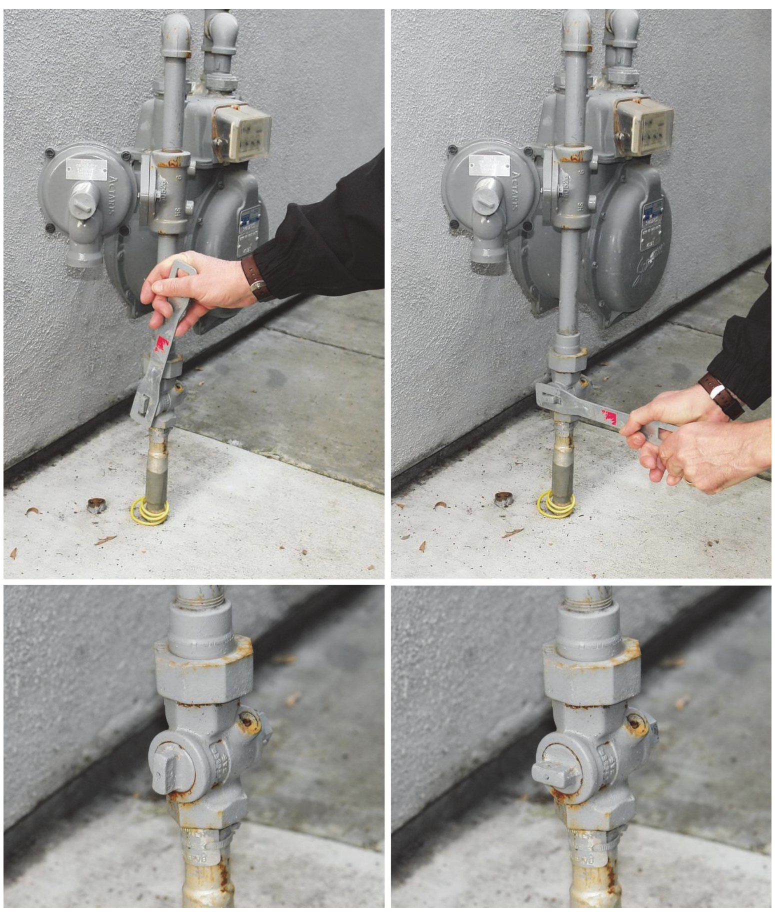


Figure 8-4 Manual gas shut-off valve, where photos on the right show the valve closed (photo credit: Exponent).

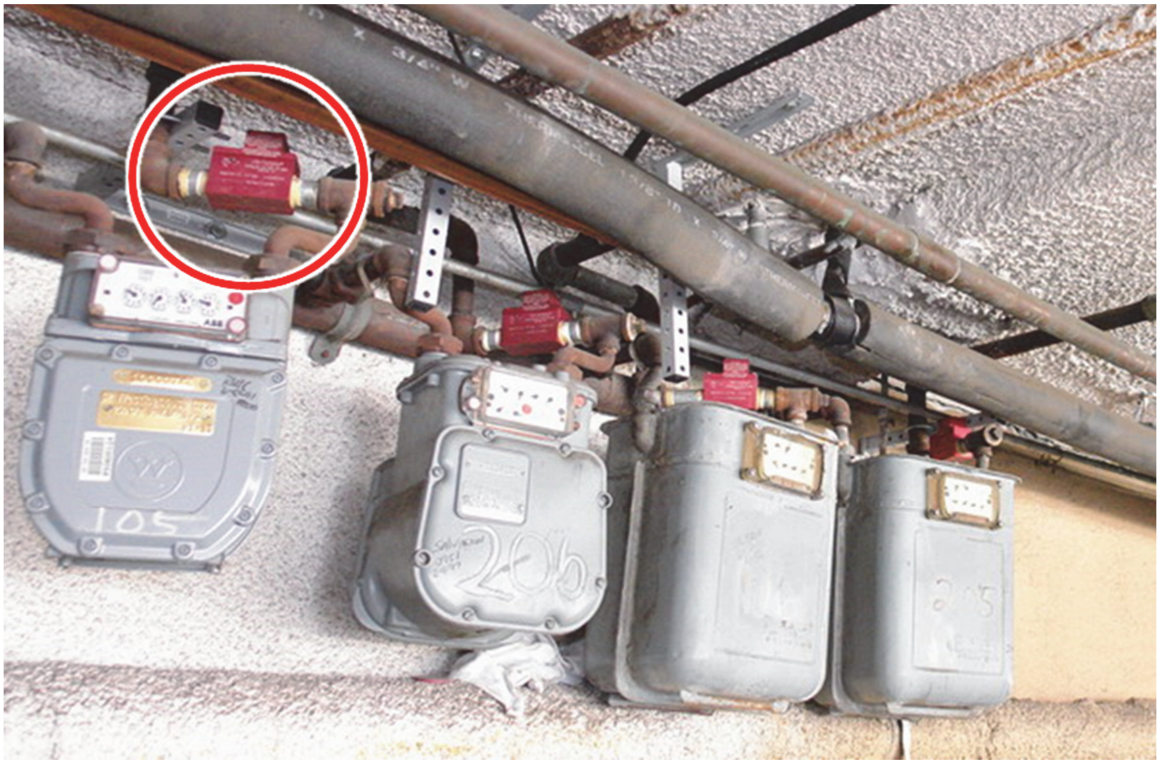


Figure 8-5 Gas meters with seismic shut-off valves (photo credit: Exponent).

Cooling is generally supplied via a split-system, which is composed of a condenser unit (which contains the compressor, a fan, and the condenser coil) and a cooling unit (which contains the expansion valve and cooling coil). The condenser unit is generally located outside, either beside the house or on the roof. The cooling unit is generally located in or adjacent to the same housing as the furnace and uses the same blower and ducting as the heating system.

Evaporative cooling units (i.e., “swamp coolers”) are common in areas of dry heat (Figure 8-6). These units use evaporation of a water mist to cool incoming air and consist of a large housing, filter media, and a large blower. The units are generally mounted on the roof and connected to the living space via direct ducting.

Figure 8-6 Toppled "swamp cooler" due to earthquake (photo credit: Exponent).

8.4.3 Electrical

Electrical power systems consist of a service drop (either overhead or underground) from the utility to an electric meter mounted on the building, a distribution panel with a main breaker (or fuse) and breakers (or fuses) for branch circuits, distribution wiring, and fixtures or electrical devices. The vast majority of residential wiring is flexible cable concealed in walls and ceilings, though plastic or steel conduit is typically used in exposed locations.

In addition to electrical power, most houses will also have a number of low-voltage electrical systems, such as telephone, doorbell, intercom, and coaxial wiring for television antennas, satellite dishes, and cable service.

8.5 Non-Earthquake Sources of MEP System Damage

8.5.1 Plumbing

Plumbing systems are subject to multiple types and sources of deterioration and distress during their service lives, much of which goes unnoticed or is routinely repaired. This section describes conditions commonly found in residential plumbing and sewer systems in the absence of earthquakes.

- Corrosion of water lines: Corrosion of metallic water lines occurs over time to both the interior and exterior of pipe. For example, poor water conditions inside the lines can lead to pitting corrosion in copper water lines, and unprotected underground steel lines can be exposed to exterior corrosion due to ground water exposure. The rates of corrosion can vary dramatically depending on factors such as water conditions, ground conditions, and the presence of dissimilar metals (e.g., copper and steel in contact). Corrosion in water lines generally appears in the form of pits or holes as opposed to cracks or breaks.

- Scale within water lines: Depending upon water chemistry, mineral deposits can accumulate within water pipes, gradually restricting flow in the pipe.
- Plugged sewer lines: Underground sewer lines are susceptible to plugging by plant or tree roots or other obstructions in the lines. These types of obstructions can generally be cleared via snaking or rooting out the lines. Underground lines will settle and shift with the surrounding soil. In cases of poor installation or unstable soil, that movement can result in sags in the line where solids collect or in breaks and offsets in the line, which restrict flow or lead to leakage from the sewer. Differential settlement of utility lines can also occur between the building and the surrounding ground, particularly for buildings supported on drilled piers, where the soil and utilities can settle independently of the building.
- Water heaters have limited service lives that depend on manufacturing quality, water chemistry, and usage. Failure typically manifests as corrosion-induced leakage.
- Washers, gaskets, hoses, and other components wear and deteriorate with time, requiring replacement from time to time to maintain proper function.

8.5.2 Mechanical

Mechanical systems are susceptible to various modes of malfunction and degradation in normal service. Some examples are provided in the following list.

- Low refrigerant pressure: Small leaks in the refrigerant loop of air conditioning systems can lead to a slow loss of refrigerant and degradation in performance.
- Contaminated refrigerant lines: Over time, debris from wear, corrosion, or other mechanisms can make the refrigerant in an air conditioning system contaminated.
- Dirt and dust accumulation: Over time, ducts, filters, supply and return registers, and blowers can accumulate dust and dirt.
- Poor lubrication, loose belts: Lubrication and belt tension are routine preventative maintenance items for mechanical systems.
- Soot and corrosion in fired furnaces: Over time, combustion products, including smoke, soot, and water, can build up along with corrosion products in combustion chambers, leading to failure of heat exchangers and flue piping.

8.5.3 Electrical

Properly installed electrical power systems are robust and do not generally require maintenance beyond replacement of lamps or an occasional switch. Low-voltage systems are often more complicated and less robust, being vulnerable to loose connections and faulty electronics.

8.6 Earthquake-Induced MEP System Damage

With a few notable exceptions, MEP systems are generally robust against the effects of earthquake shaking and do not sustain serious damage. However, MEP systems are attached to the building, rely upon the building for support, and will sustain serious damage in the event of serious structural damage or collapse.

8.6.1 Plumbing

The following is a list of the most commonly observed effects of earthquakes on plumbing systems.

- Rocking or toppling of water heaters, resulting in damage ranging from dislodged vent piping (Figure 8-7) to breakage of water piping connections and destruction of the water heater. While most water heaters in California are now required by code to be "strapped" (Figure 8-8) to reduce the chances of toppling, many of those straps are not sufficient to prevent damaging movements of the water heater during strong shaking. Newer water heaters are also connected to the house piping with flexible tubing (Figure 8-9) that will accommodate minor differential movement of the water heater without failure of the connections. Older installations may be hard piped (Figure 8-10) and are thus much more susceptible to development of leaks in the connecting piping under minor differential movement. Older water heaters (those near the ends of their service lives) may develop leaks due to thermal and pressure cycling as a result of the loss and resumption of water pressure and gas supply following an earthquake.
- Plugging of filters, aerators, and other in-line restrictions due to scale and debris that is dislodged when water supplies are reestablished following an earthquake. This condition is often misdiagnosed as either appliance failure (in the case of dishwashers and clothes washers) or obstructed piping (in the case of sink aerators).
- Breakage of water supply or drain lines due to displacement of heavy equipment (e.g., water line to refrigerator or condensate drain line on an air conditioner).
- Unseated toilets or broken closet collar bolts; broken tank covers.
- Breakage of underground water supply or sewer lines due to earthquake-induced permanent ground deformation.
- Breakage of water supply or sewer lines due to the building shifting relative to the foundation.

Figure 8-7 Earthquake-caused displacement of unsecured water heater vent (photo credit: Exponent).

Figure 8-8 Undamaged water heater with flexible piping and strapping (photo credit: Exponent).

Figure 8-9 Undamaged flexible piping between unsecured water heater and house piping (photo credit: Exponent).

Figure 8-10 Undamaged water heater with hard piping (photo credit: Exponent).

8.6.2 Mechanical

The following is a list of the most commonly observed effects of earthquakes on mechanical systems.

- Shifting or toppling of liquid tanks, such as water heaters, water tanks, fuel oil tanks, and propane tanks.
- Breakage of gas supply lines to heavy equipment (such as water heaters, furnaces, and stoves) due to differential motion. These circumstances constitute a safety hazard and the gas company should be contacted to verify proper conditions are present prior to re-establishing gas service to the property.
- Dislocation of exhaust ducts, chimneys, or flues due to motion of equipment. These situations can constitute a potential safety hazard due to the potential for carbon monoxide and other combustion products to enter the house.
- Shifting of air conditioning condenser units located outside or on the roof.
- Breakage of refrigerant, water, or other lines to equipment due to relative motion.
- Dislocation or disconnection of ducting.

8.6.3 Electrical

Electrical systems generally do not sustain significant damage from the direct effects of earthquakes. The following is a list of some observed effects of earthquakes on electrical systems.

- Damage to electrical wiring and fixtures caused by serious structural damage or collapse, as illustrated in Figure 8-11 and Figure 8-12.
- Failure of connections due to shifting or toppling of hard-wired fixed equipment, such as furnaces, air conditioners, and electric water heaters.
- Damage to hanging fixtures, such as chandeliers or ceiling fans, due to impact with walls or ceilings from earthquake-induced swaying.
- Short circuit of damaged electrical fixtures when electricity remains on or is eventually restored, possibly resulting in fire.

Figure 8-11 Earthquake-caused racking and delamination of exterior stucco resulting in damage to electrical outlet (photo credit: Exponent).

Figure 8-12 Close-up of earthquake damage to electrical outlet box (photo credit: Exponent).

8.7 Assessment Guidelines and Methodology

8.7.1 Plumbing

An assessment of potential earthquake damage to plumbing systems should include the following steps.

- Examine water heater for toppling or damage to water, gas, flue, or electric connections.
- Check pressure of water supply to the house at the hose bib close to water supply service entrance. Reduced pressure indicates a problem with the municipal supply, local well, or service lateral.
- Check water pressure or flow at all faucets, tubs, showers, and toilets. Reduced pressure can indicate clogged valves, aerators, or shower heads.
- Check water pressure at appliances that use water, such as refrigerators, dishwashers, and clothes washers. Reduced pressure can indicate clogged valves or clogged in-line filters.
- If there is evidence of earthquake-induced permanent ground deformation, contact a leak detection service or the local water and sewer utility to determine the condition of the underground sewer and water supply lines.
- Check all toilets for signs of rocking, shifting, or broken closet collar bolts.
- Visually inspect the property for signs of water damage due to pipe leaks from broken pipes inside wall cavities, crawlspaces, or attics.

8.7.2 Mechanical

An assessment of potential earthquake damage to mechanical systems should include the following steps.

- Inspect the condition of the gas meter and shut-off valve.
- Inspect the condition of the gas line to any gas-fired appliance (e.g., water heater, stove, furnace).
- Look for evidence of shifting or toppling of liquid storage tanks on the property. These can include water heaters, water tanks, fuel oil tanks, and propane tanks.
- Look for evidence of shifting or toppling of any furnace or air conditioner condenser unit.
- Look for evidence of shifting, blockage, or damage to any chimney, flue, or exhaust duct for any combustion-related equipment (such as water heater, furnace, fireplace, or free-standing wood stove).
- Turn on the furnace blower and check the airflow from all ducts to verify ducting is still connected.

If the building was constructed prior to 1980 and repair work will involve disturbance (e.g., demolition, removal, grinding, sanding) of any of the following components, a suitably qualified environmental consultant should be retained.

- Mechanical duct or flue joint tape or insulation.
- Asbestos-cement ("Transite") flue pipe. Transite pipe is an asbestos-cement product that was used in older houses for HVAC ducts and for chimney and flue material to vent residential gas-fired appliances.

The repair methods presented in this chapter presume that the building materials are free of regulated levels of hazardous materials. If testing as recommended in Section 9.2.4 indicates the presence of regulated levels of asbestos or lead, the abatement and waste disposal recommendations of the environmental consultant should be incorporated into the overall scope of repair.

8.7.3 Electrical

Generally, the greatest risk of earthquake-related damage to electrical systems is when collapse, falling objects, or flammable material damage or otherwise negatively effect electrical systems, which can result in fires or loss of functions. Connections to fixed and relocatable electrical systems and equipment should be checked in the course of inspection of that equipment.

8.8 Repair Methodologies

Following proper assessment of the nature and extent of earthquake-related damage, repair of that damage is generally straightforward and typically consists of component repair or replacement in kind. Unique considerations for repair of earthquake damage are discussed below.

8.8.1 Plumbing

If low water pressure or low flow exists, aerators at faucets, shower heads, toilet float valves, and in-line strainers at washing machines, dishwashers, and icemakers should be cleaned and piping flushed. Where buried piping has been damaged by earthquake-induced ground deformation, either a local repair or complete replacement will be necessary, depending upon the type of piping and its condition.

8.8.2 Mechanical

Natural gas supply lines to mechanical systems should be shut off if gas is smelled or leaks are heard. Repairs should initially focus on disconnecting damaged or questionable mechanical systems from potential fire sources until such time that they can be fully assessed, repaired, or replaced before their functions are restored. Pressure tests to locate leaks in systems may be warranted to fully identify repair needs.

8.8.3 Electrical

Repairs should first focus on disconnecting electricity to damaged or questionable systems until such time that they can be assessed, repaired, or replaced before their functions are restored.

8.8.4 Permits and Code-Triggered Upgrades

Depending upon the nature and scope of damage and proposed repair, building permits and other government agency approvals may be required by the local jurisdiction. In addition to normal changes in the building code over time, some jurisdictions have building code requirements that mandate varying degrees of upgrades if certain damage thresholds are exceeded. The repair guidelines presented herein are intended to represent prevailing best practices and do not include jurisdiction-specific requirements. The local building department should be contacted to determine the existence of any applicable local requirements. Where utilized, technical consultants should be asked to address any code-triggered upgrades that may be required to comply with applicable local building code requirements as part of the repair of earthquake damage. As a general rule, however, repairs may be made to components of MEP systems without upgrading the entire system as long as the repair work itself is done in accord with current code requirements.

CHAPTER 9

Working with Technical Consultants

9.1 Introduction

Following an earthquake, the services of a technical consultant might be necessary to assist with damage assessment of an affected property. The objective of this chapter is to provide guidance to building contractors, insurance claim representatives, property owners, and other users of these *General Guidelines* for interaction with technical consultants.

9.2 Circumstances Requiring Technical Consultant Services

As a class of buildings, newer single-family wood-frame houses have performed very well in past earthquakes, experiencing damage to contents and cosmetic damage but rarely experiencing structurally significant damage. Thus, the services of a technical consultant are generally *not* required for post-earthquake assessment of single-family wood-frame houses. However, technical consultants are generally required for the following conditions:

- buildings with earthquake damage compromising safety that has been identified in the course of a post-earthquake safety assessment (see Section 9.2.1 for more detail),
- buildings with damage indicating possible structural damage, instability in the ground beneath or adjacent to the building, or damage to buried utility lines (see Section 9.2.2 and subsequent sections for more detail),
- buildings with damage and configurations known to be vulnerable to earthquakes (see Section 9.2.3 for more detail),
- earthquake-damaged buildings constructed of materials other than wood-frame construction, such as adobe, brick, concrete block masonry, or reinforced concrete, or
- buildings constructed before 1980 in which repair work will disturb finishes or materials that may contain asbestos or lead (see Section 9.2.4 for more detail).

9.2.1 Safety Assessment

For a building that has been posted (or "tagged") red or yellow, a damage assessment by a structures specialist may be warranted (see Section 1.2.2 for a brief summary of the safety assessment program). If the sole reason for the yellow tag is a damaged chimney, the need for assessment by a technical consultant should be based on the criteria presented in Chapter 7. If soil failure or instability is one of the reasons for the red or yellow tag, a soils specialist may be retained as well.

9.2.2 Damage State

If any of the following conditions is present at a house, inspection of the property by a structures specialist may be warranted. See Chapter 3 through Chapter 8 for details regarding evaluation of these conditions.

- Building has collapsed or is partially collapsed. However, as a practical matter, technical assistance is probably not required if the building is obviously a total loss. Engineering assistance may be necessary for safety associated with contents removal or demolition.
- Building superstructure has shifted relative to, or off, its foundation.
- Building as a whole, any story, any walls, any cripple walls, door openings, or columns are visibly out of plumb.
- A pattern of broken windows and sticking or inoperable hinged doors. The intent here is to identify an overall pattern of racking of the building.
- Evidence of separation between various portions of the building, such as:
    - at the “split” in split-level houses,
    - at the juncture of an addition with the original building,
    - at the juncture between a floor or roof and the adjacent wall,
    - at the juncture of porch roofs or patio covers with the main building, and
    - at the juncture of breezeway roofs to adjacent buildings.
- Shifting or movement of interior walls and partitions relative to the floor.
- For hillside houses: damage to vertical supports; posts visibly out of plumb; broken, slack, or buckled diagonal bracing; damage to connection between foundation and superstructure; or visible separation of the dwelling from the foundation at the uphill side.
- Visible distortion of the roofline or significant fresh damage to attic framing.
- Damage to the structure in the vicinity of the chimney.
- A pattern of splitting of framing members (e.g., sill plates, tie down locations, floor joists).
- Linear fissures in ground parallel to the crest of a slope (not to be confused with fissuring caused by drying of expansive soil), rising or bulging of the ground surface, or signs of slope movement (above or below the building).
- Evidence of fresh settlement of floors or exterior pavement.
- Evidence of earthquake-induced permanent ground deformation (e.g., fault rupture, liquefaction, lateral spreading, landslide, ridge-top shattering) in the immediate vicinity of the property.
- Fresh fractures wider than 1/2 inch or offset by more than 1/16 inch perpendicular to the crack in concrete foundation elements or floor slabs.

9.2.3 Structural Configuration

Certain building configurations are particularly vulnerable to earthquake damage, and in some cases that damage may not be obvious. For buildings with configurations described below that exhibit damage, an inspection by a structures specialist may be warranted.

- houses with unbraced cripple walls
- hillside houses where the ground surface elevation varies by a half story or more over the footprint of the building
- multi-story buildings with one or more open sides at the first story
- multi-story buildings with irregularities, typically split-level houses
- houses with living space over the garage

9.2.4 Hazardous Construction Materials

Buildings constructed before about 1980 may have been constructed (or modified) with materials that contain asbestos or lead. There are legal requirements for evaluations, abatement procedures, and waste disposal when repair or remodeling work is being done by contractors, or if the amount of material being disturbed is larger than a few square feet. Depending on the type of material and the quantity involved, the debris can become hazardous waste, which must be handled, transported, and disposed of following appropriate regulations. If repair of earthquake damage will disturb (e.g., demolition, removal, grinding, sanding) materials that may contain asbestos or finishes that may contain lead-based paint, a suitably qualified and licensed environmental consultant should be retained to sample and test the suspect material and, if test results are positive, recommend appropriate measures to remove or otherwise mitigate the hazard and properly transport and dispose of any resulting hazardous wastes.

When was asbestos and lead banned?

The manufacture of construction materials containing asbestos or lead was banned for most construction materials during the 1970s. However, existing stock was permitted to be used in construction. Thus, there is no specific date when materials containing asbestos or lead were banned from construction. The generally accepted cut-off date for routine testing is 1980.

Materials that may contain asbestos include:

- sprayed acoustic (“popcorn”) ceiling finishes,
- gypsum joint compound (i.e., drywall “mud”),
- interior plaster,
- exterior stucco,
- vinyl floor tile or mastic,
- backing or underside of sheet vinyl,
- mechanical system insulation,
- asbestos-cement (“Transite”) flue pipe,
- roofing felt,

- roofing mastic, and
- asbestos-cement siding.

Material that may contain lead consists of enamel paint applied to:

- doors, windows, and trim,
- kitchen and bathroom walls, ceilings, and cabinetry,
- concrete floors,
- exterior walls and surfaces, and
- exterior metals.

In California, the minimum qualifications for an environmental consultant are state registration as a lead consultant and asbestos consultant. Although not required, the certified industrial hygienist credential reflects a higher level of understanding and training with respect to dealing with hazardous construction materials.

9.3 Selecting Technical Consultants

In these *General Guidelines*, the term technical consultant is used as a generic term for consultants who are qualified to assess the nature and extent of earthquake damage to residential property and recommend appropriate repairs for that damage. For most earthquake damage issues, the appropriate consultant will be a structures specialist. In California, structures specialists include licensed civil engineers specializing in structural engineering and licensed structural engineers (civil engineers who have satisfied additional experience and testing requirements and are authorized to use the title structural engineer). Licensed architects who are qualified by education, training, and experience in the technical area of post-earthquake damage assessment can also legally offer many of the same services as a licensed civil engineer. A structures specialist can evaluate all components of a building, including the foundation, for structural damage.

Where evidence of earthquake-induced permanent ground deformation is present, the structures specialist may recommend retaining the services of a soils specialist. Soils specialists include civil engineers specializing in soils (or geotechnical) engineering, geotechnical engineers (civil engineers who have satisfied additional experience and testing requirements and are authorized to use the title geotechnical engineer), and engineering geologists with expertise in geotechnical engineering. Some structures and soils specialists are adequately qualified in both areas of structures and soils to address many of the more common earthquake damage patterns. Thus, for the evaluation of typical earthquake damage at most residential properties, one consultant may be able to address all technical issues. In some circumstances, the services of consultants in other technical specialties, as described in Section 9.4, may be required to assist the structures or soils specialist.

9.3.1 When are the Stamp and Signature of an Engineer Required?

When a building inspection report relies on engineering judgment and expertise to reach conclusions and make recommendations, the stamp and signature of a *responsible* professional engineer are required (Brandow, 1997). Specific examples of work requiring a responsible professional engineer cited by Brandow are:

- opinions on structural condition or adequacy based on observation, engineering judgment, or calculations,
- recommendations about required or recommended structural upgrades, strengthening, or seismic mitigation, and
- statements comparing structural capacities, such as loading capacity or seismic resistance, to building code requirements or other standards.

> **Responsible Engineer**
>
> The term *responsible* is defined in §§ 6703 of the Professional Engineers Act (2019) of the Business and Professions Code of the California Statutes: "The phrase 'responsible charge of work' means the independent control and direction by the use of initiative, skill, and independent judgment, of the investigation or design of professional engineering work or in the direct engineering control of such projects …"

There are many areas of specialization under the civil engineering umbrella. The civil engineering specialties of interest for earthquake damage assessment are structural engineering—the analysis and design of buildings or other structures—and geotechnical engineering—the analysis and design of soil conditions for construction. In addition to the basic civil engineering license (C.E. or P.E.), California also issues two specialty titles that indicate knowledge and experience beyond that required for the civil engineering license alone.

- Structural engineer: A licensed civil engineer specializing in structural engineering may also be licensed to use the title structural engineer (S.E.). California law requires that specific school and hospital facilities be designed by a structural engineer. Otherwise, there is no legal distinction between the services that a C.E./P.E. and an S.E. may offer, so long as they practice in their areas of competence.
- Geotechnical engineer: A licensed civil engineer specializing in geotechnical engineering may also be licensed to use the title geotechnical engineer (G.E.).

While the statutory definition of civil engineering is very broad, licensure as a civil engineer (with or without the additional titles of S.E. or G.E.) does not imply expertise in all aspects of civil engineering, and not all civil engineers are qualified to investigate structural damage. California Code of Regulations (16 CCR T. 16, Div. 5, s415) restricts registered civil engineers to practice "only in the field or fields in which s/he is by education and/or experience fully competent and proficient" (California Code of Regulations, 2019).

9.3.2 *Qualifications for Technical Consultants Performing Post-Earthquake Damage Assessment*

In addition to a professional license, a structures specialist engaged in earthquake damage assessment of wood-frame construction should have the following minimum qualifications:

- related education or experience in structural or geotechnical engineering,
- experience with the investigation of damaged buildings,
- knowledge of the effects of earthquakes on buildings and their supporting soils,
- knowledge of historical regional construction practices for wood-frame construction, and
- experience in the design and construction of wood-frame buildings.

9.3.3 *Locating Potentially Qualified Engineers*

Sources of contact information for potentially qualified engineers are the regional Structural Engineer's Association of California (www.seaoc.org), the local chapter of the American Society of Civil Engineers (www.asce.org), and Consulting Engineers and Land Surveyors of California (www.celsoc.org).

9.3.4 *Contracting for Technical Consultant Services*

Unless you have knowledge of a consultant's qualifications from another engagement or a reliable source, prior to retaining a technical consultant, the following steps are suggested.

- Check the consultant's credentials by obtaining a copy of the consultant's curriculum vitae (resume) or statement of qualifications, which should include information on education, work experience, technical expertise, and professional registration (or license) number.
- Check the consultant's license. The registration status of engineers, architects, contractors, and geologists licensed in California can be verified at https://search.dca.ca.gov/.
- Review the consultant's prior experience to determine whether the consultant meets the qualifications outlined in the preceding section.

It is common and legal for engineers who are not yet licensed to work under the direction of a licensed engineer who is in responsible charge of the work. For post-earthquake safety and damage assessments, it is highly desirable that the licensed engineer in responsible charge of the investigation personally inspects the building. The licensed engineer may be assisted in the investigation by unlicensed engineers and technicians and need not remain at the site for the duration of the investigation but should spend sufficient time at the site to personally observe all essential aspects of the building condition.

Written Contract Specifying the Scope of Services

Assuming that the consultant's credentials are acceptable, the next step is entering into an agreement or contract with the consultant. The Professional Engineers Act (2019) of the Business and Professions Code of the California Statutes (§6749) requires, with some exceptions, engineers to provide their clients with a written contract specifying at a minimum:

- a description of the services to be provided to the client by the professional engineer,
- a description of any basis of compensation applicable to the contract, and the method of payment agreed upon by the parties,
- the name, address, and license or certificate number of the professional engineer, and the name and address of the client,
- a description of the procedure that the professional engineer and the client will use to accommodate additional services, and
- a description of the procedure to be used by any party to terminate the contract.

Relevant exemptions are:

- a professional engineer who has a current or prior contractual relationship with the client to provide engineering services and that client has paid the professional engineer all of the fees that are due under the contract, and
- a client who knowingly states in writing after full disclosure of this section that a contract that complies with the requirements of this section is not required.

Given the infrequent occurrence of earthquakes, most parties involved in post-earthquake damage assessment and repair are operating in unfamiliar territory. Accordingly, effective involvement of technical consultants requires effective communication between all parties if a common understanding of the technical issues is to be achieved. Effective technical consultant involvement begins with a common understanding of the questions to be addressed by the consultant. Consultants must:

- clearly distinguish between structurally significant and nonstructural damage,
- specify repairs necessary to remedy structurally significant earthquake damage and identify triggered upgrades to the building that are mandated by local codes, and
- if appropriate, separately list voluntary upgrades that the engineer believes are desirable.

While the technical consultant's scope will generally not include inspection or evaluation of non-earthquake related items, any safety-related deficiencies observed in the course of the consultant's inspection should be brought to the attention of the property owner.

Potential Scope of Technical Consultant Services

A technical consultant may be asked to perform any of the following services:

- damage identification and repair recommendations for specific structural elements (e.g., foundation),
- damage identification and repair recommendations for the entire building and grounds utilizing only nondestructive investigation methods, where appropriate,
- damage assessment and repair recommendations for the entire building utilizing both nondestructive and destructive methods, where appropriate, or
- preparation of a written report of findings and recommendations.

Section 9.5 presents a suggested outline for a comprehensive report. However, the scope and detail of the report should be tailored to the needs and circumstances of each client, and there should be a clear agreement between the consultant and client regarding the nature and scope of the report. Following a major earthquake, qualified technical consultants in an area will quickly be overwhelmed, so ask for, and agree to, the delivery time before authorizing the work.

Technical consultants generally bill for their services on a time and expense basis, although following a major earthquake, some technical consultants likely will offer a standard scope of services on a fixed fee basis. Ask for and agree to a budget before authorizing the work.

9.4 Other Consultants and Subcontractors

Based on the results of the structures specialist's initial assessment, it may be necessary to engage other consultants or subcontractors. If there are significant issues related to soil at the site, a soils specialist might be required. Subcontractors that may be necessary to assist the technical consultants or address other earthquake-related issues are listed below. In the aftermath of a major earthquake, it is essential to verify the business and professional credentials of any consultants or subcontractors prior to engagement.

- chimney inspection service to inspect the chimney flue
- general contractor to assist with opening concealed areas for inspection and repairing the inspection openings
- carpet contractor to remove and reinstall carpet to facilitate inspection of slabs-on-grade
- plumber or pipe inspection service to pressure test or inspect plumbing lines
- contractor or consultant to address integrity of the shell of swimming pools, hot tubs, and Jacuzzis
- mechanical engineer or HVAC contractor to inspect damage to ductwork, furnaces, and air conditioners
- concrete coring service to remove samples of concrete from the foundation
- utility location service to locate underground utilities
- roofing contractor to assess damage to roofing systems
- general contractor or construction cost consultant to assist with estimating the cost of unusual or complicated repair work
- environmental consultant to test for the presence of mold (if there is significant visible mold growth on building material surfaces, engage a certified industrial hygienist)

9.5 Technical Report Guidelines

The appropriate format and scope of a report by a technical consultant of a post-earthquake damage assessment depend upon the circumstances and needs of the client and may range from a verbal report at the site to a comprehensive written report. An outline for a comprehensive written report for a wood-frame house is presented below. This outline may be abbreviated, as appropriate, for the format and scope of the report requested by the client. Some of the content identified below may be applicable to either the structures or soils specialist only.

- Administrative information
  - Name of the property owner.
  - Address of the property.
  - Name and contact information of the party for whom the report has been prepared, if other than the property owner.
  - Insurance claim number, if applicable.
  - Name, contact information, registration stamp, and signature of the licensed professional in responsible charge of the investigation (in accordance with state licensing laws).
  - Reports produced after an earthquake often use a standardized format. Since these reports look alike, each report should use numbered pages and should include both the report date and property address (or another unique identifier) on every page.
- Scope and procedures
  - Objective of retention and scope of services.
  - Dates of site investigations and personnel involved.
  - Nature and extent of damage investigations, including areas not investigated.
  - Limitations and disclaimer.
- Earthquake event data
  - Ground shaking data: USGS ShakeMap or its equivalent for the earthquake, with property location indicated. For property location, relevant values from ShakeMap (or its equivalent), such as:
    - instrumental intensity,
    - peak ground acceleration,
    - peak ground velocity, and
    - spectral acceleration.
  - Where available, published data and maps for regional post-earthquake observations of permanent ground deformation with property location indicated.
  - Summary of occupant interview, if performed.
  - Discussion regarding level of expected damage based on the historical performance of houses given the level of ground shaking at the site.

- Description of site and buildings
    - Topography of site.
    - Information regarding geologic conditions and regional and site-specific soil conditions.
    - Condition of surrounding public and private lands.
    - Description of building, including:
        - existing post-earthquake safety tagging, if any,
        - general characterization of the building geometry and foundation type,
        - known relevant pre-existing conditions and modifications, and
        - repairs or modifications since earthquake.
- Identification of structurally significant earthquake damage and earthquake-induced permanent ground deformation, and appropriate repair and mitigation recommendations for each. Where appropriate, the report may also discuss observed patterns of non-earthquake damage and structurally or geotechnically insignificant earthquake damage, especially where resolution of those damage patterns has been requested by the client. This section of the report is commonly supplemented by one or more of the following:
    - A plan sketch of the house or site as needed to clarify the location of elements, damage observations, permanent ground deformation, and repair and mitigation recommendations discussed in the report text.
    - Identification of areas or elements that were not investigated and the reasons, such as lack of access.
    - Recommendations for additional investigation, such as destructive investigation to confirm or rule out suspected damage to concealed elements and subsurface investigation.
    - General quantities associated with each type of repair and mitigation recommendation, if requested by the client.
    - Expected code-triggered upgrades, if any; for clarity, these upgrades should be provided in a separate section than in-kind repair recommendations.
    - Recommended voluntary upgrades and soil mitigation measures intended only for improved performance in future earthquakes, if any; for clarity, these recommendations should be provided in a separate section than in-kind repair recommendations.
- Appendices
    - Damage investigation checklists and documentation.
    - Bibliography of information resources.
    - Copies of property-specific reports from subcontractors.
    - Thumbnail images of all inspection photographs.
    - Curriculum vitae or resume of technical consultant in responsible charge of work and key contributors.

APPENDIX A

Building Occupant Questionnaire

This appendix provides the Building Occupant Questionnaire, which presents a series of questions in checklist format intended to assist building occupants in recording their experiences during the earthquake and their observations made immediately following the earthquake.

Building Occupant Questionnaire

Where description is requested, if necessary, attach additional pages of notes and photographs keyed to the appropriate checklist item.

A. General Information

1.Occupant's Name:

....

2. Street Address of Property:

....

City: **State:** **Zip:**

....

3. Date of Interview:

....

4. Interviewer's Name:

....

B. Observations

5. Select the type of building or structure at this property: (check one)

- ◯ Single-family home or duplex
- ◯ Apartment building
- ◯ Mobile home
- ◯ Other, please describe:

....

6. Were you at this property when the earthquake occured?

- ◯ Yes
- ◯ No — Where were you?

....

House Number: ....

7. What was your situation during the earthquake? (check one)

- ◯ Inside
- ◯ Outside
- ◯ In stopped vehicle
- ◯ In moving vehicle
- ◯ Other, please describe:

....

8. Did you feel the earthquake? (check one)

- ◯ Yes
- ◯ No

9. How would you best describe the ground shaking? (check one)

- ◯ Not felt
- ◯ Weak
- ◯ Mild
- ◯ Moderate
- ◯ Strong
- ◯ Violent

10. About how many seconds did the shaking last? ....

11. How did you respond? (check one)

- ◯ Don’t remember
- ◯ Took no action
- ◯ Moved to doorway
- ◯ Dropped and covered
- ◯ Ran outside
- ◯ Other, please describe:

....

12. Did you notice the swinging of doors or hanging objects? (check one)

- ◯ Did not look
- ◯ No
- ◯ Yes, slight swinging
- ◯ Yes, violent swinging

House Number: ....

13. Did small objects (e.g., vases, books, statues) rattle, topple over, or fall off shelves? (check one)

- ◯ No shelves
- ◯ No
- ◯ Rattled slightly
- ◯ Rattled loudly
- ◯ A few toppled or fell off
- ◯ Many fell off
- ◯ Nearly everything fell off

14. Did pictures on walls move or get knocked askew? (check one)

- ◯ No pictures
- ◯ No
- ◯ Yes, but did not fall
- ◯ Yes, and some fell

15. Did any furniture or appliances slide, tip over, or become displaced? (check one)

- ◯ No
- ◯ Yes

16. Did any heavy appliance (e.g., refrigerator or range) move? (check one)

- ◯ No
- ◯ Yes

House Number: ....

17. If you were at this property, did you immediately observe any damage to the building? (check all that apply)

- ○ No damage
- ○ Hairline cracks in walls
- ○ A few large cracks in walls
- ○ Ceiling tiles or lighting fixtures fell
- ○ Cracks in chimney
- ○ One or several cracked windows
- ○ Many windows cracked or some broken out
- ○ Masonry fell from block or brick wall(s)
- ○ Old chimney, major damage or fell down
- ○ Modern chimney, major damage or fell down
- ○ Outside wall(s) tilted over or collasped completely
- ○ Separation of porch, balcony, or other addition from building
- ○ Building shifted over foundation
- ○ Water heater (damaged or toppling)

18. Do you know of any ground cracks in the area? (check one)

- ○ No
- ○ Yes, please describe:

....

19. Any repairs made since the earthquake? (check one)

- ○ No
- ○ Yes, please describe:

....

20. Any other observations:

....

....

....

....

....

....

APPENDIX B

Useful Earthquake Damage Inspection Tools

The following is a list of useful earthquake damage inspection tools:

- bright flashlight
- digital camera for documentation of observations
- accurate digital level, at least 2-feet long but preferably 4-feet long, for checking the levelness of floors and the plumbness of walls and door and window openings
- hand-held wallet-size crack gauge for quickly measuring crack widths
- pocket mirror for checking for delamination along the bottom edge of stucco
- binoculars or telephoto lens for inspection of chimneys, roofs, and upper portions of multi-story buildings
- step or extension ladder for accessing roofs
- flying or crawling drones
- first aid kit

The following is a list of useful equipment for attic and crawlspace inspections:

- personal protective equipment including a tight-fitting dust mask or respirator, gloves, coveralls, and hat
- knee and elbow pads for accessing crawlspaces
- headlamp
- compact camera with neck strap

APPENDIX C

General Earthquake Damage Inspection Checklist

This appendix provides the General Earthquake Damage Inspection Checklist, which presents a series of questions in checklist format intended to provide guidance for a systematic visual inspection of a building and site.

General Earthquake Damage Inspection Checklist

Where description is requested, if necessary, attach additional pages of notes and photographs keyed to the appropriate checklist item.

A. General Information

1. Property Ownwer's Name:

....

2. Street Address of Property:

....

City: **State:** **Zip:**

....

3. Date of Inspection:

....

4. Inspector's Name:

....

B. General Building and Site Information

*When **Yes** is marked, consider if a technical consultant is warranted.*

5. Building Department Safety Assessment Tag:

◯ None ◯ Green

◯ Yellow ◯ Red

Comments:

....

6. Utility Service Safety:

Ⓨ Ⓝ **a.** Odor of natural gas leakage?

Ⓨ Ⓝ **b.** Downed power lines?

House Number: ....

7. Repairs or Demolition:

(Y) (N) Have repairs or demolition been performed since the earthquake?

If yes, describe: ....

8. Building Site:

- ○ Flat
- ○ Sloping

9. Building Configuration: (check all that apply)

- ○ **a.** Single story
- ○ **b.** Combination one story and two story
- ○ **d.** Three story
- ○ **e.** Split level
- ○ **f.** Living space above garage
- ○ **g.** Other, describe: ....

10. Exterior Wall Finishes:

- ○ **a.** Stucco
- ○ **b.** Panel siding
- ○ **c.** Lap siding
- ○ **d.** Masonry veneer
- ○ **e.** Other, describe: ....

11. Roof Configuration:

- ○ **a.** Gable
- ○ **b.** Hip
- ○ **c.** Flat or very low slope
- ○ **d.** Shed
- ○ **e.** Other, describe: ....

12. Foundation Configuration:

- ○ **a.** Slab-on-grade
- ○ **b.** Crawlspace without cripple walls
- ○ **c.** Crawlspace with cripple walls
- ○ **d.** Exposed piers or posts at perimeter
- ○ **e.** Partial basement
- ○ **f.** Full basement
- ○ **g.** Other, describe: ....

13. Roof Covering:

- ○ **a.** Asphalt shingles
- ○ **b.** Wood shingle or shake
- ○ **c.** Concrete or clay tile
- ○ **d.** Metal shingles
- ○ **e.** Membrane
- ○ **f.** Other, describe: ....

House Number:

....

C. Exterior Inspection

*When **Yes** is marked, consider if a technical consultant is warranted.*
*The **N/A** response option stands for **Not Applicable**.*

14. General: (if yes, provide description and photos)

Y N **a.** Collapse, partial collapse, or building off foundation?

Y N **b.** Visible lean in any story?

15. Geotechnical Issues: (if yes, provide description and photos)

Y N n/a **a.** Signs of fresh cracking in or movement of hardscape?

Y N n/a **b.** Signs of fresh cracking in or movement of retaining walls?

Y N n/a **c.** Evidence of sand boils or other fresh-appearing deposits of sand or mud?

Y N n/a **d.** Evidence of rock falls or slope instability at site?

Y N n/a **e.** Ground movement or wet areas indicating possible broken underground utility lines?

16. Exterior Walls: (if yes, provide description and photos)

Y N n/a **a.** Fresh cracking at door corners or window openings?

Y N n/a **b.** Fresh cracking at building corners?

Y N n/a **c.** Door or window openings racked out of square?

Y N n/a **d.** Broken glass in windows or doors?

Y N n/a **e.** Wall leaning?

Y N n/a **f.** Bulging or delamination of stucco?

Y N n/a **g.** Pattern of cracking that extends from the ground surface through the foundation and a wall?

Y N n/a **h.** Evidence of recent relative movement at mudsill line?

Y N n/a **i.** At locations where the exterior stucco is continuous from the framing down over the foundation, is there cracking of stucco along the mudsill level accompanied by indications of permeant displacement (sliding) of the building relative to the foundation?

Y N n/a **j.** Collapse, partial collapse, or separation of masonry veneer?

Y N n/a **k.** Severe cracking, separation, or offsets at building discontinuities?

House Number: ....

17. Foundation: (if yes, provide description and photos)

Ⓨ Ⓝ (n/a) **a.** Fresh cracking of exposed perimeter foundation?

Ⓨ Ⓝ (n/a) **b.** Relative movement between slab and footing in “two-pour” slab-on-grade foundation?

Ⓨ Ⓝ (n/a) **c.** Has the house been seismically retrofitted?

Ⓨ Ⓝ (n/a) **d.** If the house was retrofitted, were bolts added to connect the house to the foundation?

Ⓨ Ⓝ (n/a) **e.** If the house was retrofitted, was plywood or other sheathing added to any cripple walls under the house?

Ⓨ Ⓝ (n/a) **f.** If the house was retrofitted and work other than (d) and (e) was completed, please describe the work:

....

Ⓨ Ⓝ (n/a) **g.** If the house was retrofitted, what year was the work completed? ....

18. Chimney: (if yes, provide description and photos)

Ⓨ Ⓝ (n/a) **a.** Present on exterior wall?

Ⓨ Ⓝ (n/a) **b.** Present at interior location?

Ⓨ Ⓝ (n/a) **c.** Collapse or partial collapse?

Ⓨ Ⓝ (n/a) **d.** Visible damage or cracking?

Ⓨ Ⓝ (n/a) **e.** Visible tilting or separation from building?

Ⓨ Ⓝ (n/a) **f.** Shifted or loose clay flue tile segments and displaced joint mortar?

Ⓨ Ⓝ (n/a) **g.** Deterioration of exposed mortar?

Ⓨ Ⓝ (n/a) **h.** Does the top of the chimney rock when pushed?

19. Roof: (if yes, provide description and photos)

Ⓨ Ⓝ (n/a) **a.** Shifted or dislodged clay or concrete roof tile?

Ⓨ Ⓝ (n/a) **b.** Impact damage to roof from a falling chimney?

Ⓨ Ⓝ (n/a) **c.** Displaced rooftop mechanical or electrical equipment?

Ⓨ Ⓝ (n/a) **d.** Significantly sagging roof ridge lines?

Ⓨ Ⓝ (n/a) **e.** Signs of movement between rafter tails and wall finishes at eaves?

Ⓨ Ⓝ (n/a) **f.** Buckled or dislodged flashing or tearing of roof membrane at chimneys, roof-wall intersections, additions, appendages, porches, or other building irregularities?

Ⓨ Ⓝ (n/a) **g.** Tearing of roof membrane or deck waterproofing at re-entrant corners?

Ⓨ Ⓝ (n/a) **h.** Toppling, shifting, damage, or leakage at refrigerant or electrical line of rooftop mechanical equipment?

Ⓨ Ⓝ (n/a) **i.** Shifting of or damage to solar panels?

House Number: ....

20. Attached or Abutting Improvements: (if yes, provide description and photos)

- (Y) (N) (n/a) **a.** Collapse, partial collapse, or separation of attached porches, carports, patio covers, or awnings?
- (Y) (N) (n/a) **b.** Evidence of recent settlement or displacement of exterior steps, patios, or walkways relative to the building?
- (Y) (N) (n/a) **c.** Signs of movement between building floor or garage floor and exterior hardscape or retaining wall along the uphill side of homes on steeply sloping sites?
- (Y) (N) (n/a) **d.** Toppling, shifting, damage, or leakage at refrigerant or electrical lines of mechanical equipment?

21. Independent Exterior Improvements: (if yes, provide description and photos)

- (Y) (N) (n/a) **a.** Damaged detached garage?
- (Y) (N) (n/a) **b.** Damage to fences or privacy walls?
- (Y) (N) (n/a) **c.** Damage to retaining walls?
- (Y) (N) (n/a) **d.** Damage to pool or pool deck?
- (Y) (N) (n/a) **e.** Evidence of leakage from irrigation supply lines?
- (Y) (N) (n/a) **f.** Toppling, shifting, damage, or leakage at fuel connection of propane tanks?
- (Y) (N) (n/a) **g.** Broken piping or shifting of pool or spa equipment?
- (Y) (N) (n/a) **h.** Exterior septic system damage?

D. Interior Building Inspection (including basement and attached garage, if present)

*When **Yes** is marked, consider if a technical consultant is warranted.*
*The **N/A** response option stands for **Not Applicable**.*

22. General Information

a. If interior access is not possible, identify reason:

- ◯ **i.** Not applicable, interior is accessible
- ◯ **ii.** Safety assessment yellow or red tag
- ◯ **iii.** Hazardous materials
- ◯ **iv.** Other, describe: ....

b. Typical wall and ceiling finishes:

- ◯ **i.** Drywall
- ◯ **ii.** Plaster on gypsum lath
- ◯ **iii.** Plaster on wood lath
- ◯ **iv.** Other, describe: ....

House Number: ....

23. Interior Walls: (if yes, provide description and photos)

- Y N n/a **a.** Fresh cracking, buckling, spalling, or detachment of interior wall finishes at door corners and window openings?
- Y N n/a **b.** Fresh cracking of wall finishes at wall corners or wall-ceiling intersections?
- Y N n/a **c.** Door or window openings racked out of square?
- Y N n/a **d.** Wall leaning?
- Y N n/a **e.** Pattern of cracking that extends from the floor slab through a wall?
- Y N n/a **f.** Movement or sliding of walls relative to the floor?
- Y N n/a **g.** Severe cracking, separations, or offsets at building irregularities?
- Y N n/a **h.** Doors damaged, difficult to operate, or inoperable?
- Y N n/a **i.** Windows damaged, difficult to operate, or inoperable?

24. Ceilings: (if yes, provide description and photos)

- Y N n/a **a.** Collapse of ceiling finishes?
- Y N n/a **b.** Fresh cracking of ceiling finishes, especially at re-entrant corners; cracks along corner bead at stairwell openings; cracking or tearing of finishes at ceiling-wall juncture; or multiple nail pops?
- Y N n/a **c.** Damage to ceiling finishes in vicinity of chimneys or fireplaces?
- Y N n/a **d.** Separations or cracks in ceiling finishes at split levels, re-entrant corners, additions, appendages, or other building discontinuities?
- Y N n/a **e.** Water damage or evidence of recent leakage from plumbing lines or roofing?

25. Floors: (if yes, provide description and photos)

- Y N n/a **a.** Evidence of recent sloping, sagging, settlement, or displacement of floors?
- Y N n/a **b.** In slab-on-grade locations, fresh cracking of floor slab or floor finishes?
- Y N n/a **c.** Significant sagging or unusual bounciness of wood-frame floors over crawlspace?
- Y N n/a **d.** Separations or cracks in floor finishes at split level, re-entrant corners, additions, appendages, or other building irregularities?
- Y N n/a **e.** Signs of movement between floor (including garage floor) and exterior hardscape or retaining wall along the uphill side of homes on steeply sloping sites?
- Y N n/a **f.** A pattern of fresh cracks, gaps, or joint separations in floor finishes?
- Y N n/a **g.** Impact damage to floor finishes from falling contents?

House Number: ....

26. Fireplace: (if yes, provide description and photos)

- (Y) (N) (n/a) **a.** Collapse, partial collapse, or separation of interior fireplace facing from, or movement relative to, adjacent wall of firebox?
- (Y) (N) (n/a) **b.** Differential movement between fireplace insert and firebox?

27. Mechanical and Plumbing Systems: (if yes, provide description and photos)

- (Y) (N) (n/a) **a.** Displaced connection of appliance flues connected to chimneys?
- (Y) (N) (n/a) **b.** Toppling, shifting, damage, or leakage at water heater; displaced flue connection; or damage or leakage at gas line or electrical connection?
- (Y) (N) (n/a) **c.** Shifting, damage, or leakage at gas line, flue connection, electrical connection, refrigerant line, or condensate drain connection of furnace or air conditioning fan coil unit?
- (Y) (N) (n/a) **d.** Damage to gas line of gas stoves or gas-fueled clothes dryers?
- (Y) (N) (n/a) **e.** Damage to toilets?
- (Y) (N) (n/a) **f.** Decreased or restricted water pressure at appliances, faucets, or toilets?
- (Y) (N) (n/a) **g.** Toppling or shifting of free-standing wood stove or flue?
- (Y) (N) (n/a) **h.** Toppling, shifting, damage or leakage at fuel connection of fuel oil tank?

28. Architectural Woodwork and Special Finishes: (if yes, provide description and photos)

- (Y) (N) (n/a) **a.** Shifting of or damage to kitchen or bathroom cabinetry?
- (Y) (N) (n/a) **b.** Impact damage to countertops from falling objects?
- (Y) (N) (n/a) **c.** Cracking of ceramic tile in tubs or showers or their enclosures consistent with earthquake damage to adjacent wall finishes?

E. Contingent Inspections

29. Is a crawlspace present? (if yes, see the Crawlspace Checklist)

(Y) (N)

30. Is an attic present? (if yes, see the Attic Checklist)

(Y) (N)

F. Conclusions

31. Based on this inspection, should use of a technical consultant be considered?

(Y) (N)

If yes, which question(s) drove this decision: ....

If yes, describe the reasons: ....

APPENDIX D

Crawlspace Earthquake Damage Inspection Checklist

This appendix provides the Crawlspace Earthquake Damage Inspection Checklist, which presents a series of questions in checklist format intended to provide guidance for the inspection of crawlspaces.

In the absence of conspicuous visible external damage, earthquake-induced damage in crawlspaces is unlikely. In addition, there are hazards associated with entry into crawlspaces, especially those with tight access. Accordingly, in the absence of external visible damage, entering crawlspaces for post-earthquake inspection is not recommended. If a crawlspace inspection is conducted, it should be performed by an individual qualified by training and experience. Damage and abnormal conditions should be documented with photographs. Where description is called for in the checklist, attach additional pages of notes and photographs keyed to the appropriate checklist item (e.g., 10d).

Due to safety concerns associated with entry into a confined space, inspection of these areas may require the presence of a second individual. Inspectors should be equipped with appropriate personal protective equipment and be knowledgeable of appropriate safety precautions. Safety precautions for crawlspace inspections are provided in Appendix F.

Crawlspace Earthquake Damage Inspection Checklist

Where description is requested, if necessary, attach additional pages of notes and photographs keyed to the appropriate checklist item.

A. General Inspection Information

1. Property Ownwer's Name:

....

2. Street Address of Property:

....

City: **State:** **Zip:**

....

3. Date of Inspection:

....

4. Inspector's Name:

....

B. General Crawlspace Information

5. Extent of Crawlspace:

- ◯ **a.** Full
- ◯ **b.** Partial
- ◯ **c.** Partitioned (A partitioned crawlspace has two or more areas that are not interconnected and must be accessed from multiple entry locations.)
- ◯ **d.** Other, describe:

....

6. Access Locations:

....

House Number: ....

7. Crawlspace Framing:

- ◯ **a.** None (for example, mudsill sits directly on concrete stemwalls)
- ◯ **b.** Perimeter stemwall with interior wood posts
- ◯ **c.** Interior cripple walls
- ◯ **d.** Steel pipe columns and diagonal steel rod bracing
- ◯ **e.** Other, describe:

....

8. Location of Stemwalls:

- ◯ **a.** None
- ◯ **b.** Perimeter
- ◯ **c.** Interior

9. Type of Stemwalls:

- ◯ **a.** Not applicable
- ◯ **b.** Concrete
- ◯ **c.** Concrete masonry unit (CMU)
- ◯ **d.** Brick
- ◯ **e.** Other, describe:

....

C. Crawlspace Inspection

*When **Yes** is marked, consider if a technical consultant is warranted.*
*The **N/A** response option stands for **Not Applicable**.*

10. Framing: (if yes, provide description and photos)

- Y N n/a **a.** General pattern of tilting of posts or cripple walls?
- Y N n/a **b.** Isolated tilting of posts or cripple walls?
- Y N n/a **c.** Loose posts?
- Y N n/a **d.** Split sill plates?
- Y N n/a **e.** Fractured, buckled, or loose diagonal braces?
- Y N n/a **f.** Shifting or sliding of framing relative to foundation?
- **g.** Other abnormal conditions, describe:

....

House Number: ....

11. Foundation: (if yes, provide description and photos)

(Y) (N) (n/a) **a.** Fresh cracks greater than 1/2-inch wide or offset by more than 1/16-inch out of plane?

(Y) (N) (n/a) **b.** Damage to masonry beneath fireplaces?

(Y) (N) (n/a) **c.** Piers or stands shifted or fallen over?

d. Other abnormal conditions, describe: ....

12. Plumbing: (if yes, provide description and photos)

(Y) (N) (n/a) **a.** Evidence of active leakage?

(Y) (N) (n/a) **b.** Broken pipe or joint separations in sewer piping?

(Y) (N) (n/a) **c.** Broken pipe or joint separations in water piping?

d. Other abnormal conditions, describe: ....

13. Forced Air Heating and Cooling Ductwork: (if yes, provide description and photos)

(Y) (N) (n/a) **a.** Crushed ductwork?

(Y) (N) (n/a) **b.** Separated joints?

(Y) (N) (n/a) **c.** Presence of asbestos insulation or joint taping?

(Y) (N) (n/a) **d.** Damaged asbestos insulation or joint taping?

e. Other abnormal conditions, describe: ....

D. Conclusions

14. Based on this inspection, should use of a technical consultant be considered?

(Y) (N)

If yes, which question(s) drove this decision: ....

If yes, describe the reasons: ....

APPENDIX E

Attic Earthquake Damage Inspection Checklist

This appendix provides the Attic Earthquake Damage Inspection Checklist, which presents a series of questions in checklist format intended to provide guidance for the inspection of attics.

In the absence of conspicuous visible external damage, earthquake-induced damage in attics is unlikely. In addition, there are hazards associated with entry into attics, especially those with tight access. Accordingly, in the absence of external visible damage, entering attics for post-earthquake inspection is not recommended. If an attic inspection is conducted, it should be performed by an individual qualified by training and experience. Where description is called for in the checklist, attach additional pages of notes and photographs keyed to the appropriate checklist item (e.g., 10c).

Due to safety concerns associated with entry into a confined space, inspection of these areas may require the presence of a second individual. Inspectors should be equipped with appropriate personal protective equipment and be knowledgeable of appropriate safety precautions. Safety precautions for attic inspections are provided in Appendix F.

Attic Earthquake Damage Inspection Checklist

Where description is requested, if necessary, attach additional pages of notes and photographs keyed to the appropriate checklist item.

A. General Inspection Information

1. Property Ownwer's Name:

2. Street Address of Property:

City: **State:** **Zip:**

3. Date of Inspection:

4. Inspector's Name:

B. General Attic Information

5. Extent of Attic:

- ◯ **a.** Full
- ◯ **b.** Partial
- ◯ **c.** Partitioned (A partitioned attic has two or more areas that are not interconnected and must be accessed from multiple entry locations.)
- ◯ **d.** Other, describe:

6. Attic Framing:

- ◯ **a.** Conventional field framed
- ◯ **b.** Metal plate connected trusses
- ◯ **c.** Other, describe:

House Number: ....

7. Roof Sheathing: (check one)

- ◯ **a.** Spaced board sheathing (i.e., skip sheathing)
- ◯ **b.** Plywood or oriented strand board (OSB) sheathing
- ◯ **c.** Other, describe: ....

C. Attic Inspection

*When **Yes** is marked, consider if a technical consultant is warranted.*
*The **N/A** response option stands for **Not Applicable**.*

8. Framing: (if yes, provide description and photos)

- Y N n/a **a.** Damage to top and bottom connections of diagonal braces between ridge board and ceiling framing or failing of braces?
- Y N n/a **b.** Separation of framing at ridge board?
- Y N n/a **c.** Fresh fractures in framing members?

9. Chimney: (if yes, provide description and photos)

a. Masonry

- Y N n/a **i.** Visible cracks or offsets?
- Y N n/a **ii.** Damage to framing adjacent to chimney?
- Y N n/a **iii.** Damage to framing where metal tie straps attach masonry to framing?

b. Metal Flue

- Y N n/a **i.** Open or offset joints?

10. Plumbing: (if yes, provide description and photos)

- Y N n/a **a.** Evidence of active leakage?
- Y N n/a **b.** Broken pipe or joint separations in sewer vent piping?
- Y N n/a **c.** Broken pipe or joint separations in water piping?
- **d.** Other abnormal conditions, describe: ....

House Number: ....

11. Forced Air Heating and Cooling Ductwork: (if yes, provide description and photos)

Y N n/a **a.** Crushed ductwork?

Y N n/a **b.** Separated joints in ductwork or appliance flues?

Y N n/a **c.** Damage of insulation or joint taping on ductwork or appliance flues?

Y N n/a **d.** Shifted or disconnected furnaces or fan coil units?

e. Other abnormal conditions, describe:

....

D. Conclusions

12. Based on this inspection, should use of a technical consultant be considered?

Y N

If yes, which question(s) drove this decision: ....

If yes, describe the reasons: ....

APPENDIX F

Attic and Crawlspace Inspection Safety

The following is a list of safety guidelines when inspecting an attic or crawlspace:

- Never enter an attic or crawlspace without informing another individual of your entry and the approximate time you intend to be in the attic or crawlspace.
- Always use appropriate personal protective equipment (see Appendix B). Tight-fitting dust mask or respirator, gloves, coveralls, and hat are the minimum. Make sure you have a clean line of site through any respirator or hat.
- Kneepads and elbow pads are desirable accessories for crawlspace inspections.
- Be aware of potential biological hazards, including human or animal waste, pesticides, rodents, reptiles, or insects.
- Beware of and avoid electrical wiring that is loose or exposed.
- Beware of and avoid exposed nails.
- Do not enter crawlspaces, or portions thereof, contaminated with sewage.
- Safe maneuvering in attic spaces requires both hands to be unencumbered. Use a headlamp for lighting. Carry a compact camera on a neck strap or secured in a pocket. Do not move while you are looking through the camera lens. Establish safe footing and then use the camera.
- When moving in an attic, always maintain three points of contact (both feet and one hand or one foot and two hands). Verify that there is solid support before stepping. Step only on 2× or heavier framing—avoid stepping on 1× ties and braces. Never step on insulation or gypsum wallboard.

APPENDIX G

Recommendations for Crack Repair by Epoxy Injection in Residential Concrete

The following recommendations are offered to ensure effective repair of cracks in residential foundations and slabs-on-grade. These recommendations do *not* constitute a construction specification or instructions to a contractor. They are general guidelines for use in arranging, pricing, and monitoring the work.

G.1 General Recommendations

1. Work should be performed by a California licensed contractor specializing in epoxy injection. The status of a California contractor's license may be verified with the Contractors State License Board at: http://www.cslb.ca.gov/.
2. All work must comply with applicable building codes and regulations, including interpretations and guidelines of the local building department. In some cases, a deputy building inspector or an approved special inspector may be required to provide continuous inspection of the epoxy injection work.
3. The key objective of the work is to adequately fill all identified cracks with a structural epoxy resin that is adequately bonded to the concrete crack surfaces. To achieve this objective, the contractor is expected to exercise judgment regarding material selection and procedures, based on prior experience.
4. Prior to epoxy injection, surfaces adjacent to the crack or other areas of application should be cleaned of dirt, dust, oil, efflorescence, paint, or other foreign material detrimental to establishing a bond of the sealing material.
5. Cracks should be clean prior to injection. Remove loose debris in the crack with 100 psi compressed air using a needle tip nozzle. Clean older cracks with silt or clay in them with high pressure water, or, if tightly packed, a combination of high-pressure water and compressed air. Allow crack surfaces to dry if water is used for cleaning or if the concrete is in a wet environment. If debris remains in the crack, inject with Grade 1 material, followed with a more viscous grade depending on the width of the crack and the extent of capping.
6. Injection ports should be located either on the crack surface or in a drilled hole intersecting the crack. Ports should be spaced at a distance along the crack not less than the thickness of the slab, stemwall, or footing.
7. Following completion of injection and curing of epoxy, remove surface seal and any installed ports that protrude from the surface of the concrete using heat and a razor scraper or grinding.
8. Clean and remove all spills, leaks, and stains.

G.2 Crack Width Criteria

The following guidelines are subject to review and approval by the building official and the design engineer, if any:

1. Cracks narrower than 1/32 inch wide need not be injected.
2. Where cracks can be adequately sealed on all edges with a combination of an epoxy paste cap on exposed surfaces and firm soil or an epoxy-soil cap on concealed surfaces, cracks up to and including 1/4-inch wide should be injected with adhesive conforming to the requirements of ASTM C881, Type IV, Grade 1 (ASTM, 2015).
3. Where cracks cannot be adequately sealed on all edges, cracks should be injected with adhesive conforming to the requirements of ASTM C881, Type IV and of an appropriate grade. In the absence of contractor's experience, the following guidelines are offered:
   a. grade 1 for cracks widths up to 1/16 inch
   b. grade 2 for crack widths of 1/16 inch to 1/8 inch
   c. grade 3 for crack widths of 1/8 inch to 1/4 inch

   Where cracks vary in width over their length or depth, use of multiple viscosities of epoxies may be required. Viscosity is temperature dependent, and the above recommendations may need to be modified for temperatures significantly different from 70°F.
4. Cracks wider than 1/4 inch may be prepacked with coarse sand or pea gravel aggregate and injected with an adhesive conforming to the requirements of ASTM C881, Type IV, Grade 1.
5. Cracks up to 1/2-inch wide may be injected with a low exotherm adhesive conforming to the requirements of ASTM C881, Type IV.

G.3 Footings or Stemwalls

1. For footings or stemwalls surrounding a crawlspace, access as much of one side as possible and as much of the other side as practical (accounting for possible obstruction by plantings, hardscape, and property line limits). On the backside, seal the crack down to firm soil; on the front side (the exposed side from which the grout is injected), excavate to bottom of footing. Do not excavate beneath the footing. Clean crack, install ports, seal, and inject crack with appropriate grade material.
2. For footings or thickened edges surrounding slab-on-grade floors, only one-sided access is practical. Expose the concrete to the bottom of the footing. Do not excavate beneath the footing. Clean crack, install ports, seal, and inject crack with appropriate grade material.
3. For either one-sided or two-sided access, injection should begin at the lowest port and proceed upward to the top of the stemwall or footing.

G.4 Slabs-on-Grade

1. For slabs-on-grade, cracks should be cleaned, ports or 1/4-inch wide masking tape placed at a spacing no more than the slab thickness, the exposed surface sealed, and the masking tape (if used) removed.
2. Begin injection at one end of the crack and proceed port to port along the length of the crack. If there is a noticeable difference in elevation from one end of the crack to the other, start at the lowest elevation and proceed upslope. Two methods are effective for injecting cracks where the backside is not accessible:
   a. Method A: Inject Grade 1 material and allow it to seep into the soil bedding or backfill and jell (about 1.5 hours). Reinject crack with Grade 1. Repeat process until crack is completely filled.
   b. Method B: Inject crack with appropriate grade material.

G.5 Quality Assurance and Quality Control

In the course of the injection work, the contractor should follow the quality control guidelines of Sections 2.1 and 2.2 of ICRI Guideline No. 210.1R-2016 (ICRI, 2016), as appropriate for the job. The most common problem with epoxy injection, especially where access is available on only one side, is epoxy seeping out before it jells. In addition to concurrent quality control referenced above, quality assurance testing for this condition consists of grinding or chipping away the epoxy seal (near the top of the stemwall, anywhere along the length of a slab-on-grade crack) to visually inspect the injected crack. If the crack is filled to the top surface, loss of epoxy fill due to seepage has not occurred. If loss of epoxy due to seepage has occurred, reinjection of the crack with epoxy is required.

Where the repair is deemed structural by the structures specialist or building official, the effectiveness of the injection process should be evaluated in accord with the procedures of Section 2.3 of ICRI Guideline No. 210.1R-2016 by random coring, at the rate of two cores for the first 100 lineal feet of crack injected and one core for every additional 100 lineal feet of crack injected. Local jurisdictions may require a higher sampling rate. Three alternatives are available:

1. Small diameter (about 3/4 inch) core angled at 45 degrees to the concrete surface and located so as to intersect the crack plane at roughly the mid-thickness of the element. Visually examine the core for complete filling of the crack. Apply a sharp hammer blow to the side of the core to verify integrity of the repair.
2. Two-inch diameter core (or a 4-inch diameter core if the crack does not extend roughly perpendicular relative to the concrete surface) perpendicular to the concrete surface through the crack. Visually examine the core for adequate filling of the crack. Per ICRI Guideline No. 210.1R-2016, fill is considered adequate if 90% of the crack is filled with adhesive, as viewed from the exposed length of the crack on the sides of the core. Apply a sharp hammer blow to the side of the core to verify integrity of the repair.
3. Four-inch diameter core perpendicular to concrete surface through the crack. Visually examine the core for complete filling of the crack. Per ICRI Guideline No. 210.1R-2016, fill is considered adequate if 90% of the crack is filled with adhesive, as viewed from the exposed length of the crack on the sides of the core. Submit the core to a testing laboratory for a splitting tensile test.

Evaluation of the results is the same for all three testing alternatives. Fracture of the core through the parent concrete away from the repair indicates satisfactory performance. The presence of shiny or glassy areas on a face of hard cured epoxy adhesive exposed by the test fracture indicates that the glassy or shiny area cured while exposed to air and that there is no effective bond because the crack was not adequately filled with epoxy adhesive. If inadequate fill is found, the crack should be reinjected and retested.

Test core holes should be filled using a two-component epoxy grout mix, applied by hand trowel, thoroughly rodded, and tamped in place. For exposed concrete surfaces in plain view, the surface finish should match the color and texture of the adjacent surface.

Glossary and Acronyms

I.1 Glossary

The definitions and descriptions provided here are intended for use with these *General Guidelines* only. They may differ from definitions of similar or identical terms used in the *Engineering Guidelines*, in building codes, or in other technical standards or references.

acceleration. The rate of change of the velocity (speed in a particular direction) as a function of time. Increasing speed over time is sometimes referred to as acceleration and decreasing speed as deceleration. Ground shaking during an earthquake is typically recorded as an acceleration that varies rapidly. The peak ground acceleration is the largest instantaneous acceleration recorded by a particular station during an earthquake. The accelerations recorded in an earthquake can be used to determine how much force the earthquake creates in a building.

accelerogram. The recording of the acceleration of the ground during an earthquake.

accelerograph. An instrument that records the acceleration of the ground during an earthquake.

active fault. A fault that is likely to have another earthquake sometime in the future. Faults are commonly considered to be active if they have moved one or more times in the last 10,000 years.

adobe clay. A heavy, expansive clay common to many areas of California. Expansive clay soils expand with increasing moisture content and shrink upon drying, commonly resulting in damage to buildings and pavements constructed upon them.

adobe construction. Buildings constructed using sun-baked bricks of adobe clay. Adobe construction is highly vulnerable to damage and collapse during earthquakes.

aerator. A plumbing fitting attached to the end of a faucet used to mix air with water.

aesthetic element. A portion of a building that contributes to the appearance but not the structural function of a building. If the aesthetic element were not there, the safety and stability of the structure would not be compromised.

aftershock. An earthquake that follows the largest earthquake, or main shock, of an earthquake sequence and originates in or near the rupture zone of the larger earthquake. Generally, major earthquakes are followed by a number of aftershocks, decreasing in frequency with time.

alluvium. Gravel, sand, silt, or clay transported and deposited by moving water.

anchor bolt. A steel bolt that attaches wood sill plates (or mudsills) to foundations. Typically anchor bolts are 1/2- or 5/8-inch diameter and are embedded in the concrete foundation when the concrete is cast.

anchorage. A term used to describe the connection of the structure to the foundation.

appurtenance. A term used to describe a structure, such as an attached patio cover, that sits on the same parcel of land as the main house, such that it becomes a part of that property.

architect. In California, someone who has been granted a license by the Board of Architectural Registration to practice architecture and to use the professional title architect.

architectural. Pertaining to elements of a structure that are not part of the load-resisting system but serve to protect the building from the elements or provide other nonstructural functions.

asbestos. Any of several minerals (such as chrysotile) that readily separate into long flexible fibers, that cause asbestosis and have been implicated as causes of certain cancers. Asbestos was formerly used as a fireproof insulating material.

asphalt composition shingles. Roof covering consisting of an asphalt-impregnated felt base covered on the exposed side with mineral granules.

asphalt saturated felt. Roof underlayment made from paper or fiberglass saturated with asphalt.

at-grade. At ground level.

attenuation. The decrease in the amplitude or intensity of ground shaking with increasing distance from the earthquake rupture plane. The process is analogous to a pebble thrown into a pond that makes waves on the surface move out from the place where the pebble entered the water. The waves are largest where they are formed and gradually get smaller as they travel away. This decrease in size, or amplitude, of the waves is attenuation.

awning window. Window that opens by swinging outward on hinges at the top of the window frame.

backfill. Soil used to refill an excavation, typically behind a retaining wall or around exterior foundation walls.

beam. Generically, any horizontally spanning structural member that supports vertical loads; in common usage, these terms are used to describe beams, from the largest to smallest: girder, beam, joist, purlin, sub-purlin. Headers, or lintels, are short beams spanning over doors and windows.

bearing wall. A structural wall that carries weight from the building above.

bedrock. Relatively hard, solid rock that commonly underlies softer rock, sediment, or soil.

bending. A bending load tries to curve or fold a structural member, as opposed to a compression or tension load that compresses or stretches a member along its length.

blind fault. A fault whose rupture is not evidenced at the ground surface.

blind thrust fault. A thrust fault that does not rupture all the way up to the surface, so there is no evidence of it on the ground. It is "buried" under the uppermost layers of rock in the crust.

blocking. Members placed in between studs or joints, perpendicular to the studs or joists, to provide additional lateral stability.

board and batten siding. An exterior finish composed of wood boards with thin wood strips (battens) covering the vertical joints between the boards.

bond beam. A masonry course constructed and reinforced to serve as a beam, or a bearing course for structural members.

brace. Structural element that provides stability (i.e., resistance to racking or buckling) and helps position and support structural members.

branch circuit. The portion of an electrical system extending from the final over-current device protecting a circuit to the outlets served by the circuit.

breaker. A switch that automatically shuts off an electric current to prevent too much current from damaging an appliance in the circuit or causing a fire. As opposed to a fuse, a circuit breaker can be reset without replacing any components.

brown coat. The middle coat in a three-coat stucco system.

building pad. A level section of ground on which a structure is constructed.

building paper. Thick paper composed partly of asphalt that is applied to exterior walls and roofs as a first layer of weatherproofing.

built-up membrane. Several alternating layers of building paper (or felt) and hot asphalt topped with gravel or a mineral cap sheet that serves as the waterproofing membrane on a flat roof.

buttonboard. See **gypsum lath**.

cantilever. A structural element that is fixed at one end and free to move at the other end.

cantilever retaining wall. A retaining wall that acts as a cantilever to resist the force of the mass it is retaining.

capacity. The amount of load, force, displacement, or rotation a structural element can support or withstand without collapse or permanent deformation.

casement window. A window that swings open like a door.

cast-in-place. Concrete poured in the location it will be used at the site, as distinct from pre-cast concrete.

cathedral ceiling. A ceiling that extends to the full height of the roof framing, also known as a vaulted ceiling.

ceiling joist. A beam that is part of the framing that encloses the top of a room to which the ceiling finish is attached.

cement-asbestos shingle. A cement-based shingle reinforced with asbestos fibers.

cement board siding. An exterior finish consisting of cement-based boards, often reinforced with cellulose fibers.

chase. Wood-frame decorative enclosure of a flue that may be finished with wood siding, stucco, or stone masonry veneer.

checking. A condition where apparent "splits" are visible in larger (typically 4×4 or larger) wood members resulting from normal curing of the wood. The checking is actually a separation in wood fibers across the annual rings of the wood and normally is not a structural concern (see also splitting).

chimney strap. A thin strip of metal used to attach a chimney to the surrounding wood framing to prevent toppling of the chimney during an earthquake.

chimney sweep. A tradesman who cleans, maintains, and repairs chimneys.

cold joint. The intersection of two different concrete placements. This joint forms if the second placement begins after the first placement has begun to set. Cracks and separation often occur at this joint.

collapse. A complete loss of capacity of all or a portion of a structure resulting in the structure not being able to support its own weight.

color coat. The top layer of a stucco system, also called the finish coat.

column. Vertical structural element designed to support axial compression loads (a crushing force applied in the direction of the length of the member); wood columns are often called posts.

community internet intensity. A measure of the severity of earthquake ground shaking determined by responses to an online questionnaire compiled from citizens in affected areas and summarized as a map showing the assigned Modified Mercalli Intensity (MMI) level for each ZIP code.

compressional stress. The stress that squeezes something; synonymous with compressive stress. It is the stress component perpendicular to a given surface, such as a fault plane, that results from forces applied perpendicular to the surface or from remote forces transmitted through the surrounding rock. The value of compressional stress is expressed in units of force per unit cross-sectional area (e.g., pounds per square inch, or psi).

compressive strength. The maximum amount of compressive stress a material can withstand.

concrete. A mixture of Portland cement, sand, gravel, and water. The water hydrates the Portland cement forming a solid material that holds the sand and gravel together.

concrete block. A block made of Portland cement, sand, gravel, and water formed into a rectangular prism with one or more hollow spaces and used to construct walls. Synonymous with hollow concrete block, concrete masonry unit (CMU), or cinder block; may be either reinforced or unreinforced.

construction joint. A joint formed during construction, typically between two vintages of the same material or two different materials; a common location for cracks and separation. A construction joint may be deliberately formed to permit movement of building components relative to one another.

continuous footing. A foundation element that extends along an entire dimension or around the perimeter of a structure, as opposed to a pier or post that supports a single element.

Contractors State License Board. The California state government entity that licenses and regulates contractors in predetermined classifications that constitute the construction industry. The status of a contractor's license can be verified at the board's website: http://www.cslb.ca.gov/.

control joint. A groove, saw cut, or insert that forms a straight line intended to be the place where concrete shrinkage cracks will form; sidewalks commonly have control joints every few feet, for example.

core. A cylindrical section of concrete that is removed from a structure for testing and analysis.

corner bead. Thin metal angle applied to wallboard corners to form a neat edge and provide some protection against impacts.

cosmetic damage. Damage that is nonstructural and has only aesthetic significance.

cosmetic repair. Repair of nonstructural damage; typically involves repair or replacement with like kind and quality to restore a reasonably uniform appearance.

counter flashing. Flashing folded down to cover base flashing and prevent water intrusion at the flashing joint.

crawlspace. The area below the first floor enclosed by foundation walls or cripple walls.

crazing. A multitude of tiny cracks oriented randomly.

creep. Slow, more-or-less-continuous movement occurring on faults due to ongoing tectonic deformation. Faults that are creeping do not tend to have large earthquakes. Also refers to long-term movement of soil, particularly on a slope.

cripple walls. Short stud walls extending from the foundation to the framing of the lowest floor.

crust. The thin outer layer of the Earth's surface, averaging about 10-km thick under the oceans and up to about 50-km thick on the continents. The uppermost 15 km–35 km of the crust is brittle enough to produce earthquakes. This is the only layer of the earth that humans have actually seen.

cut. Soil removed from a slope to form a level building pad. See also **cut-and-fill**.

cut-and-fill. To form a level pad beneath the building footprint, a slope may be excavated (cut) or soil may be placed on the slope (fill), or a single building lot may be a combination of both. Engineered fill has been compacted by earth-moving equipment to minimize settlement.

cut-in bracing. Wood diagonal bracing in older construction that is installed in short segments between the wall studs, like diagonal blocking.

delamination. The process of building materials becoming separated, particularly loss of adhesion or connection between a material and its substrate (e.g., detachment of stucco from the wood framing).

desiccation crack. A soil crack resulting from expansive soil movement.

destructive investigation. An investigation that requires some form of damage to the structure, such as removing wallboard to examine framing or taking a core from a concrete slab.

diagonal brace. An inclined member installed to provide stability to a structure.

diaphragm. A solid area of wall or floor that, by virtue of its shear stiffness and strength, resists racking due to lateral forces.

differential settlement. Settlement of one area of soil that is more than at a nearby location, as when one corner of a building settles more than elsewhere within the building footprint.

dip-slip fault. An inclined fracture where the blocks have mostly shifted vertically. If the rock mass above an inclined fault moves down, the fault is termed normal, whereas if the rock above the fault moves up, the fault is termed reverse. A thrust fault is a reverse fault with a dip of 45 degrees or less. Oblique-slip faults have significant components of different slip styles.

doorjamb. See **jamb**.

drop ceiling. A ceiling finish suspended below the framing to provide space for piping or ductwork.

drying shrinkage. A reduction in volume as a result of water loss that typically occurs in wood as it dries and in concrete as it cures.

drywall. A wall finish system consisting of gypsum panels attached to wall framing and coated with joint compound and tape to form interior wall and ceiling finishes.

drywall tape. A tape, typically paper or mesh, used to seal the joints between drywall panels.

ductile. Able to undergo a large amount of deformation before failure; flexible.

earthquake. Ground shaking and radiated seismic energy most often caused by a sudden slip on a fault.

earthquake load. An inertial force developed on a building element as a result of earthquake ground shaking.

efflorescence. Whitish staining of concrete or masonry caused by water seeping through the material, dissolving salts, and depositing them on the exterior, where they remain after the water evaporates.

elastomeric. A flexible, rubber-like adhesive used as a sealant.

engineer. An appropriately qualified and licensed civil engineer, who may or may not also have a Structural Engineer or Geotechnical Engineer title authority.

engineered repair. A repair designed or specified by an appropriately qualified and licensed engineer or architect.

engineered wall panels. In wood-frame buildings, wall panels of plywood, oriented strand board (OSB), or other engineered materials are deliberately designed to be fastened to the wall studs to provide lateral (horizontal) load resistance.

engineering geologist. A geologist with a focus on how soil conditions affect structures.

epicenter. That point on the Earth's surface directly above the hypocenter of an earthquake.

expansive soil. Soil that has a fluctuating volume based upon the addition or removal of water.

exterior insulation and finish system (EIFS). An exterior cladding consisting of a reinforced polymer attached to foam plastic insulation that is attached to sheathing or directly to framing.

face/facing. Decorative finish of brick or stone masonry applied over the front edge of the firebox and the surrounding wall.

failure surface. The plane along which a structural member or a fault cracks or ruptures.

fault. A weak zone in the earth's crust and upper mantle where the rock layers have ruptured and slipped. Faults form during earthquakes, and earthquakes are likely to recur on pre-existing faults.

fault plane. The planar (flat) surface along which there is slip during an earthquake.

fault rupture. Movement along a fault plane manifested at the ground surface.

fault trace. Intersection of a fault with the ground surface; also, the line commonly plotted on geologic maps to represent a fault.

felt underlayment. A heavy, asphalt-saturated paper placed underneath exterior finishes to weatherproof the building.

fiber composite shingle. A roofing material made of fibers cast in a polymer or cementitious matrix.

fill. Soil used to fill in a portion of a slope to create a level building pad. See also **cut-and-fill**.

fireplace insert. A prefabricated firebox installed as a retrofit in an existing fireplace.

flashing. Material, generally sheet metal or building paper, applied at penetrations and joints to prevent water intrusion to the interior of a structure.

flat roof. A roof with no slope or minimal slope to permit drainage, often covered with a built-up membrane.

flexibility. The ability to deform without breaking.

flexural strength. The stress at failure in bending.

floor diaphragm. The elements of a floor, typically the framing together with the sheathing, that resist lateral (horizontal) loads applied to the structure.

floor slab. Concrete slab to which floor finishes are applied.

focal depth. The depth of an earthquake hypocenter below the earth's surface.

focus. That point within the earth from which originates the first motion of an earthquake and its elastic waves. See also **hypocenter**.

footing. The section of the foundation that transfers the load from the structure to the supporting soil.

foreshock. A small tremor that commonly precedes the largest earthquake in a series, or main shock, by seconds to weeks, and that originates in or near the rupture zone of the larger earthquake.

foundation. The substructure, usually of concrete, that supports the wood-frame building and transfers loads to the ground.

framing. The skeleton of a structure, the underlying support elements.

frequency. The number of times a cyclic event occurs in a certain period of time, such as the ground shaking up and down or back and forth during an earthquake.

gable end wall. An exterior wall that comes to a triangular point to support a sloped roof.

gable roof. Roof that has a single ridgeline forming two roof planes with rafters extending to opposite sides of the space below; two roof planes sloping from central ridge.

geocode. To determine the latitude and longitude of a street address.

geotechnical engineer. a licensed civil engineer who specializes in geotechnical engineering (soils and foundation engineering) as it relates to the design of structures. A civil engineer who has satisfied additional experience and testing requirements can have Geotechnical Engineer title authority.

geotechnical engineering. Analysis and design of foundations and soil conditions for construction.

geotechnical investigation. Determination of soil properties for use in design and repair of ground failure, foundations, and retaining walls. A geotechnical investigation might include soil borings to determine the soil profile and soil sampling for laboratory analysis.

girder. Typically, a larger, main beam that supports joists or other smaller beams. See also **beam**.

grade. The ground surface on which a structure is built.

grade beam. A reinforced concrete beam embedded in the soil that spans between and ties together other foundation elements, such as piers or piles.

grading. The preparation of a soil for building a foundation (i.e., creation of a level building pad).

gravity load. A force on an element resulting from the weight of the element and other elements supported by the element.

green lumber. Also called "wet lumber" because of its high internal moisture content; lumber that has not been dried prior to use in construction, typically shrinking after installation as it loses moisture.

green tagged. A building that has been inspected after an earthquake and that may have suffered damage but is deemed safe for occupancy by a building official.

ground deformation. A permanent change in the ground surface resulting from ground failure.

ground failure. A general reference to landslides, liquefaction, lateral spreads, and any other consequence of shaking that affects the stability of the ground.

ground motion (shaking). Movement of the earth's surface from earthquakes or explosions. Ground motion is produced by waves that are generated by sudden slip on a fault or sudden pressure at the explosive source and travel through the earth and along its surface.

gypsum lath. A gypsum-based panel to which an interior plaster finish is applied, also known as buttonboard.

gypsum wallboard. A smooth interior finishing material made from gypsum and typically installed in 4-feet by 8-feet panels. The key component of drywall.

hardscape. Any exterior pavement, such as sidewalks, driveways, patios, and pool decks.

hardware. The metal fittings and fastenings used in construction.

header. A beam that spans over door and window openings. See also **beam**.

heating, ventilation and air conditioning (HVAC) systems. Systems and equipment related to house heating, ventilation, and air conditioning.

heave. Lifting of structural elements as a result of swelling of expansive soil.

heavy timber floor framing. 4× beams spaced 48 inches apart and supporting 1 1/2-inch thick wood sheathing or 1 1/8-inch thick plywood.

hip roof. Roof that has ridge lines extending to the four corners of the rectangular space beneath forming four roof planes; may or may not come to a single point.

hold down. A connection used to tie a wall to a floor or a roof to a wall to prevent the wall from overturning or the roof from uplifting due to lateral loads. Also called a tie-down.

horizontal diaphragm. See **diaphragm**.

horizontal slab-footing joint. A cold joint, often visible along the exposed exterior slab edge, formed when a concrete slab-on-grade is placed after a concrete perimeter footing is placed.

hypocenter. The calculated location of the focus of an earthquake. The point within the earth where an earthquake rupture starts.

inertia. In the context of the effects of earthquake ground shaking on structures, the phenomenon of a structure's tendency to remain stationary while the ground beneath it wants to move. As a result, horizontal (lateral) forces, called inertial forces, develop in the structure.

instrumental intensity. The numerical value of ground shaking intensity, derived from recorded ground motions, as shown on a ShakeMap.

intensity. A measure of the effects of an earthquake at a particular place on humans, structures, or the land itself. The intensity at a point depends on, among other factors, the strength of the earthquake (magnitude), the distance from the earthquake to the point, and the local geology (soil conditions) at that point.

invasive inspection. See **destructive investigation.**

isoseismal line. A line connecting points on the earth's surface at which earthquake intensity is the same. It is usually a closed curve around the epicenter.

isoseismal map. A map connecting points on the earth's surface at which earthquake intensity is the same. Common isoseismal maps are generated using the Modified Mercalli Intensity (MMI) scale or instrumental intensity values (ShakeMap).

jamb. The vertical portion of a door or window frame.

joist. A support beam that is at least 6-inches deep and either 2- or 4-inches thick that typically supports floor and ceiling loads.

landslide. An abrupt movement of surface material down a slope in response to gravity. Landslides can be triggered by an earthquake or other natural causes. Undersea landslides can cause tsunamis.

lateral-force-resisting system. See **seismic-force-resisting system.**

lateral load path. The connection of horizontal diaphragms and shear walls that transfers lateral loads applied to a structure to the ground.

lateral spreading. Horizontal movement in sloping ground resulting from liquefaction.

lath. Thin wood strips, gypsum panels, or wire mesh, running crosswise to the wall or ceiling framing, providing a base for the application of plaster on interior walls; thin metal lath is common on exterior walls to provide the base for the application of stucco.

lath and plaster. Interior wall finish system consisting of plaster applied to a base consisting of thin wood strips, gypsum panels, or wire mesh.

latitude. The location of a point north or south of the equator. Latitude is shown on a map or globe as east-west lines parallel to the equator.

leak test. A test performed by a plumber or other qualified contractor to locate leaks in water or gas lines.

let-in bracing. Typically, a 1×4 or 1×6 diagonal brace; it is nailed to the studs, which are notched to allow the brace to fit within the depth of the stud wall framing; see also **cut-in bracing**.

leveling compound. Floor leveling compound is any mix used to fill low areas and imperfections or add as a topcoat to existing flooring.

lightweight concrete. Concrete made with more porous aggregate than conventional concrete, giving it a lower unit weight.

liquefaction. The process in which water-saturated soil loses strength and takes on the characteristics of a liquid. This effect can be caused by earthquake ground shaking, and typically results in a loss of the soil's ability to support the structures built on it.

load. A force on a member resulting from gravity, environmental sources, such as temperature fluctuations, or other sources of energy, such as wind, earthquake ground shaking, or impacts.

load bearing. A structural system or member designed to support applied forces in addition to its own weight.

longitude. The location of a point east or west of the prime meridian. Longitude is shown on a map or globe as north-south lines left and right of the prime meridian, which passes through Greenwich, England.

lurching. Lunging of a portion of the ground's surface in an earthquake that results in a permanent deformation (such as ground cracks); not the same as the temporary (transient) movement or vibration of the ground that lasts during shaking.

magnitude. A measure of the strength of an earthquake or strain energy released by it.

main shock. The largest earthquake in a sequence, sometimes preceded by one or more foreshocks, and almost always followed by many aftershocks.

masonry. Brick, concrete block, stone, or adobe assembled using mortar.

mastic. An asphalt-based adhesive commonly used to patch flashing joints.

mechanical, electrical, and plumbing (MEP) systems. Systems and equipment related to house mechanical, electrical, and plumbing systems. Mechanical systems commonly include HVAC systems.

mesh tape. An adhesive used to join wallboard panels and to repair wallboard cracks. The use of mesh tape as part of the repair reduces the likelihood of the crack reopening.

metal connector plate. Sheet metal plate with teeth used to join members of a wood truss.

Modified Mercalli Intensity (MMI) scale. A scale, designated by Roman numerals, composed of 12 increasing levels of intensity that range from imperceptible shaking to catastrophic destruction. Used to characterize the intensity of ground shaking based on observation of the effects of that shaking on people, buildings, building contents, and the natural environment.

moisture intrusion. Infiltration of liquid water or water vapor to the interior of a structure.

moment magnitude. See **magnitude**.

mortar. A combination of cement and sand, water, and sometimes other materials, used between masonry units and beneath tile and stonework on floors.

mudsill. A beam or plank that is laid on the ground or the foundation to support wood-framing.

nail pop. A circular crack or slight bump in the finish over a fastener caused by incomplete fastener installation or shrinkage of wood framing after wall finish application. Nail pops also develop in floor and roof sheathing due to improper installation, framing shrinkage, and thermal and moisture cycling.

natural frequency. The frequency at which a particular object or system vibrates when pushed by a single force or impulse, and not influenced by other external forces or by damping. If you hold a slinky by one end and let it hang down and then give it one push up from the bottom, the rate of up-and-down motion is its natural frequency.

natural period. The time it takes an object or system to complete one cycle of motion (back and forth or up and down) when excited at its natural frequency.

non-bearing wall. A wall that serves only as a partition of space and does not support the weight of any other structural or finish elements.

nondestructive. In the context of this document, typically referring to investigation or testing that does not require exposing covered elements, such as wall cavities or excavating soil.

nonstructural. Not a part of the structure of the building that holds it up and is designed to resist horizontal forces.

offset. With respect to any flat surface, an out-of-plane difference in the surface location across a crack or joint, measured perpendicular to the plane of the surface.

open exterior wall line. On the exterior of the residence, a line of wall that does not have at least two solid-sheathed wall panels, each at least 32-inches wide, or a line of wall that does not have one such bracing element at least every 25 feet; indicative of a side of the building at that level that may not have the usual degree of horizontal resistance.

oriented strand board. A board made of layers of pressed wood chips, commonly used for sheathing and subflooring.

panel siding. Exterior finish made of panels.

partition. An interior nonstructural, non-load-bearing wall.

pavement. Layer of concrete or asphalt placed to form a road, driveway, patio, or walkway.

penetration. Opening in a roof, ceiling, floor, or wall.

perceptible. That which can be observed or detected without additional measurement or visualization capabilities. For example, a floor slope of less than about 1 inch in 20 feet is generally not perceptible.

pier. In wood-frame construction, a short concrete post or column holding up part of the ground-level floor framing; also may be concrete foundation element of column shape embedded in the ground to provide vertical support for the upper portion of the foundation.

plain concrete. Synonymous with unreinforced concrete; concrete that has no reinforcement or less than the minimum amount specified in the building code for reinforced concrete. Many residential foundations and slabs-on-grade are constructed of plain concrete.

plaster. A mixture of gypsum or lime, water, and sand applied wet and allowed to harden. Commonly used as an interior finish material; exterior plaster is called stucco.

plot plan. A drawing indicating the boundaries of a property and the location and orientation of buildings on the property.

posting. See "tagging."

post-tension slabs. Before a post-tension slab is poured, high-strength steel strands or cables are laid in the concrete in a tight grid. When dry, this results in a slab of concrete that has been pre-stressed and therefore increases the strength of the concrete.

prefabricated fireplace. Sheet metal factory-assembled fireplace installed at the site; alternative to a masonry fireplace.

pressure test. A test to locate leaks in gas, water, or sewer lines.

prestressed concrete. Concrete that has steel cables running through it tensed up (stressed) to compress the concrete; thereby, reducing the effects of applied tensile loads and increasing its load-carrying capacity; an alternative to reinforced concrete.

prestressing cable tendons. Thick steel wires used to apply a prestress.

purlin. An intermediate horizontal wood member that supports the ends of roof rafters. In house construction, a purlin is only needed if the distance between supporting walls is too long for the rafters to span.

rack(ing). An out-of-plumb, no-longer-square distortion that ranges from a fraction of an inch per story in buildings with cosmetic damage to several inches per story in buildings with widespread, structurally significant damage. Most easily seen in doors or windows that no longer open or close as they did before the earthquake.

rafter. A roof framing element connecting the ridge member with the exterior wall; sloping joist of a roof.

rafter tail. The end of a rafter that is visible from the exterior of a building, along the eaves.

rat slab. A thin slab of nonstructural concrete poured over the soil surface of a crawlspace. A rat slab may be used to deter rodents from entering the crawlspace or to help control the collection and discharge of water entering the crawlspace.

rebar. A steel reinforcing bar used in concrete.

red tagged. A building that has been inspected by a building official and deemed unsafe to enter following an earthquake.

re-entrant corners. Corners whose intersecting walls make an exterior angle of less than 180 degrees.

reinforcing. Elements added to a member to increase its load-carrying capacity. In concrete, reinforcing is typically steel bars; in a slab-on-grade, reinforcing can also be in the form of welded wire mesh.

reinforced concrete. Concrete that has no less than the minimum amount of prestressing steel or non-prestressed reinforcement, as specified in the building code.

reinforced masonry. Masonry, such as brickwork or concrete block, that has steel reinforcing in it.

responsible charge of work. As defined in §§ 6703 of the Professional Engineers Act of the Business and Professions Code of the California Statutes: "The phrase 'responsible charge of work' means the independent control and direction by the use of initiative, skill, and independent judgment, of the investigation or design of professional engineering work or in the direct engineering control of such projects …"

retrofit. To modify an existing structure, typically to enhance its performance.

ridgeboard or ridge beam. Framing member that runs along the ridge of the roof to which rafters are attached.

ridge shattering. Disruption of ground surface, often resembling plowed ground, along a narrow ridge, resulting from focusing of ground shaking due to topographic effects.

safety assessment. A function of the local government building department; assesses whether a building is safe to occupy and is distinct from the process covered in this document, namely the assessment of any earthquake-caused damage and the repairs needed to restore the building to its pre-earthquake condition.

sand boil. Sand and water that come out onto the ground surface during an earthquake as a result of liquefaction at shallow depth.

scratch coat. The first of three coats in a stucco system.

scuttle. Opening in the ceiling through which the attic is accessed.

seiche. A temporary disturbance or oscillation from earthquake shaking in the water of a lake or other enclosed body of water.

seismic. Of or pertaining to earthquakes.

seismic compression. Decrease in volume of soil above ground water table during earthquake ground shaking that results in ground surface settlement and lateral movement near slopes; prevalent in earth fills and loose sands; magnitude directly related to thickness of susceptible material.

seismic-force-resisting system. The components, such as shear walls, in a building that transfer lateral (horizontal) loads applied to a structure to the ground.

seismic resistance. The ability of a structure to withstand seismic forces.

seismic vulnerability. The susceptibility of a structure to earthquake damage.

seismic wave. An elastic wave generated by an earthquake. Seismic waves may travel either along or near the earth's surface (Rayleigh and Love waves) or through the earth's interior (P- and S-waves).

serviceability. The ability of a structural, architectural, or other element to perform its intended function.

settlement. Downward vertical movement of ground surface (and any structures above it) resulting from densification of soft or loose soils; may occur in soft natural ground, but more often the result of inadequate compaction of fill materials. See also **seismic compression**.

ShakeMap. A rapidly produced map of earthquake ground shaking severity distributed over the Internet by the USGS. An automated analog of the MMI map that presents the variation in intensity of ground shaking based on interpolated data from available instruments and information about the topography and geology of the area.

shear stress. The stress component parallel to a given surface, such as a fault plane, that results from forces applied parallel to the surface or from remote forces transmitted through the surrounding rock.

shear wall. A vertical structural element that resists the shearing or racking deformations generated by the inertial forces in the building.

shed roof. Roof composed of one plane, sloping one direction.

shrink/swell. Movement occurring in expansive soil. As the water content decreases, the soil shrinks. As the water content increases, the soil swells.

shrinkage. The reduction in volume over time of construction materials, particularly wood and concrete or cement-based materials, resulting from a loss of water. If the material is restrained from shrinking, cracking can occur.

shrinkage cracking. Cracking that results when an element is restrained from shrinking freely. As the element tries to shrink, stresses develop that lead to cracking. Shrinkage cracking is extremely common in concrete and other cement-based materials, such as stucco.

sill. The horizontal member at the bottom of a door or window opening. Also, the lowest horizontal member of a frame that rests on the foundation.

sill line. Joint between the wood-frame superstructure and the concrete foundation.

sill plate. See **mudsill**.

single-pour system. A concrete foundation placement technique in which the slab-on-grade floor and the perimeter footing are formed at the same time.

slab-on-grade. Concrete slab (floor slab or pavement) that is directly against the soil and derives its support from the underlying soil.

slab-on-ground. See **slab-on-grade**.

slope creep. Slow downslope movement of soil or rock, usually confined to areas along a slope face or near the top of a slope.

slope failure. See **landslide**.

Soft story. A story in a multi-story building that has significantly less lateral stiffness to resist earthquake forces than other stories in the building and therefore sustains greater drift during an earthquake; in wood-frame buildings, generally a story with fewer walls than other stories above. See also **weak story**.

soil boring. Excavation of a column of soil to determine the soil profile.

soil profile. The vertical arrangement of layers of soil down to the bedrock.

soil stabilization. Remediation of ground failure such that the soil will be able to support existing structures again.

soils specialist. Licensed civil engineer specializing in soils or geotechnical engineering; licensed geotechnical engineers (civil engineers who have satisfied additional experience and testing requirements and are authorized to use the title Geotechnical Engineer); and licensed engineering geologists.

spaced sheathing. Roof framing covering consisting of boards placed with spaces in between each board.

spalling. The deterioration of a structure or surface by chipping or scaling of small pieces (spalls).

split level. A residence constructed with adjacent floor levels that have vertical offsets, often by about half a story.

splitting. A condition in wood members where cracking occurs along the grain, but not completely through the member.

spread footing. Shallow concrete footing located under the building perimeter and usually under some interior walls to spread the building weight out over a sufficient area of soil to avoid excessive settlement.

stability. The ability of an element or structure to withstand loading without buckling, racking, or extreme deformation.

stemwall. Portion of the concrete foundation that forms a short vertical wall extending slightly above grade; in a modern house foundation with spread footing, the stem wall is the vertical portion of an inverted T.

stiffness. A measure of how much a material deforms under a given load. For example, glass is stiffer than rubber. If you pull on a piece of glass, it does not appear to deform at all, but it is very easy to stretch a rubber band.

strain. Change in length per unit length or volume per unit volume of a body. In the context of an earthquake, small changes in length and volume associated with deformation of the earth by tectonic stresses or by the passage of seismic waves.

strength. The ability of a material to withstand applied forces. In material testing, the stress in material at failure.

stress. Force per unit area acting on a plane within a body. Six values are required to characterize completely the stress at a point: three normal components and three shear components.

stress concentration. An area of higher stress within a body. Generally, stress is distributed uniformly throughout a body, such as a wall or beam, but changes in geometry, such as a door or window opening, or the presence of flaws can create areas where stresses are much higher than throughout the rest of the body.

structures specialist. Licensed civil engineers specializing in structural engineering, licensed structural engineers (civil engineers who have satisfied additional experience and testing requirements and are authorized to use the title Structural Engineer), and licensed architects with expertise in structures.

structural capacity. The extent to which an element can provide strength and stability.

structural engineer. Licensed civil engineer specializing in structures. A civil engineer who has satisfied additional experience and testing requirements can have Structural Engineer title authority.

structural repair. A repair that restores the structural capacity of an element, as opposed to a non-structural (or cosmetic) repair.

stucco. Exterior plaster applied in layers to form the exterior wall finish material.

subsurface investigation. See **geotechnical investigation**.

superstructure. The portion of the building above the foundation.

surface faulting. Displacement that reaches the earth's surface during slip along a fault. Commonly occurs with shallow earthquakes, those with hypocenters less than 20 km deep. Surface faulting also may accompany a seismic creep or natural or man-induced subsidence.

surface fault rupture. Tearing and offsetting of the ground surface where the earthquake fault intersects the surface.

tag. A building-department-issued red, yellow, or green placard attached to a building following a post-earthquake safety assessment.

tagging. Synonymous with safety assessment; posting of a safety assessment placard on a building by the authority of the local jurisdiction. Red means unsafe, do not enter; yellow is accompanied by notes indicating some localized hazardous condition (e.g., a damaged chimney) that restricts safe occupancy to a portion of a building or temporary access; green indicates the building inspection found the property safe to occupy. Safety assessments are conducted using different criteria than assessments of required repairs that are discussed in this document.

tape joint. Joint between two adjacent wall board panels, finished by smoothing joint compound over paper tape to hide the joint.

tar-and-gravel roof. See **built-up membrane.**

technical consultant. A broad term used in this document to describe the various specialties that may be needed to assist with assessment and repair of earthquake damage. This can include any of the various types of engineers (e.g., civil, structural, geotechnical) or building specialists, like those who focus on plumbing or chimneys.

telegraphing a crack. Propagation of an underlying crack through another material, as when the trace of a shrinkage crack in a slab-on-grade appears in the floor finish.

test pit. A hand-dug excavation to obtain soil samples for laboratory analysis and to expose and examine foundation elements.

thermal movement. A change in position as a result of temperature fluctuations.

thickened edge. A deepened edge of concrete around the perimeter of a slab-on-grade, forming a footing to support loads from walls above.

thrust fault. See **fault**.

toe. The base of a slope or landslide.

toe bulging. Outward displacement of soil at the base of a slope, indicative of ground failure.

top plate. The highest horizontal member of a framed wall on which rafters or joists rest.

transient earthquake ground movement. Ground shaking that occurs during an earthquake, as opposed to permanent ground deformation, such as ground failure.

truss. A structural assembly whose members are generally loaded in axial tension or compression (loads applied parallel to the member), commonly found in residential roof construction.

tsunami. A sea wave that results from large-scale seafloor displacements associated with large earthquakes, major submarine slides, or exploding volcanic islands.

twisting. Deformation of a wood member by rotation.

two-pour system. Rather than pouring the concrete slab-on-grade and underlying spread foundation elements together, first the foundation is poured and hardened and later the slab-on-grade is poured, introducing a construction joint between these concrete elements.

underpinning. Deep foundation elements (e.g., piers, piles) installed beneath a shallow foundation to extend vertical support down to stable soil.

uninterrupted wall line. A wall without any openings (e.g., doors or windows).

unreinforced masonry. Masonry, such as brickwork, with no steel reinforcing.

weatherproofing. Materials applied to protect the building and its occupants from the elements, mainly to keep water out.

weak story. A story in a multi-story building that has significantly less lateral strength to resist earthquake forces than other stories in the building; in wood-frame buildings, generally a story with fewer walls than other stories above. See also **soft story**.

weep screed. A thin-gauge strip of metal placed behind the stucco where the wood-frame wall meets the foundation that directs water behind the stucco so it can drip out; where a weep screed has been used, the stucco does not extend down over the concrete foundation to the ground.

wind load. Forces resulting from wind on a building. Similar to earthquake forces, wind loads are applied horizontally.

wire mesh. Light-gauge reinforcing in stucco, sometimes referred to as chicken wire.

wood lath. Narrow, thin wood strips that serve as a base to which plaster is applied for an interior wall finish.

wood-frame construction. Synonymous with light timber-frame or light wood-frame construction; also called 2×4 construction or stick-built construction. Construction in which the structural elements of the walls, floors, ceilings, and roof consist mostly of lumber nominally 2-inches thick.

worsen. To alter the damage state of pre-existing damage.

yellow tagged. A building that has been inspected by a building official and declared damaged and unsafe for habitation, although some restricted use is permitted.

I.2 Acronyms

ACI — American Concrete Institute

ASTM — American Society for Testing and Materials (now known as ASTM International)

ATC — Applied Technology Council

ATC-20 — shorthand reference to the standardized process for post-earthquake safety assessments, also known as "tagging." Derived from the publication number of the Applied Technology Council series of publications, *Procedures for Postearthquake Safety Evaluation of Buildings.*

CGS — California Geological Survey

CISN — California Integrated Seismic Network

CMU — concrete masonry unit

COSMOS — Consortium of Organizations for Strong Motion Observation Systems

CSMIP — California Strong Motion Instrumentation Program

CUREE — Consortium of Universities for Research in Earthquake Engineering

EERI — Earthquake Engineering Research Institute

EIFS — exterior insulation and finish system

HVAC — heating, ventilation, and air conditioning

ICRI — International Concrete Repair Institute

MEP — mechanical, electrical, and plumbing

MMI — Modified Mercalli Intensity

NISEE — National Information Service for Earthquake Engineering (UC Berkeley)

OSB — oriented strand board

OSHA	Occupational Safety and Health Administration
PEER	Pacific Earthquake Engineering Research Center
SEAOC	Structural Engineers Association of California
USGS	U. S. Geological Survey

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