# Secondary Risk Characteristics for AIR Earthquake Models

AIR

Publication Date: August 2017

## Copyright



## Trademarks



## Confidentiality



## Contact Information

AIR is headquartered in Boston with additional offices in North America, Europe, and Asia. For information on our office locations, visit www.air-worldwide.com/About-AIR/Offices/.

AIR Worldwide Corporation c/o Verisk Analytics
Lafayette City Center, 2nd Floor
Two Avenue de Lafayette
Boston, MA 02111
USA

Tel: (617) 267-6645
Fax: (617) 267-8284

AIR welcomes feedback on its documentation. To contact us regarding this document please email us at: ModelDocumentationFeedback@air-worldwide.com.

## Revision History

| Revision Date | Description |
|---|---|
| August 2017 | Initial document release |
| September 2017 | Item 9 (Gypsum board) added to Table 27 (Valid options for wall type). |
| May 2018 | Updated the document with the new AIR branding, replaced Light Metal (8) photograph in Table 18, and updated text and figures in Sections 3.15 (Short Column) and 3.16 (Soft Story). |
| February 1, 2022 | Fixed broken URL |

# Table of Contents

# List of Figures

# List of Tables

# 1 Introduction

Secondary risk characteristics (SRCs) are features of a building and its environment that have a significant impact on the building's vulnerability to damage during an event. The SRCs are important contributing factors to losses sustained by residential, commercial, and industrial properties. This document serves as a guide to the SRCs used in AIR earthquake models (shake damage).

AIR uses a knowledge-based, expert system designed to estimate the performance of residential, commercial, and industrial buildings during earthquakes. The use of SRCs further enhances this process.

AIR's method is based on engineering principles and observed performance data from historical earthquakes. In addition, AIR engineers collaborated with Dr. Dimitrios Vamvatsikos and his students at the National Technical University of Athens, School of Engineering (2009), to develop the methodology for loss adjustment based on SRCs.

Examples of SRCs for shake vulnerability include:

- Building Shape
- Foundation Type/Anchorage
- Ornamentation
- Structural Irregularity
- Wall Type

AIR determines the loss adjustment factors accounting for secondary features using various approaches. Loss factors for some features, such as Building Shape and Torsion, are determined through nonlinear dynamic analyses performed on buildings. For other features, such as Structural Irregularity and Soft Story, loss factors are obtained through literature studies, historical damage observations, and expert judgement.

This document includes 24 building features, supported as SRCs in the AIR earthquake models. These features have been identified as having significant impacts on building vulnerability during earthquakes. For a complete list of the SRCs, see Chapter 3. Options corresponding to each SRC are based on construction practices. The AIR model in Touchstone supports any combination of SRCs.

# 2 Damage Estimation Overview

The base damage functions for shake in AIR models have been developed for a “typical” building at a particular location that has certain primary risk characteristics, including:

- Construction class
- Occupancy class
- Height
- Age

AIR’s general damage functions have been validated and calibrated using historical earthquake data, peer-reviewed literature, as well as well-regarded organizations, such as FEMA-HAZUS and GEM.

The AIR model takes the user-supplied SRC and applies it as a modification factor to the general damage functions, reflecting the performance enhancement or diminution of a wide variety of secondary structural characteristics. This allows for consideration of the difference between the performance of a building with known structural and environmental characteristics and that of a “typical” building. User input overrides the default SRC.

## 2.1 Ground Shaking

AIR engineers have developed damage functions to estimate losses induced by ground shaking. Information regarding the development of ground shaking damage functions is available in Chapter 5 of any of the AIR earthquake models, available through the AIR Client Portal. Figure 1 shows a typical damage function for ground shaking in AIR’s earthquake models. The x-axis represents the Ground Motion Intensity Measure (IM), which reflects shaking characteristics (e.g., peak ground acceleration) or the response of the building to ground motion (e.g., spectral acceleration). On the y-axis, mean damage ratio represents the expected loss (ground-up), normalized to the total replacement value of the building. The building is assumed to have “typical” secondary features. For example, it is assumed that no soft story, no irregularity, no short-column, no cripple wall, and no retrofit, etc. secondary features are present.

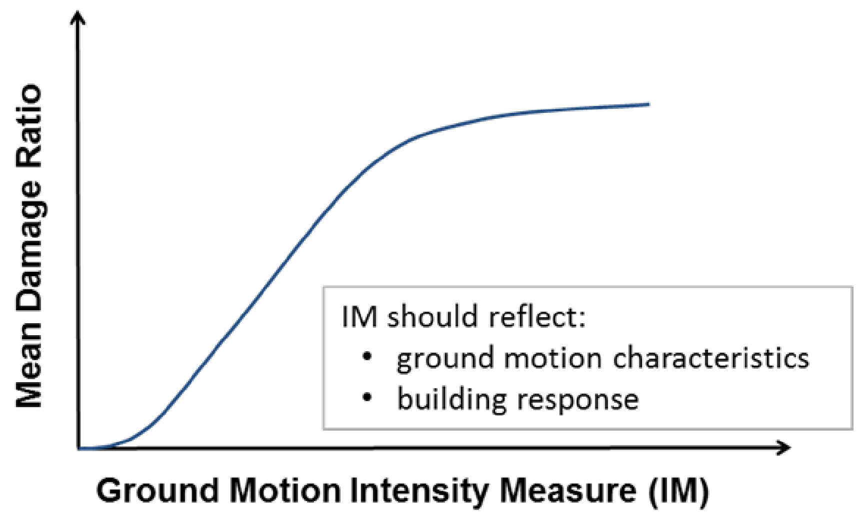



Figure 1. Typical damage function for any risk type

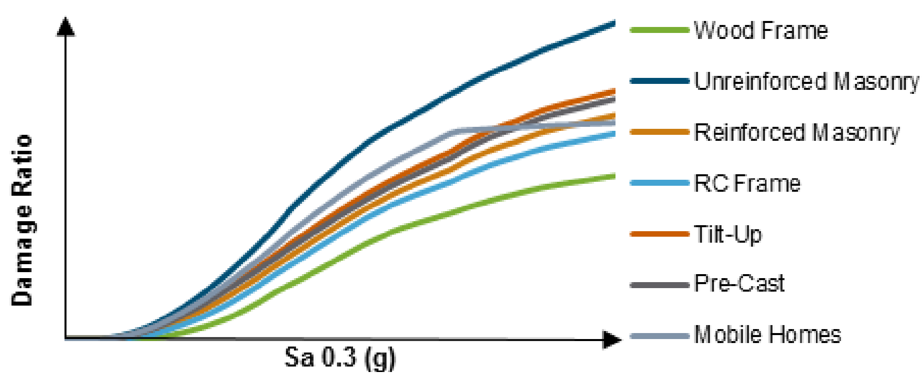



Figure 2. AIR damage functions for different construction types in Los Angeles (low-rise, unknown year built)

# 3 Secondary Risk Characteristics for Shake Damage

The first step in the development of the modification functions is the identification of building characteristics that impact the performance of a building during an earthquake. Based on research and damage surveys, structural and non-structural building components (Figure 3) are included in the models as SRCs. The SRCs for shake damage are provided in Table 1.

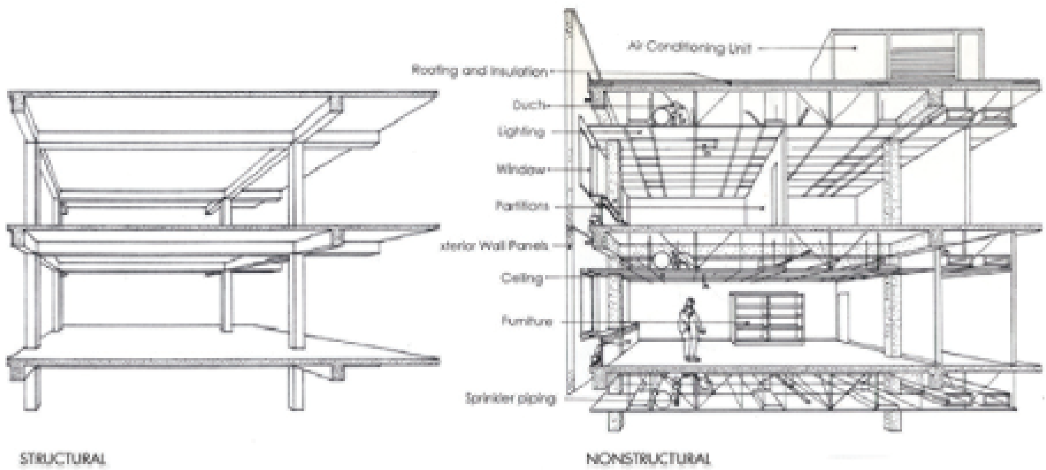



Figure 3. Structural and nonstructural components of a building
Source: FEMA, 2006b; modified by AIR

Table 1. Secondary Risk Characteristics (SRCs) for shake damage

| General | Structural | Nonstructural[1] |
|---|---|---|
| Building condition | Building exterior opening | Brick veneer |
| | Building shape | Chimney |
| | Foundation connection | Equipment |
| | Foundation type | Ornamentation |
| | Internal partition | Pounding |
| | Redundancy | Tanks |
| | Retrofit measures | Wall siding |
| | Roof deck | Water heater |
| | Short column | |
| | Soft story | |
| | Special earthquake-resistive systems | |
| | Structural integrity | |
| | Tall one-story | |
| | Torsion | |
| | Wall type | |

The following sections describe each SRC as well as the available input values for Touchstone. In addition, the *Touchstone Exposure Validation Reference*, available at www.unicede.com, provides:

- Validation rules for each location field in the Touchstone input file
- List of AIR models to which each SRC applies

Some features apply only to buildings of a certain type, age, or height. Table 2, Table 3, and Table 4 list common building groups, as defined by construction type, year built, and height, respectively. Individual SRC descriptions may include references to these groups.

Table 2. Construction group definition for earthquake SRCs

| Construction Group Name | Construction Class ID |
|---|---|
| Wood | 101 – 104 |
| Masonry | 111 – 119 |
| Reinforced Concrete | 131 – 135, 137 |
| Tilt up | 136 |
| Steel | 151 – 155 |

[1] Nonstructural indicates the feature does not carry a load

Table 3. Age (year built) group definition for earthquake SRCs

| Age Group | Wood | Masonry | Reinforced Concrete | Tilt up | Steel |
|---|---|---|---|---|---|
| Group 1 | ≤ 1950 | | | | |
| Group 2 | 1951 – 1975 | | | 1951 – 1985 | 1951 – 1995 |
| Group 3 | 1976 – 2000 | | | 1986 – 2000 | 1996 – 2000 |
| Group 4 | ≥ 2001 | | | | |

Table 4. Height group definition for earthquake SRCs

| Height Group | Number of Stories |
|---|---|
| Low-rise | 1 – 3 |
| Mid-rise and taller | ≥ 4 |

## 3.1 Brick Veneer

Brick veneer is used on exterior walls and typically consists of a single layer of ordinary brick or thinner brick (< 4 inches thick). Using an adhesive, the veneer is attached to an underlying wall for vertical and horizontal support. In areas of seismic activity, current building codes include requirements to prevent brick veneer from falling off during an earthquake. However, older structures that do not meet current seismic safety requirements can experience brick veneer separating from the building when subjected to shaking.

Figure 4 presents photographs of brick veneer, and Table 5 provides the valid options for Touchstone user-input values.

Please note, this feature should only be used for construction class 103.


Figure 4. (a) Brick veneer under construction and (b) collapsed brick veneer in the 1989 Loma Prieta earthquake
Source: (a) FEMA, 2009b, and (b) C. E. Meyer, USGS; cropped by AIR

Table 5. Valid options for brick veneer

| Value | Description |
|---|---|
| 0 | Unknown/default (50 – 90% brick) |
| 1 | > 90% brick |
| 2 | 25 – 50% brick |
| 3 | 0 – 25% brick |

## 3.2 Building Condition

The building condition feature qualitatively measures the status of a building's load-resisting system. The external appearance of cladding and maintenance gives a qualitative estimate of expected performance. For example, buildings with signs of distress or duress, such as cracking due to aging and ground settlement, overloading, or damage from previous earthquakes, are likely to experience additional damage during an earthquake. There are three options in Touchstone for building condition - average, poor, and good. The default option is unknown, which is equivalent to average.

Building condition should not be based on visual observations from a brief tour of a building. Rather, AIR recommends a professional engineer or person with trained earthquake engineering knowledge inspect and evaluate a building's condition. The following list includes actions to be conducted during a building condition evaluation:

- Understand the structural system and identify critical areas
- Identify allowable working loads in order to evaluate usage and the possibility of overloading
- Verify if unauthorized additions or alterations compromise the structural system
- Identify signs of material deterioration, misuse and abuse, or any deviation from intended use
- Inspect the foundation and identify soil conditions if signs of settlement exist
- Identify retrofit works

The loss adjustment factors for the building condition feature are based on expert judgements and historical damage observations. Table 6 provides the valid options for Touchstone user-input values for building condition.

Table 6. Valid options for building condition

| Value | Description |
|---|---|
| 0 | Unknown |
| 1 | Average/default |
| 2 | Good |
| 3 | Poor |

## 3.3 Building Exterior Opening

Exterior walls are essential structural components in wood and masonry buildings. They carry both vertical and lateral loads. Too many openings on a wall (over 50%) can significantly reduce a building's capacity to resist earthquake loads. The percentage of open wall refers to the area occupied by window and door openings. It should be noted, this feature only applies to wood and masonry buildings.

To compute modifiers for this feature, AIR completed nonlinear dynamic analyses on 3D building models. The shear capacity of shear walls varies, reflecting the different opening percentages. Then AIR compared the differences in roof drift ratio for structures with different exterior opening percentages and used them to determine the loss adjustment factors for this feature. Table 7 provides the valid options for Touchstone user-input values for building exterior opening.

Please note: This feature applies to wood and masonry buildings only.

Table 7. Valid options for building exterior opening

| Value | Description |
|---|---|
| 0 | Unknown |
| 1 | < 50% of wall open / default |
| 2 | > 50% of wall open |

## 3.4 Building Shape

Shape is critical for the performance of a structure, especially for large commercial buildings. In general, simple forms, like squares and rectangles, perform better than combinations of those shapes, such as L- and T-shaped buildings. The sharp corners in these complex shapes are vulnerable. During an earthquake, lateral loads tend to concentrate around wall intersections and corners. Consequently, the complexity of a building's shape will affect its performance (Figure 5).

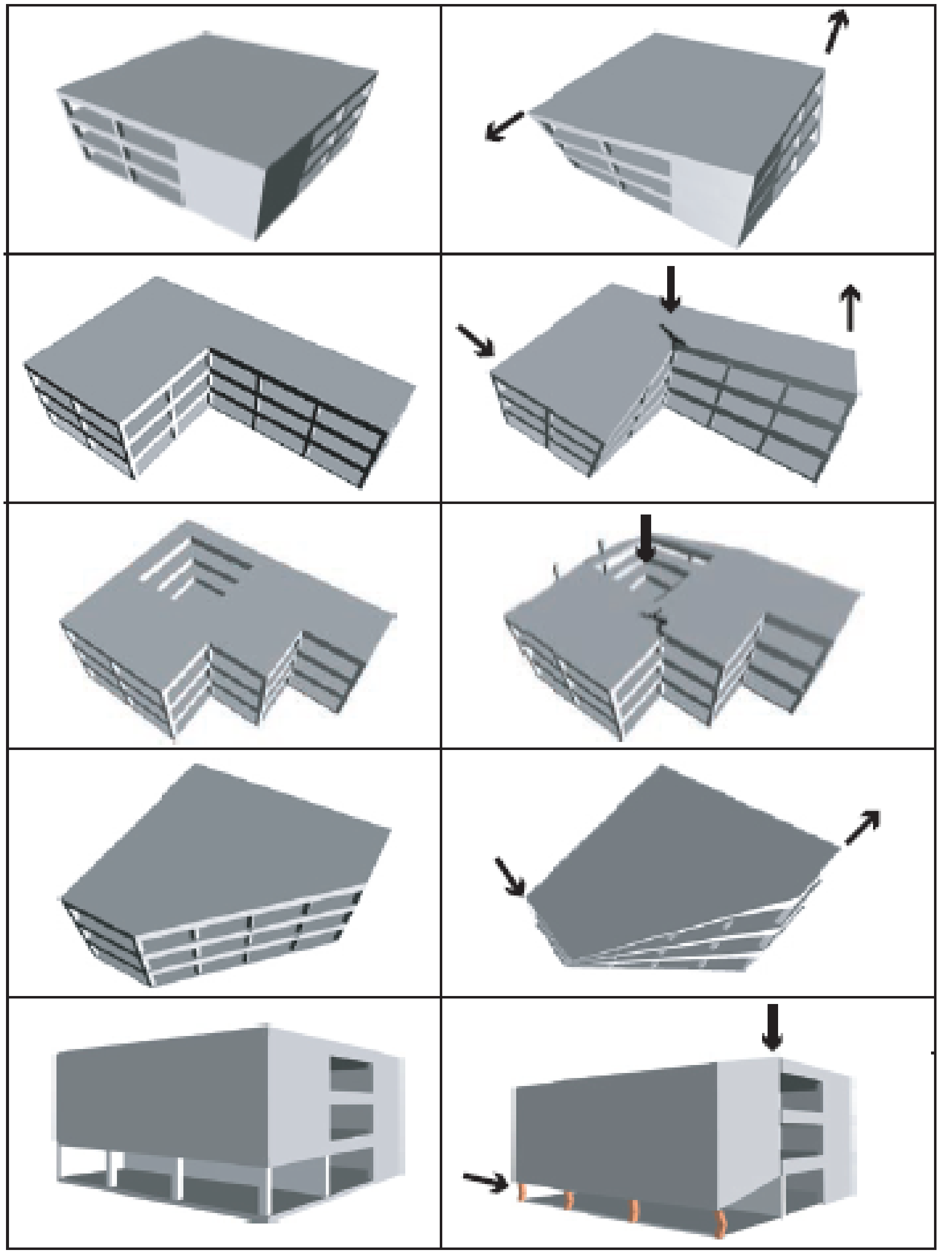


Figure 5. Various building shapes (left) and resulting failure patterns (right)
Source: FEMA, 2006b; modified by AIR

To determine modifiers for the building shape feature, AIR used 3D, nonlinear structural models with different building shapes. AIR engineers computed inter-story drifts and floor response accelerations when these buildings were subjected to a suite of ground motions, using the incremental dynamic analysis (IDA) procedure (Vamvatsikos and Cornell, 2002). These demand parameters were then related to structural and nonstructural damage and resulting losses. Table 8 provides the valid options for Touchstone user-input values for building shape.

Please note, the building shape and torsion SRCs are highly correlated. The user should select only one of these features (building shape or torsion) to avoid double counting the loss modifier.

Table 8. Valid options for building shape

| Value | Description |
|---|---|
| 0 | Unknown/default |
| 1 | Square |
| 2 | Rectangle |
| 3 | Circular |
| 4 | L-shaped |
| 5 | T-shaped |
| 6 | U-shaped |
| 7 | H-shaped |
| 8 | Complex |

## 3.5 Chimney

Like any other type of masonry construction, masonry chimneys are vulnerable in an earthquake. The taller the chimney is, the higher the risk of damage. To prevent chimneys from falling during an earthquake, building codes for high seismicity regions include chimney construction requirements. Chimneys in old houses or those constructed poorly or without authorization could significantly increase the probability of damage during an earthquake. Figure 6 presents examples of chimney damage from earthquakes.


Figure 6. Chimney damage due to earthquakes: (a) 1994 Northridge and (b) South Napa Earthquake
Source: (a) FEMA, 2006a and (b) J. Maffei, CEA, in FEMA, 2015; modified by AIR

Modifiers of the chimney feature primarily account for roof damage due to chimney collapse during an earthquake. AIR engineers developed fragility functions for masonry chimneys based on literature reviews and performed a Monte Carlo simulation to compute losses from chimney damage and secondary damage from the chimney falling on an adjacent roof.

It should be noted that the chimney feature only applies to wood and masonry construction (i.e., it does not apply to reinforced concrete and steel buildings).

Table 9 provides the valid options for Touchstone user-input values for chimney.

Table 9. Valid options for chimney

| **Value** | **Description** |
|---|---|
| 0 | Unknown/default |
| 1 | No chimney |
| 2 | Chimney, height ≤ 2 feet |
| 3 | Chimney, height 2 – 5 feet |
| 4 | Chimney, height > 5 feet |

## 3.6 Equipment

During an earthquake, damage to mechanical and electrical equipment can be prevented by anchoring equipment to the floor and/or bracing it against structural elements. Modern building codes, such as the California Building Code (CBC) and International Building Code (IBC), usually have specific requirements for seismic bracing. For example, in the IBC, seismic restraints are required for medical gas, vacuum pipe, compressed air, and other hazardous pipes ≥ 1 inch in diameter. Similarly, all electrical conduits ≥ 2.5 inches in diameter require seismic bracing. Figure 7 provides examples of equipment bracing.

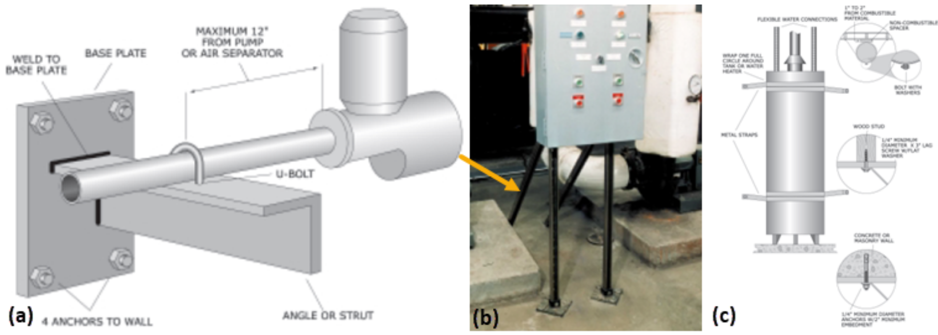



Figure 7. Seismic bracing and constraints: (a) In-line piping support using angle and U-bolt; (b) Control panel supported using angle bracing; and (c) Water tank constrained using metal straps
Source: FEMA, 2002; modified by AIR

AIR used fragility analysis to determine the relative vulnerability of buildings, based on how well equipment is braced to the structure. Using acceleration design demands computed from building code requirements [American Society of Civil Engineers (ASCE)-7, using equivalent static procedures], AIR determined the mean capacity of a well-braced piece of equipment. This information was then used, with an assumed coefficient of variation (COV), to establish fragility function parameters for a lognormal probability distribution that captures the probability of damage occurring. The ATC-58 project (ATC 2006) used a similar procedure. AIR also obtained fragility function parameters for average bracing and unbraced equipment by reducing the mean acceleration but assuming the same COV. These fragility functions were then used in Monte Carlo simulation to obtain losses and gauge relative performance. Table 10 provides the valid options for Touchstone user-input values for equipment.

Table 10. Valid options for equipment

| Value | Description |
|---|---|
| 0 | Unknown |
| 1 | Well-braced |
| 2 | Average-braced/default |
| 3 | Unbraced |

## 3.7 Foundation Connection

The foundation connection feature applies only to wood-frame buildings and refers to the method in which a structure is attached to its foundation. These connections are vital, as older structures may slide off their foundations during a large earthquake (Figure 8). Touchstone accounts for various foundation connection types – hurricane ties, nails/screws, anchor bolts, gravity/friction, adhesive/epoxy, and structurally connected. With properly designed hold down connectors, shear walls can transfer the lateral loads and uplift loads to the foundation (Figure 9). Building codes usually have specific requirements for hold down connectors. During an earthquake, buildings with nails/screws or gravity/friction connections will experience higher losses than ones with proper hold down devices.

Figure 8. House dislodged from foundation during the Loma Prieta earthquake in 1989
Source: J.K. Nakata, USGS; modified by AIR

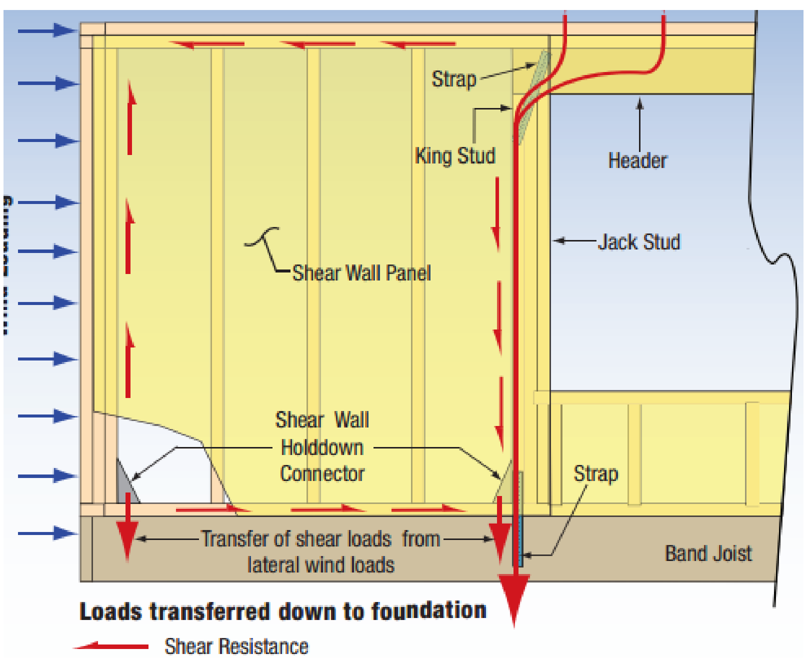



Figure 9. Wood shear wall connected to foundation by hold down connectors
Source: FEMA, 2009a; modified by AIR

AIR used the American Wood Council (AWC)'s connection calculator to obtain foundation connection capacities. These capacities were then compared with seismic design loads to calculate demand capacity ratios. AIR then used the demand capacity ratios to infer loss adjustment factors for the various foundation connections.

Table 11 presents the valid options for Touchstone user-input values for foundation connection. Options 0 (default), 4 (Gravity/friction), and 6 (Structurally connected) are also used for large-scale industrial facilities (occupancy class 400 series) to differentiate levels of engineering design.

Table 11. Valid options for foundation connection

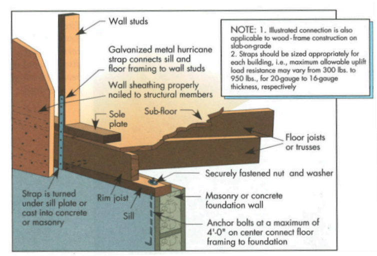
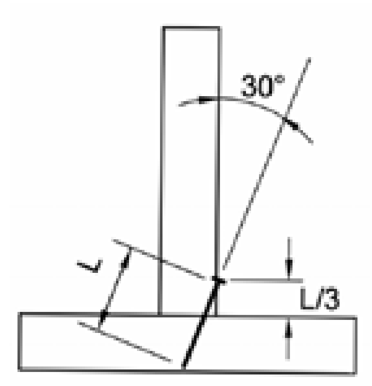
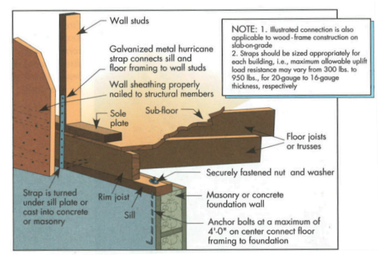
<table>
<tr><th>Value</th><th>Description</th><th>Details</th><th>Pictures</th></tr>
<tr><td>0</td><td>Unknown/ default</td><td>No designation/ unknown<br><br>When this option is used for industrial facilities, it means that engineering design and construction information are unknown.</td><td></td></tr>
<tr><td>1</td><td>Hurricane ties</td><td>Hurricane ties secure the structure to the foundation, which helps to transfer uplift forces as well as shear forces.<br><br>Hurricane ties usually are embedded in the concrete foundation and nailed to the wall studs in timber frame construction.</td><td>


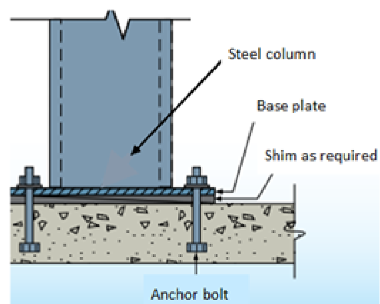

Figure 10. Diagram of hurricane straps cast into concrete or masonry foundation and nailed into wall studs

Source: FEMA, 1992

Figure 11. Example of a raised foundation (post) tied to a floor joist

Source: FEMA/D. Saville
</td></tr>
</table>

| Value | Description | Details | Pictures |
|---|---|---|---|
| 2 | Nails/ screws | In timber frame construction, usually the studs are connected to a base plate (or sill plate), which is connected to the foundation.<br><br>There may be bolts or other anchorage keeping the base plate in place, but the weakest connection is at the connection between the base plate and the studs.<br><br>Toe nails or screws are often used to fasten the studs to the base plate or foundation. | <br><br>Figure 12. Diagram of a toe nail driven through a stud and base plate, into foundation<br><br>Source: FEMA, 2006a |
| 3 | Anchor bolts | Anchor bolts secure the base plate or columns to the foundation.<br><br>They are embedded in the concrete slab or foundation and come in a variety of shapes and sizes.<br><br>Anchor bolts help transfer shear and uplift loads from the walls to the foundation. | <br><br>Figure 13. Diagram of anchor bolts connecting concrete or masonry foundation to floor framing<br><br>Source: FEMA, 1992<br><br><br>Figure 14. Example of an anchor bolt<br><br>Source: HD-bolts by B. Bradley, CC BY-SA 3.0 |

| Value | Description | Details | Pictures |
|---|---|---|---|
| 4 | Gravity/ friction | Some structures are not connected to the foundation or slab using a mechanical system. Rather, they rely solely on their own weight to resist uplift or shear loads.<br>These structures are prone to sliding from their base if the lateral loads are high enough.<br>When this option is applied to industrial facilities, it means that seismic design is not considered. | <br>Figure 15. Example of a gravity/ friction foundation<br>Source: Chalot tenons mortaises by Nico88-62, Public domain |
| 5 | Adhesive/ epoxy | This connection is similar to a gravity/friction system except that an adhesive or epoxy is used to bind the structure to the foundation to keep the structure attached to the base. | |
| 6 | Structurally connected | Structurally connected implies that all foundation connections adequately fasten the main structure to the footing, pile, or slab foundation by means of base plates, mechanical attachments, tie rods (in the case of concrete structures) or welding (steel structures).<br>When this option is applied to industrial facilities, it means that seismic design is considered. | <br>Figure 16. Diagram of a structurally-connected foundation<br>Source: FEMA, 2006d; modified by AIR |

## 3.8 Foundation Type

Foundations are the interface between a house and the supporting soil. In selecting the foundation type for a structure, several features are considered including site topography, soil conditions, retaining requirements, static and dynamic loads from the structure, and environmental conditions (e.g., frost depth, termites, and corrosion). Foundations primarily provide support for vertical gravity loads from the weight of a structure and its contents, but they also provide resistance to horizontal forces and overturning moments resulting from earthquake ground motions or wind loads. Figure 17 presents different foundation configurations.

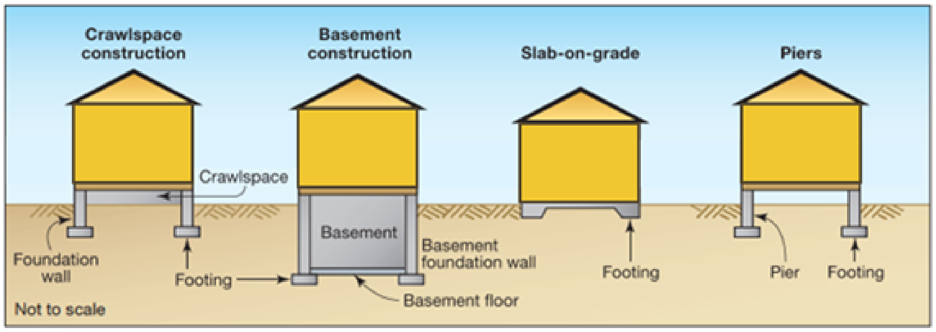



Figure 17. Various foundation types
Source: FEMA, 2013a; modified by AIR

Touchstone includes a variety of options for foundation type (Table 12). Details for each construction type are presented alphabetically in the sections that follow.

Table 12. Valid options for foundation type

| Value | Description | Notes |
|---|---|---|
| 0 | Unknown/default | |
| 1 | Masonry basement | |
| 2 | Concrete basement | |
| 3 | Masonry wall | No longer supported in Touchstone |
| 4 | Crawl space cripple wall (wood) | Wood-frame buildings only |
| 5 | Crawl space masonry (wood) | Wood-frame buildings only |
| 6 | Post & pier | |
| 7 | Footing | |
| 8 | Mat/slab | |
| 9 | Pile | |
| 10 | No basement | Mapped as Unknown (0) in Touchstone |
| 11 | Engineering foundation | |
| 12 | Crawlspace, raised (wood) | Wood-frame buildings only |

## Crawlspace

Crawlspace refers to the opening between the ground and the first floor in a raised foundation (Figure 18). Raised foundations are popular in new construction in areas where full basements are too costly and flat-slab foundations are not appropriate (e.g., flood zones). Depending on the construction method, raised foundations may increase the seismic vulnerability of a house. Crawlspaces are typically found only in wood-frame buildings, and are generally created using cripple walls, masonry walls, and stem walls. Descriptions of these different types of construction are provided below.


Figure 18. Crawlspace: (a) Exterior view and (b) Interior view
Source: (a) FEMA, 2008a and (b) Crawl-space-inside by N. Post, Public domain; modified by AIR

### *Crawlspace Cripple Wall (Wood)*

A cripple wall is a framed wall that extends from the stem wall or foundation slab to the floor joists, creating the crawlspace (Figure 19). Cripple wall construction is common in older wood-frame houses, and cripple walls without bracing and anchorage are susceptible to costly damage in earthquakes (Figure 20).

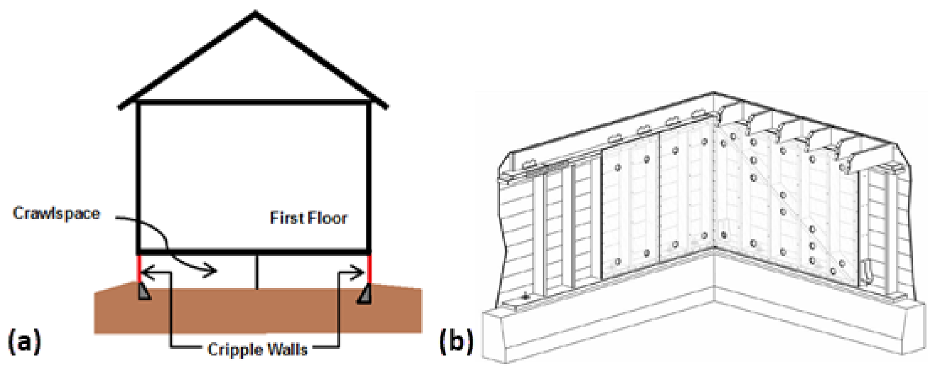



Figure 19. Cripple wall: (a) Location in a structure and (b) Close-up of a cripple wall, constructed of 2 x 4 studs covered by a sheathing board, with overlying joists
Source: FEMA, 2015; modified by AIR

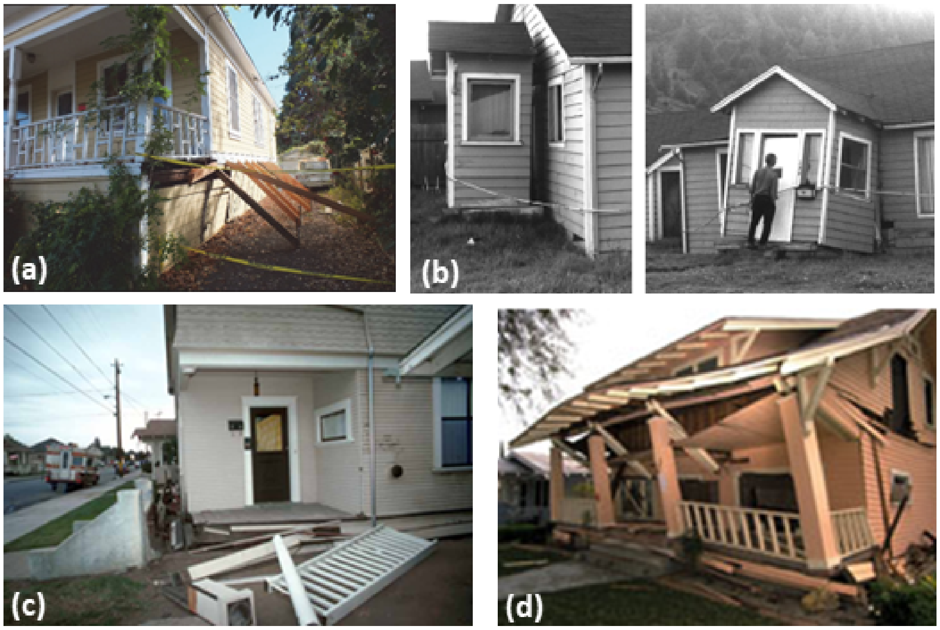



Figure 20. Examples of cripple wall damage: (a) 2014 South Napa earthquake; (b) Cape Mendocino earthquake; (c) 1989 Loma Prieta earthquake; and (d) 1994 Northridge earthquake
Source: (a) FEMA, 2015, (b) FEMA, 2006a, (c) J. K., Nakata, USGS, and (d) USGS; modified by AIR

### *Crawlspace Masonry (Wood)*

Another method for creating a crawlspace is through the construction of a masonry wall (Figure 21). Masonry wall foundations perform better than cripple wall foundations during earthquakes. However, like all masonry constructions, masonry walls are vulnerable during earthquakes because of the weak shear resistance.

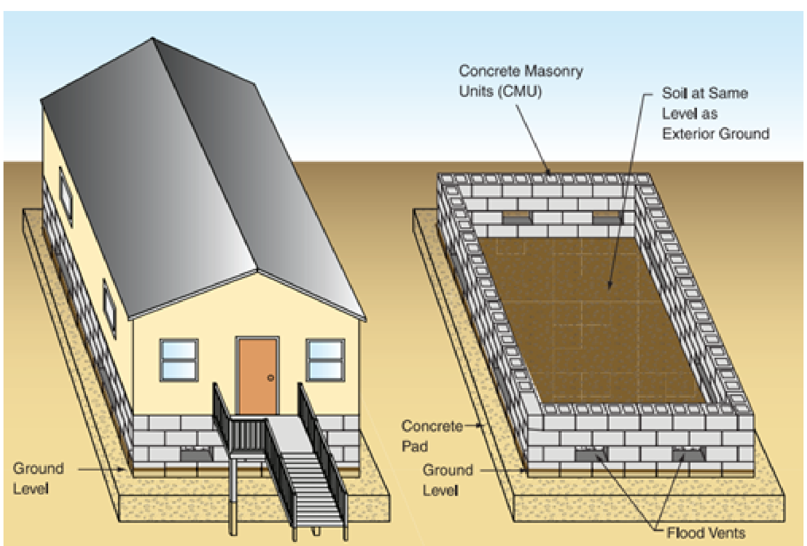



Figure 21. Crawlspace created by masonry foundation wall
Source: FEMA, 2009c; modified by AIR

### *Crawlspace - Raised (Wood)*

In Touchstone, "Crawlspace – Raised (Wood)" refers to reinforced concrete stem walls. A stem wall is a continuous short wall built along the perimeter of a building, providing vertical support to the house and its contents. This wall requires a continuous footing beam beneath it to spread the vertical load to the ground.

In general, a stem wall can be constructed with bricks, reinforced concrete (as shown in Figure 22), concrete masonry units, or rubble stone. If a masonry stem wall is not properly engineered with adequate rebar, anchorage, and bracing, it is vulnerable to lateral load damage from ground motion. Houses built with poorly engineered stem walls have higher vulnerability and increased expected losses due to ground shaking. However, a stem wall can also be built with poured-on-site reinforced concrete. In this case, the stem wall and its footing are usually engineered and constructed together. The sill beams and sill plates of exterior walls are usually tied down to the foundation.

In the AIR earthquake models, the "Crawlspace – Raised (Wood)" of the Foundation feature refers to reinforced concrete stem walls only and has no impact on the seismic vulnerability of a house.

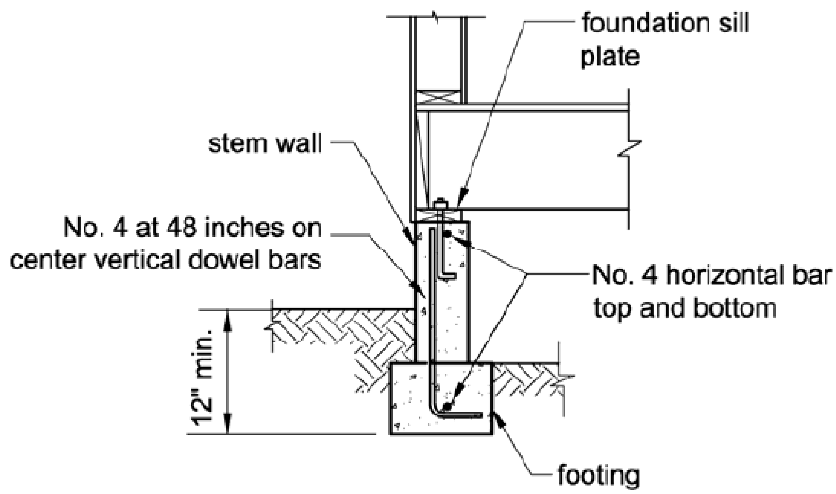



Figure 22. Perimeter foundation with separately placed footing and reinforced concrete stem wall
Source: FEMA, 2006a; modified by AIR

## Engineering Foundation

Engineering foundations are deep foundations, usually recommended for buildings with very large design loads or poor site conditions. Engineering foundations are designed to be integral components of engineered buildings.

Figure 23 presents an example of an engineered foundation under construction.

Figure 23. Construction of the foundation for the Tiara United Towers in Dubai
Source: Tiara United Towers Under Construction on 20 December 2007 by I. Solt, CC BY-SA 3.0; modified by AIR

In Touchstone, the seismic resistance capacity of an engineered building is already considered in the damage function. Hence, the foundation does not have additional impact on a building's seismic vulnerability.

## Footing

A footing is another type of foundation, as shown in Figure 24. Columns and walls are directly connected to footings, which transfer loads to the ground. The first floor is usually a concrete slab poured on the ground (minimum thickness of 3.5 inches). Such construction is also referred to as a "slab-on-grade" foundation. Since the first floor of the house is constructed directly on the slab and there is no crawl space, a footing foundation does not affect a building's seismic vulnerability.

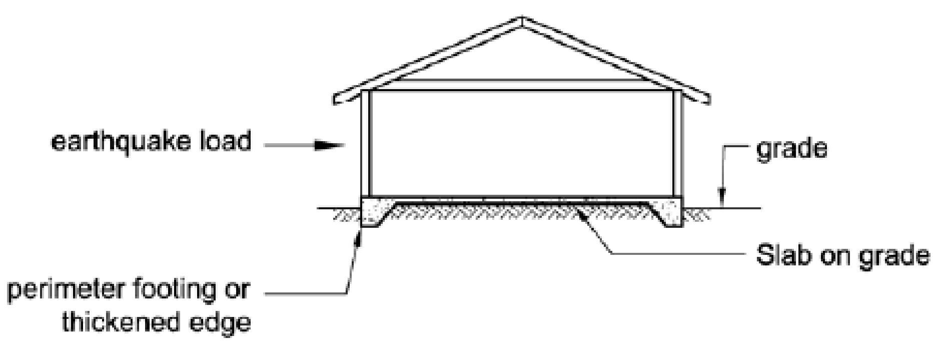



Figure 24. Structure with a footing foundation
Source: (a) FEMA, 2006a; modified by AIR

## Masonry or Concrete Basement

While homeowners may view basements as storage space, additional living space, and a place to house equipment (e.g., furnaces, circuit breakers, hot water tanks, etc.), from a structural resistance perspective, basement walls are critical components of a building. These walls transit vertical load from the super structure above to the ground, resist lateral load from groundwater and soil, and prevent groundwater and contaminants from entering the basement.

Basement walls are typically constructed using masonry bricks, rubble or dressed stones, reinforced concrete, or concrete blocks (Figure 25). During earthquakes, basement walls can be damaged in several ways. The most common form of damage is cracking due to excessive lateral load. For a typical single-family house, repair costs could range from hundreds to thousands of dollars (USD) depending on length and width of the cracks.

Figure 25. Concrete masonry unit (CMU) basement wall
Source: CMUs by Skepticsteve; Public domain

In addition to the walls, basement floors are also vulnerable to earthquake damage. Basement floors are usually constructed using 4-inch thick, poured concrete with minimal rebar or welded-wire mesh. They are vulnerable to settlement, liquefaction, and ground failure.

## Masonry Wall

It should be noted that Touchstone no longer supports (3) Masonry wall as a SRC. If selected by the user, Touchstone will map this value to (4) Crawl space cripple wall (wood) upon import.

## No basement

While the no basement feature indicates that a building does not include a basement, it does not provide information about the foundation type. A no-basement building can have mat foundation or cripple-wall crawl space, or other types described in this document. As these different options have different impacts on a building's seismic vulnerability, the selection of (10) No basement is equivalent to (0) Unknown foundation type in AIR's earthquake models.

## Mat or Slab Foundation

A mat foundation is a large concrete slab that supports staggered column or line loads. These foundations provide an economical solution to difficult site conditions, such as soils with low bearing capacity or a location vulnerable to subsidence (e.g., located in a mining area or in an area with uncertain groundwater conditions). Mat foundations are typically well engineered, and may be thin (< 1 foot), reinforced with cross beams, or thick (> 1 foot). Figure 26 shows a mat foundation before (a) and during (b) the concrete pour.

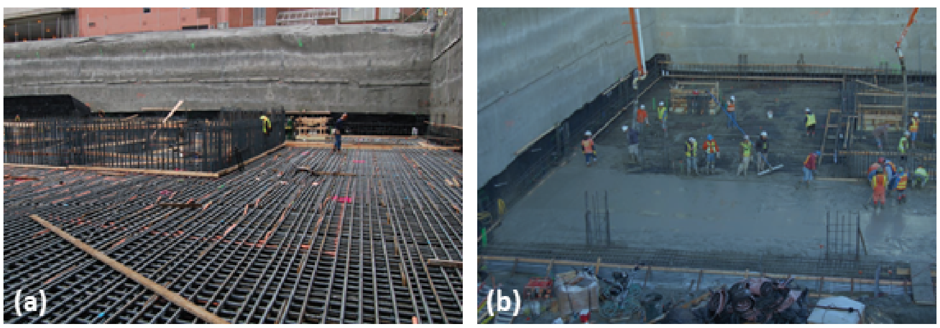



Figure 26. Mat foundation under construction: (a) Reinforcements of a mat prior to concrete pouring and (b) Workers pouring the concrete mat
Source: (a) NEHRP, 2012; modified by AIR

## Pile Foundation

Deep foundations, such as pile foundations, are usually recommended for buildings with very large design loads or poor site conditions. Piles are vertical structural elements that penetrate low density soil and lock into high density soil or rock. Typically, groups of piles are connected at the top by a cap (a large concrete structure), which distributes the load to the piles. Figure 27 presents a schematic of a pile foundation, as well as pile installation. Piles can be made of wood, reinforced concrete, or steel. A pile foundation should be well designed and properly constructed.

Buildings supported by pile foundations are often tall / high-rise, very well engineered, reinforced concrete, or steel frame structures. In AIR's earthquake models, a pile foundation is the default foundation for tall / high-rise structures. As the impact of a pile foundation is an integral part of the vulnerability function, there is no need for the user to select this SRC for tall / high-rise structures. The pile foundation is already considered.

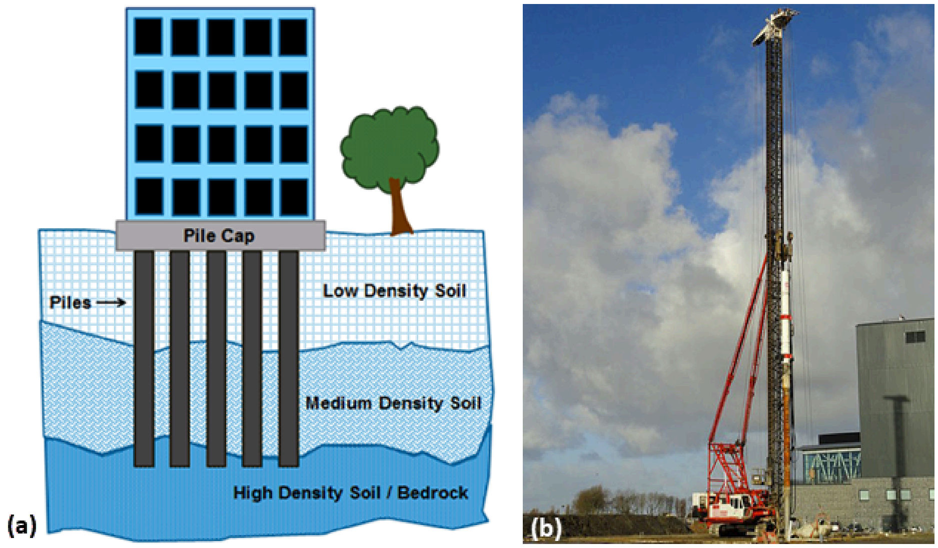



Figure 27. Pile foundation: (a) Cross-sectional view and (b) Hydrohammer driving piles
Source: (b) Hydrohammer driving piles (S-70 Hydrohammer on Hitachi CX900PD of the Dutch piling company NHB by A. van Beem, CC0 1.0; modified by AIR

## Post and Pier

Post and pier construction involves the distribution of a structure's weight across a series of posts installed beneath the building and mounted to piers. Piers are wedge-shaped concrete blocks that distribute weight to the ground (Figure 28). In this type of construction, there is no perimeter foundation or foundation pad. Typically posts and piers are mounted around the perimeter and at key points in the middle of the structure (Figure 29).

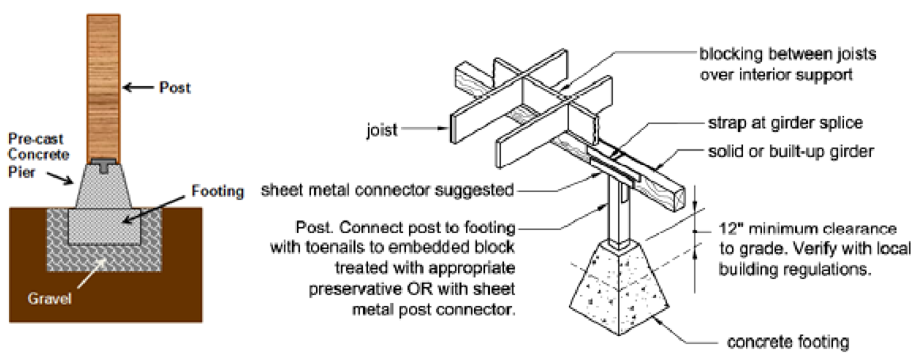



Figure 28. Post and pier construction
Source: FEMA, 2006a; modified by AIR

Figure 29. Example of pier layout
Source: Post and beam 2 by WTF Formwork, CC BY-SA 3.0

Prior to the 1960's, post and pier construction was a common practice used to elevate houses in flood-prone areas. Due to lack of bracing and lateral resistance, post and pier foundations are very vulnerable to seismic loads. Higher losses are expected for buildings supported on post and pier foundations in an earthquake compared to other foundation types.

## 3.9 Internal Partition

This feature is used to describe the finishing layer of interior walls. The amount of damage an internal partition may suffer during an earthquake is largely related to its construction materials.

Table 13 presents the valid options for Touchstone user-input values for internal partition.

AIR constructed fragility functions for each partition wall type, based on literature review and engineering judgments. The fragility functions were then integrated with repair costs using an approach similar to HAZUS to obtain relative loss values. AIR then adjusted these values to account for the loss of internal partition wall relative to replacement cost of the entire building.

Table 13. Valid options for internal partition

| Value | Description | Details | Pictures |
|---|---|---|---|
| 0 | Unknown/ default | The internal partition type is unknown. | |

| Value | Description | Details | Pictures |
|---|---|---|---|
| 1 | Wood | Wood boards nailed to studs turn interior walls into shear walls, resulting in a much higher load resistance, and lower losses. |  Figure 30. Example of a wood internal wall<br>Source: HABS ORE,20-SPRIF,2—14, Library of Congress, Public domain; modified by AIR |
| 2 | Gypsum boards | Often called drywall, wallboard, or plasterboard, gypsum board has a non-combustible core composed primarily of gypsum, which is surrounded by a surfacing on the face, back, and long edges. The facing can be made of paper, fiberglass, or other materials. |  Figure 31. Example of gypsum boards<br>Source: Drywall by Amaxon, Public domain |
| 3 | Plastered masonry | Plastered masonry is vulnerable to earthquake loads, especially when they are not reinforced. Therefore, masonry interior walls will increase seismic losses. |  Figure 32. Plaster application<br>Source: Plasterer at work on a wall arp by Adrian Pingstone, Public domain |

| Value | Description | Details | Pictures |
|---|---|---|---|
| 4 | Brick | Bare bricks are vulnerable to earthquake loads, especially when they are not reinforced. Therefore, masonry interior walls will increase seismic losses. |  Figure 33. Example of a brick internal wall<br>Source: HABS OHIO,48-TOLED,7--12, Library of Congress, Public domain; modified by AIR |
| 5 | Other | | |

## 3.10 Ornamentation

Ornamentation refers to decorative (non-structural) components of a building's exterior. An example of extensive ornamentation is provided in Figure 34, which shows the exterior of the basilica of Santa Maria della Salute in Venice, Italy. Ornamentation is usually fragile and vulnerable in an earthquake. Moreover, repair costs of ornamentation are high due to their high standard of craftsmanship.

Figure 34. Example of ornamentation - Santa Maria della Salute basilica in Venice, Italy
Source: Santa Maria della Salute in Venice 001 by Moonik, CC BY-SA 3.0

Table 14 provides the valid options for Touchstone user-input values for ornamentation. This feature does not apply to tilt up construction.

Table 14. Valid options for ornamentation

| Value | Description |
|---|---|
| 0 | Unknown |
| 1 | None/default |
| 2 | Average |
| 3 | Extensive |

## 3.11 Pounding

Pounding refers to the collision of adjacent buildings when subjected to ground shaking. If there is little or no clearance between structures, they may strike each other and suffer damage (Figure 35). Pounding damage may be particularly severe if the floors of adjacent buildings are at different elevations. During collision, one building's floors may destroy the columns of the other. This process is not limited to adjacent buildings. Figure 36 presents evidence of pounding between the original structure and a later addition. The construction joint, which appeared to be seamless before the earthquake, was not designed with sufficient separation to prevent pounding.

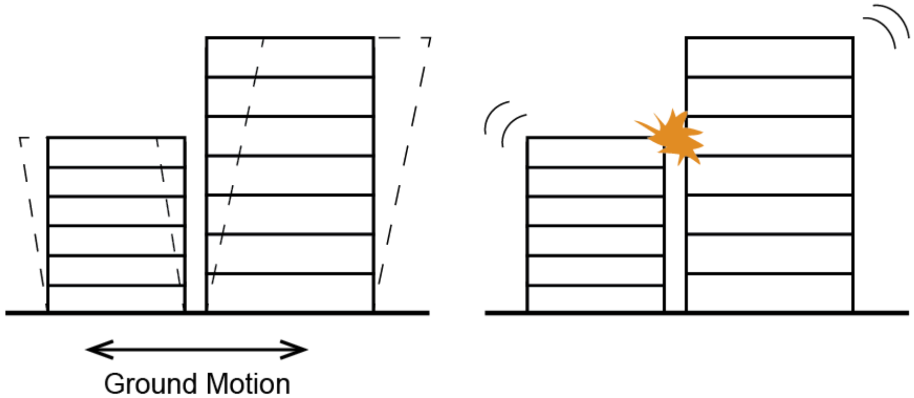



Figure 35. Pounding
Source: FEMA, 2011b; modified by AIR

Figure 36. Pounding damage, Santiago Chile, 2010
Source: AIR

In Touchstone, the SRC for pounding refers to the distance from a building to the closest structure. Table 15 provides the valid options for Touchstone user-input values for pounding.

Table 15. Valid options for pounding

| Value | Description (distance between structures) |
|---|---|
| 0 | Unknown/default |
| 1 | 0 – 0.25 m |
| 2 | 0.25 – 0.5 m |
| 3 | 0.5 – 1.0 m |
| 4 | 1.0 – 2.0 m |

| Value | Description (distance between structures) |
|---|---|
| 5 | > 2.0 m |

## 3.12 Redundancy

Redundancy is a term used to describe the presence of multiple lateral load-resisting elements (frames or shear walls) in a structure. Redundancy is a desirable feature - if one structural system fails during an earthquake, another system is present to resist the lateral earthquake forces and avoid catastrophic collapse.

Although redundancy has been long recognized as an important feature, it only became the focus of research after the 1994 Northridge and 1995 Kobe earthquakes. A redundancy factor was initially introduced into building codes/guidelines in National Earthquake Hazards Reduction Program (NEHRP) 1997, Uniform Building Code (UBC) 1997, and IBC 2000. Later, in ASCE-7 and NEHRP 2003, the redundancy factor was updated to achieve consistent reliability in designs of different structures.

Table 16 provides the valid options for Touchstone user-input values for redundancy. This feature only applies to reinforced concrete and steel construction groups.

Table 16. Valid options for redundancy

| Value | Description |
|---|---|
| 0 | Unknown/default |
| 1 | No |
| 2 | Yes |

## 3.13 Retrofit Measures

Retrofitting of buildings improves building performance during an earthquake and saves lives by preventing collapse. Some types of construction have specific inadequacies which have been addressed by the modification of seismic building codes. The structural retrofit feature applies to buildings which have been retrofitted to provide superior earthquake resistive capabilities.

Touchstone considers the following retrofit measures: bracing (for cripple walls, parapets, or soft story), foundation anchorage, glass/window strengthening, tilt up retrofitting, and other general measures.

Retrofit measures are typically considered for buildings constructed in the absence of building codes or following outdated ones. Hence, the retrofit measures feature only applies to buildings in age groups 1 and 2. Table 17 provides the valid options for Touchstone user-input values for retrofit measures, and details of these measures are provided below, alphabetically.

Table 17. Valid options for retrofit measures

| Value | Description |
|---|---|
| 0 | Unknown/default |
| 1 | Bracing of cripple walls |
| 2 | Bracing of parapets |
| 3 | Bracing of soft story |
| 4 | Foundation anchorage (bolting) |
| 5 | Glass/window strengthening |
| 6 | Tilt up |
| 7 | General |

## Bracing of Cripple Walls

Cripple walls are usually used to provide a crawlspace or accommodate elevation change for structures built on hillsides. These walls have no shear resistance and tend to perform poorly in earthquakes. Depending on the severity of their failure during an earthquake, damage to the building may be total.

Bracing may be added to cripple walls to provide additional support and stability. The fundamental components of cripple wall bracing are presented in Figure 37.

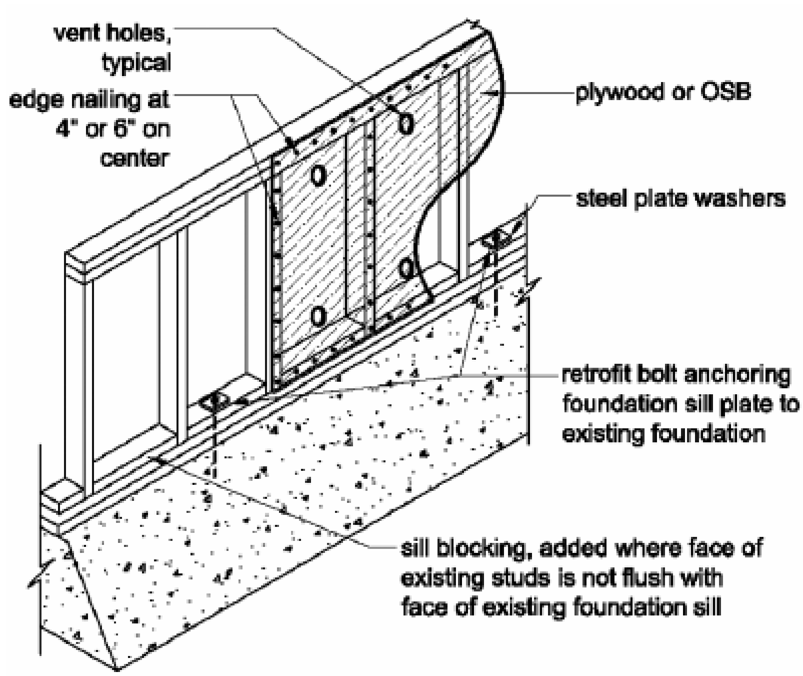



Figure 37. Cripple wall bracing
Source: FEMA, 2006a

In addition to the walls, basement floors are also vulnerable to earthquake damage. Basement floors are usually constructed using 4-inch thick, poured concrete with minimal rebar or welded-wire mesh. They are vulnerable to settlement, liquefaction, and ground failure.

## Bracing of Parapets

A parapet is an extension of a wall at the edge of a roof, terrace, balcony, or other structure (Figure 38). Parapets are usually unreinforced masonry (URM) structures, and they are easily damaged. During earthquakes, parapets tend to fall from buildings (Figure 39). Proper bracing of parapets reduces their damage potential significantly (Figure 40).


Figure 38. Building with masonry parapet (white)
Source: Shoreditch barley mow 1 by Tarquin Binary, CC BY-SA 2.5; modified by AIR

Figure 39. Fallen URM parapet, 1992 Petrolia earthquake
Source: NGDC, in FEMA, 2011a

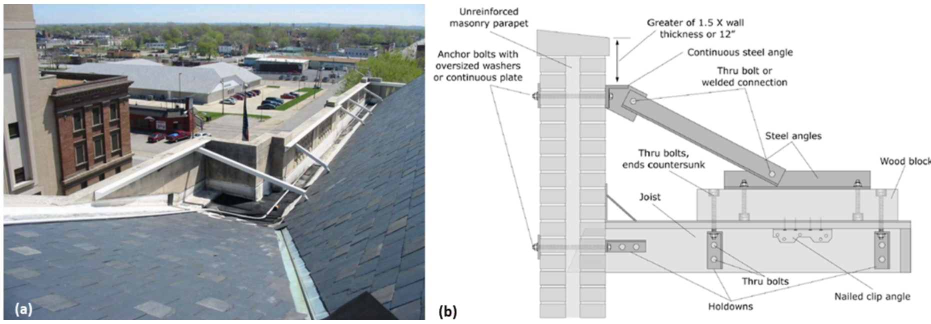



Figure 40. (a) Braced parapets; (b) Typical brace configuration
Source: Degenkolb Engineers in FEMA, 2011b; modified by AIR

## Bracing of Soft Story

Buildings with soft story construction sustain excessive deformation and stresses in a major earthquake. Bracing (Figure 41) increases the stiffness of the first story, reducing damage to the structure.

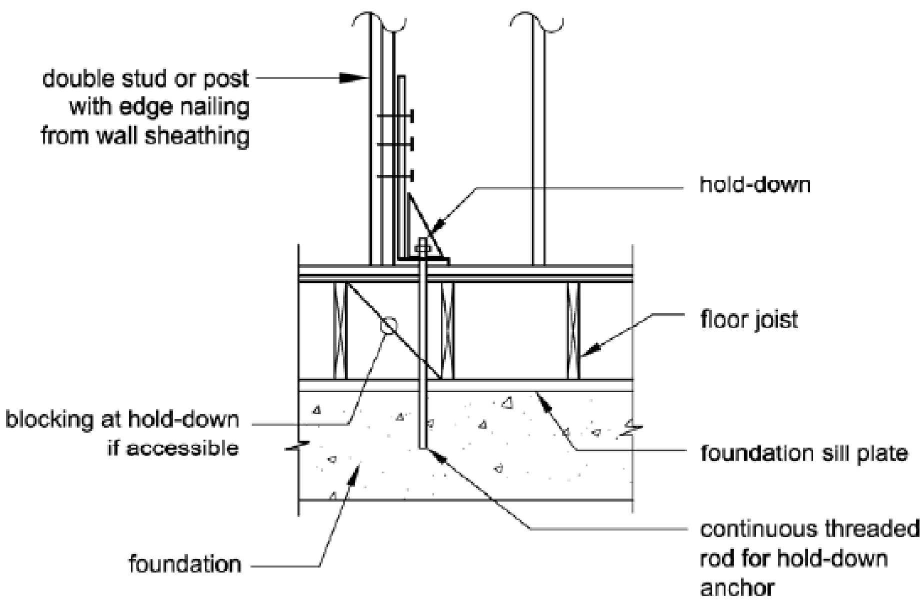



Figure 41. Soft story bracing
Source: FEMA, 2011b

## Foundation Anchorage (Bolting)

Wood frame homes built before 1940 may not have been bolted to their foundations during construction. A strong earthquake could cause such buildings to slide off their foundations, causing significant damage. In fact, anchoring the frame to the foundation has proven to be the most essential means of protection against earthquake damage in wood frame structures.

The foundation can be assumed to be bolted (Figure 42) if there are bolts ≥ 0.5-inch diameter extending from the footing and tied to the sill plate at about 5 feet on center.

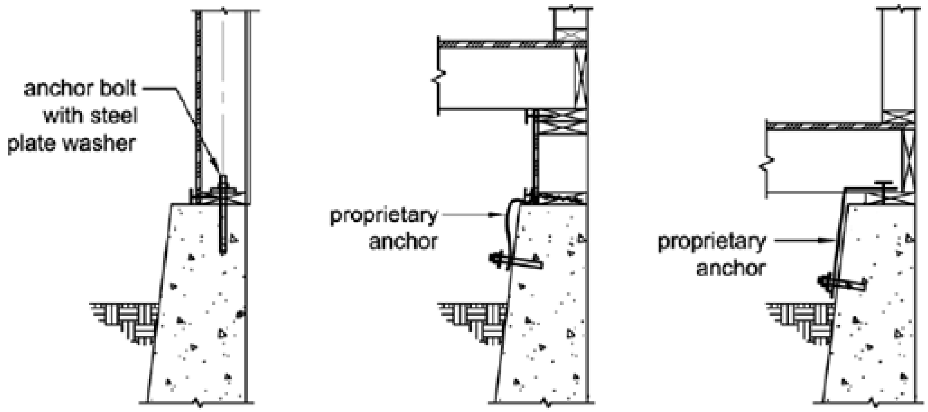



Figure 42. Common foundation anchorage configurations
Source: FEMA, 2011a

## General Retrofitting

General retrofitting can be anything that is carried out for the purpose of improving the serviceability, resilience, or function of a building.

## Glass/Window Strengthening

From an earthquake perspective, the Glass/Window Strengthening feature primarily applies to glass curtain walls (Figure 43). Glass curtain walls are vulnerable in earthquakes as glass panes are unable to follow inter-story drift. Existing construction methods allow glass curtain walls to accommodate minor drift. One technique involves a margin between the glass panes and aluminum profiles. However, with major earthquakes, such methods are not always satisfactory, particularly for steel frame structures.

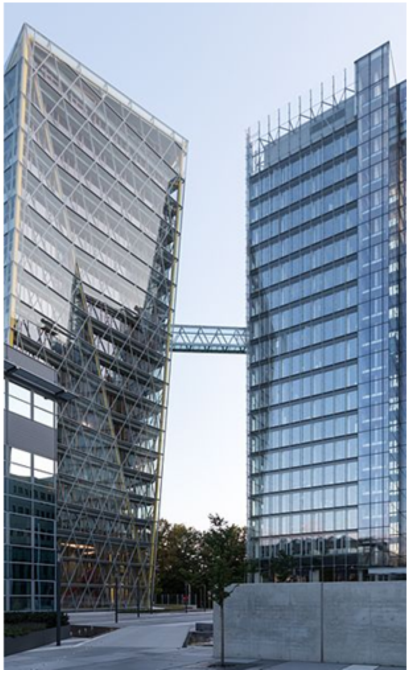


Figure 43. Glazed exterior wall
Source: Münster, LVM - 2015 – 7487 by Dietmar Rabich, CC BY-SA 4.0

Various retrofit methods are available for strengthening existing glass curtain walls and providing sufficient resistance against seismic loads. One method involves retrofitting a building to limit the inter-story drift allowance. Building code ASCE/SEI 7-10 (2010) and rehabilitation standard ASCE/SEI 41-06 (2007) provide minimum inter-story drift requirements, designed to keep glass panels in place (and avoid falling from the glazing assembly). Other methods, intended to limit or prevent the falling of broken glass, include the installation of safety glass (ANSI Z97.1-1984) or application of plastic films (FEMA, 2011b). Typically, a seismic vulnerability evaluation (e.g., Memari et al., 2014) is performed before the retrofit.

## Tilt-Up Retrofit (Anchoring)

Tilt-up is a building technique for concrete structures. The term "tilt-up" refers to the manner in which a building is constructed. Building elements (walls, structural supports, etc.) are cast on site, horizontally, and once cured, the panels are erected (or "tilted up") and moved into place (Figure 44).


Figure 44. Tilt-up construction
Source: (a) Tilt slab construction by Duk, CC BY-SA 3.0 and (b) Temporary-casting-pad by B. Bradley, CC BY-SA 2.5; modified by AIR

In older tilt-up structures, connections between the tilt-up walls and the roof framing system were inadequately designed for earthquake resistance. In strong earthquakes, these connections may fail, causing the walls to collapse. For example, tilt-up structures constructed before 1973 are at risk of collapse due to weak connections between the tilt-up walls and the roof framing system. This type of failure can be prevented by the addition of special anchors that strengthen the connection between the walls and the framing system (Figure 45).

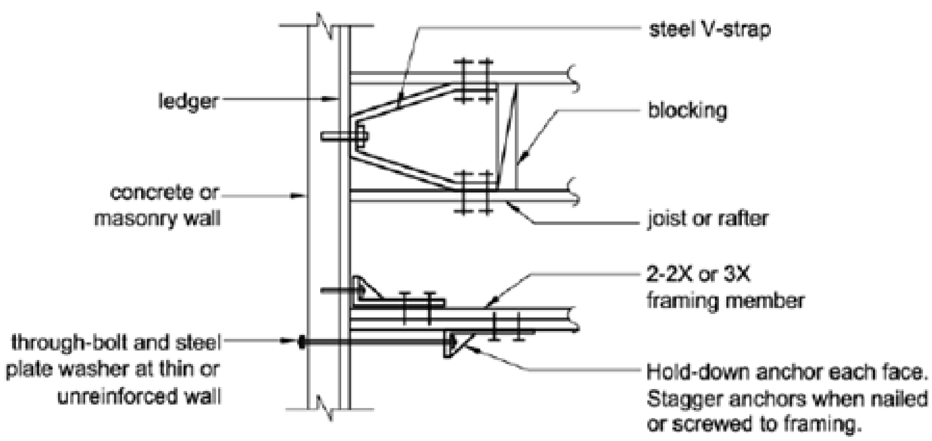



Figure 45. Anchorage of concrete or masonry walls to floor, roof, or ceiling framing
Source: FEMA, 2006a

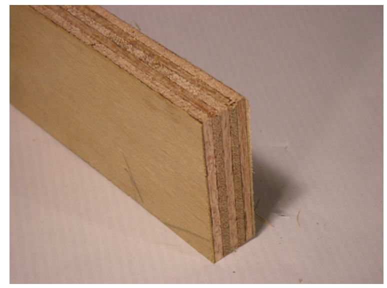
## 3.14 Roof Deck

Roof deck construction materials can influence the seismic vulnerability of a building, depending on the construction class. The weight of the roof can be critical, with regard to seismic performance. A heavy roof introduces higher lateral forces in the structure during shaking.

AIR determined the modifiers for this category primarily through engineering judgment based on the relative weight of the roof deck (compared with the structure) and the deck strength.

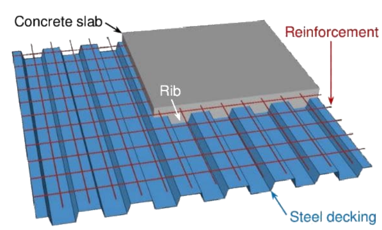
Previous studies on decks (Rogers and Tremblay, 2004) were used to supplement the expert opinion. Table 18 provides the valid options for Touchstone user-input values for roof deck.

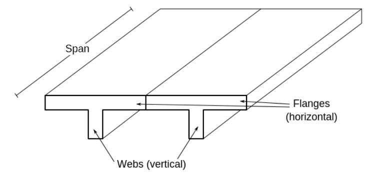
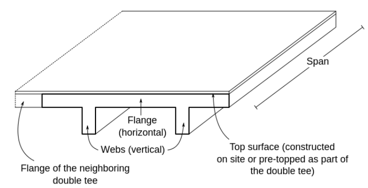
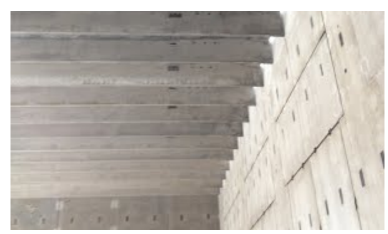
Table 18. Valid options for roof deck

| Value | Description | Details | Pictures |
|---|---|---|---|
| 0 | Unknown/ default | No designation/ unknown | |
| 1 | Plywood | Plywood panels used for roof deck materials are standard 4-ft x 8-ft panels that come in various thicknesses, wood species, and qualities.<br>They are generally used in frame construction for residences.<br>Plywood roof decking is attached to trusses or joists by screws or nails. | <br>Figure 46. Example of a plywood panel<br>Source: Plywood by Rotor DB, CC BY-SA 3.0 |

| Value | Description | Details | Pictures |
|---|---|---|---|
| 2 | Wood planks | Wood planks are a less common roof deck type.<br><br>Some varieties, such as tongue and groove, interlock along the edge for added strength and water resistance.<br><br>Each plank in the system requires fastening to the supporting truss, which increases the total number of fasteners. | <br>Figure 47. Example of a wood plank ceiling<br><br>Source: Interior building details of Building D, Room D-101 partition wall with multi-pane wood sash, timber wood truss ceiling; northerly view - San Quentin State Prison, Building 22, Point San Quentin, San Quentin, Marin County, CA by Robert A. Hicks, HABS CA-2804-A-127; cropped by AIR<br><br><br>Figure 48. Example of tongue and groove wood planks<br><br>Source: Dusheme.jpg by Petko Yotov, CC BY-SA 3.0 |

| Value | Description | Details | Pictures |
|---|---|---|---|
| 3 | Particle board/ OSB | Particle board is made of compressed wood chips and shavings, which are mixed with synthetic resins and formed into a usable wood panel.<br><br>Oriented Strand Board (OSB) is a similar wood product that is more common as an exterior wood construction material.<br><br>OSB is generally cheaper and denser than standard plywood.<br><br>Historically, OSB was susceptible to swelling and nail withdrawal when exposed to water. However, current treatment/ manufacturing processes have reduced this risk, making them comparable to plywood in terms of strength but at a lower cost. | <br>Figure 49. Example of particle board<br><br>Source: Particle board close up-big-plane face PNr°0099.jpg by D-Kuru, CC BY-SA 3.0<br><br><br>Figure 50. Example of Oriented Strand Board (OSB)<br><br>Source: Oriented strand board at Courtabœuf 2011.jpg by Lionel Allorge, CC BY-SA 3.0 |

| Value | Description | Details | Pictures |
|---|---|---|---|
| 4 | Metal deck with insulation board | This roof deck material is common in commercial construction, such as warehouses or retail establishments with flat roofs.<br>Steel purlins or joists support a metal/steel deck.<br>Insulation (foamed plastic or rigid) is added for climate control and fire resistance.<br>The insulation is connected to the deck by means of adhesive epoxy or by mechanical attachment at the manufacturer-specified spacing.<br>An optional barrier board is mechanically attached to the deck and covered by a metal roof cover. | <br>Figure 51. Example of hurricane damage sustained by rigid insulation installed over a steel deck<br>Source: FEMA, 2007<br><br>Figure 52. Close-up example of damage to insulation installed over a steel deck<br>Source: FEMA, 1999 |
| 5 | Metal deck with concrete | Often referred to as a composite deck, metal decks with concrete are common in commercial steel frame construction.<br>Metal purlins, trusses, or I-beams are connected to a metal deck by either welding or mechanical fasteners.<br>Reinforced concrete is poured in place on the metal deck at a specified thickness.<br>Lateral loads are transferred by shear studs, which are welded to the metal deck and underlying supports. | <br>Figure 53. Example of light-weight concrete poured over a metal roof deck<br>Source: https://theconstructor.org/building/lightweight-concrete-floor-systems/27324/ |

| Value | Description | Details | Pictures |
|---|---|---|---|
| 6 | Pre-cast concrete slabs | Pre-cast roof panels are poured offsite and shipped to the jobsite during construction.<br><br>These slabs are common in concrete commercial structures or in steel structures. | <br>Figure 54. Diagram of a Single T pre-cast concrete slab<br><br>Source: Diagram of two T-beams.svg by Z22, CC BY-SA 4.0; modified by AIR<br><br><br>Figure 55. Diagram of a Double T pre-cast concrete slab<br><br>Source: Diagram of double tee.svg by Z22; edited by AIR, CC BY-SA 4.0<br><br><br>Figure 56. Example of precast concrete walls and roof<br><br>Source: Precastbuilding.jpg by A. Engel, CC BY-SA 3.0; cropped by AIR<br><br><br>Figure 57. Example of a precast hollow core plank being placed<br><br>Source: pannbetonFertigdecke Montage.jpg by M. Schmahl, CC BY-SA 3.0; cropped by AIR |

| Value | Description | Details | Pictures |
|---|---|---|---|
| 7 | Reinforced concrete slabs | Reinforced concrete slabs are similar to precast slabs but are poured at the jobsite.<br><br>Reinforcements include steel rebar, wire mesh, or, in some cases, carbon/steel fibers, which aid in resisting tension. | <br>Figure 58. Example of rebar-reinforced concrete slabs under construction<br><br>Source: Suspended-slab-formwork.jpg by Bill Bradley/ billbeee, CC BY-SA 3.0 |
| 8 | Light metal | A light metal deck does not include insulation or a composite concrete deck.<br><br>A light metal deck can be attached to a steel framing system or to a timber frame system.<br><br>These decks are typically used in agricultural buildings (e.g., poultry farm sheds) and in low-occupancy buildings (e.g., warehouses). | <br>Figure 59. Example of light metal panels<br><br>Source: AIR |

## 3.15 Short Column

The term "short column" applies when there is a difference in height between columns on the same story/level of a building. Significantly shorter columns exhibit greater stiffness compared to the other, taller, columns. Greater stiffness attracts increased seismic loads, resulting in increased potential for damage during an earthquake. The short column feature applies to engineered concrete and steel structures and can be found in several construction scenarios. Examples include:

- Buildings with short columns at the basement level
- Buildings with ground level columns of varying height due to differences in ground level
- Commercial buildings with mezzanine floors (Figure 60(a)) or loft slabs that are added in between two regular floors
- Buildings constructed on a slope (Figure 60(b))
- Buildings with partial height of brick infill walls (Figure 61), among others

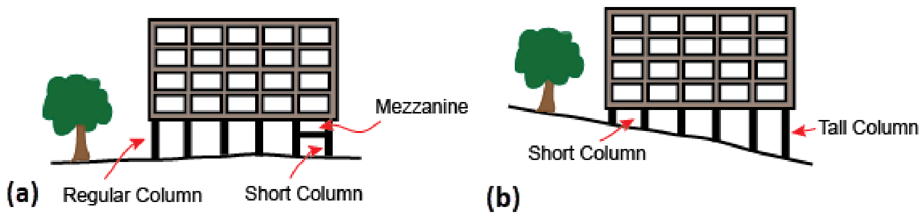



Figure 60. Short column due to the presence of (a) a mezzanine and (b) construction on a slope

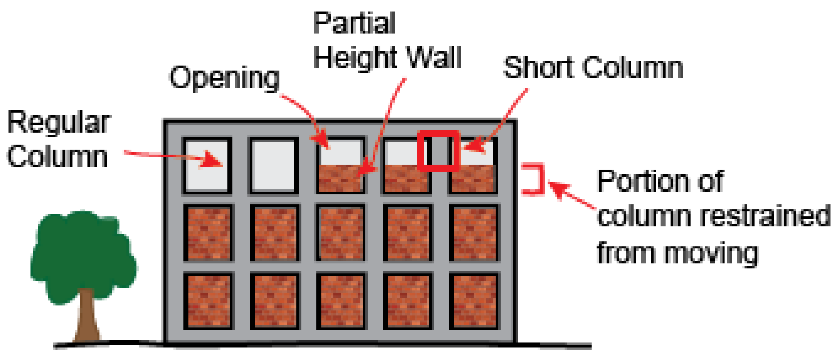



Figure 61. Short column associated with partial infill walls

As described above, the short column is a feature susceptible to damage during an earthquake, due to differential stiffness between columns on a given floor. Figure 62 presents examples of short column damage from the 1994 Northridge and 2001 Peru earthquakes. In Figure 62(a), the column's span is shortened by the balcony parapets on either side (the actual column is identified by the red box). Although the building appears to have shear walls, several columns like it were damaged in the 1994 Northridge earthquake. Similar damage can be seen in Figure 62(b).

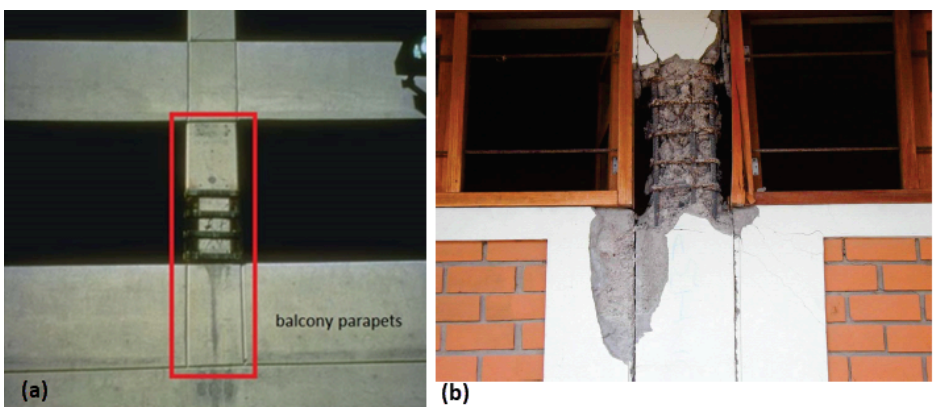



Figure 62. Short column damage: (a) 1994 Northridge earthquake and (b) 2001 Peru earthquake
Source: (a) M. Celebi, USGS, and (b) Eduardo Fierro, BFP Engineers, in FEMA, 2011b; modified by AIR

In addition to the scenarios listed above, short columns are often found in parking structures (Pourzanjani, 2010). Ramps typically connect stories in a parking structure. In building codes, these ramps are not considered lateral-resisting elements. Consequently, ramps can be detrimental to the intended seismic performance of parking structures. As shown in Figure 63, the ramp constrains the bending behavior of supporting columns, resulting in short columns that are prone to shear damages.

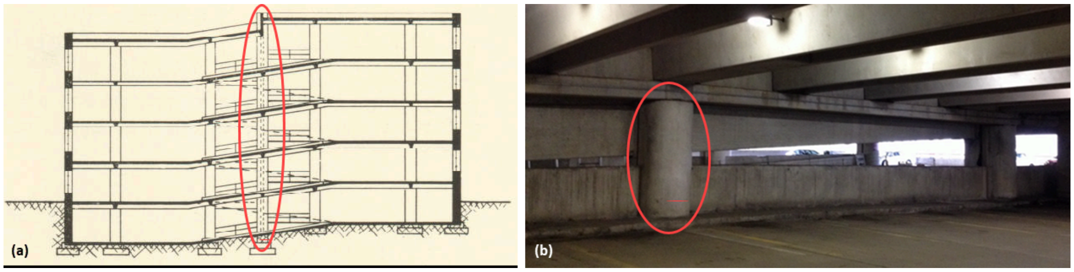



Figure 63. Parking structure ramp creates short columns circled in red
Source: (a) Ramp Buildings Corporation, c. 1929, and (b) Alewife Station parking garage, Cambridge, MA, J. Thibeau, AIR Worldwide; modified by AIR

AIR used 3D numerical models to determine modifiers of the short column feature. Some columns were assumed to be short columns. Using the incremental dynamic analysis (IDA) procedure (Vamvatsikos and Cornell, 2002), AIR computed inter-story drifts and floor response accelerations for buildings when subjected to a suite of ground motions.

Please note, this feature only applies to reinforced concrete and steel construction groups. Table 19 provides the valid options for Touchstone user-input values for short column.

Table 19. Valid options for short column

| Value | Description |
|---|---|
| 0 | Unknown/default |
| 1 | No |
| 2 | Yes |

## 3.16 Soft Story

Soft story refers to a particularly weak, flexible, or otherwise vulnerable, ground floor. Most common in older, wood-frame, multi-story buildings, a soft story often features relatively large window and door openings, with fewer partitions (less bracing) than the overlying levels. Examples of structures with a soft story include a house with the living space constructed over the garage or an apartment building with storefronts on the ground floor (Figure 64).


Figure 64. Typical soft story cases in residential buildings in California, U.S.
Source: (a) USA-San Francisco-2785 Jackson Street by E. Zelenko, CC BY-SA 4.0, (b) San Francisco houses 1156 by M. Stiburek, CC BY-SA 4.0, and (c) San Francisco houses 1154 by M. Stiburek, CC BY-SA 4.0; modified by AIR

Ground floor openings cause that floor to be less stiff (softer) than overlying stories. During earthquake shaking, the soft story experiences a sudden reduction in lateral stiffness and larger story drift, resulting in a concentration of deformation in the ground floor. As illustrated in Figure 65 and Figure 66, this can cause severe damage up to total collapse. In the 1994 Northridge earthquake, soft story buildings were responsible for at least 16 of the 57 deaths.

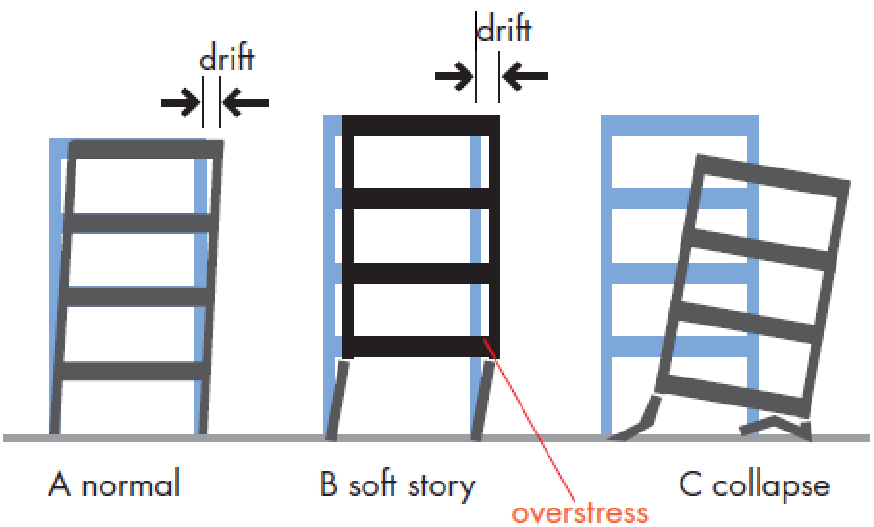



Figure 65. Soft first story failure mechanism
Source: FEMA, 2006b


Figure 66. Soft story damage, 1989 Loma Prieta earthquake
Source: (a) J. K. Nakata, USGS, (b) C. E. Meyer, USGS, and (c) J. K. Nakata, USGS; modified by AIR

### Soft Story Buildings in North America

Recently, San Francisco (City and County of San Francisco, Department of Building Inspection) and Los Angeles, California (City of Los Angeles, Department of Building and Safety) established soft-story retrofit programs. Such community-level efforts are designed to ensure the earthquake safety of the building stock through the retrofitting of old, wood-framed, multi-family residential buildings with a soft-story condition.

During the implementation of retrofitting programs, building characteristics qualification for soft-story are similar, if not identical, across agencies. The City and Council of San Francisco defines a soft-story building as a wood-frame, multi-family residential building of three or more stories, containing five or more dwelling units and constructed prior to 1978 (City and County of San Francisco, 2013). The City of Los Angeles identifies soft-story buildings as wood-frame of two or more stories, constructed under building code standards enacted prior to 1978, and containing ground floor parking or other similar open floor space (City of Los Angeles, Department of Building and Safety, 2015).

### Soft Story Options in Touchstone

In the AIR models, the loss adjustment factors for the soft story feature are based on a literature review (Fragiadakis et al., 2006). Table 20 provides the valid options for Touchstone user-input values for soft story. Please note, this feature does not apply to tilt-up construction.

Table 20. Valid options for soft story

| Value | Description |
|---|---|
| 0 | Unknown/default |
| 1 | No |
| 2 | Yes |

## 3.17 Special Earthquake-Resistive Systems

Some new commercial buildings (primarily in California and Japan) have special devices or design elements that resist earthquake loads. Touchstone considers the following special earthquake-resistive systems: base isolation, visco-elastic dampers, and other energy dissipaters. These systems are described in the following sections, and Table 21 provides the valid options for Touchstone user-input values.

Table 21. Valid options for special earthquake-resistive systems

| Value | Description |
|---|---|
| 0 | Unknown |
| 1 | Base isolation[2] |

[2] Applies to masonry, reinforced concrete, and steel structures

| Value | Description |
|---|---|
| 2 | Visco-elastic dampers |
| 3 | Other energy dissipators |

## Base Isolation

Base isolation is a collection of structural elements designed to protect a structure's integrity by substantially decoupling the superstructure from the ground during shaking. Buildings with base isolation float on a pad that dampens seismic waves during an event (Figure 67). This prevents the kinetic energy of the earthquake from transferring into elastic energy in the building. Base isolation raises both a structure's seismic performance and its seismic sustainability considerably.

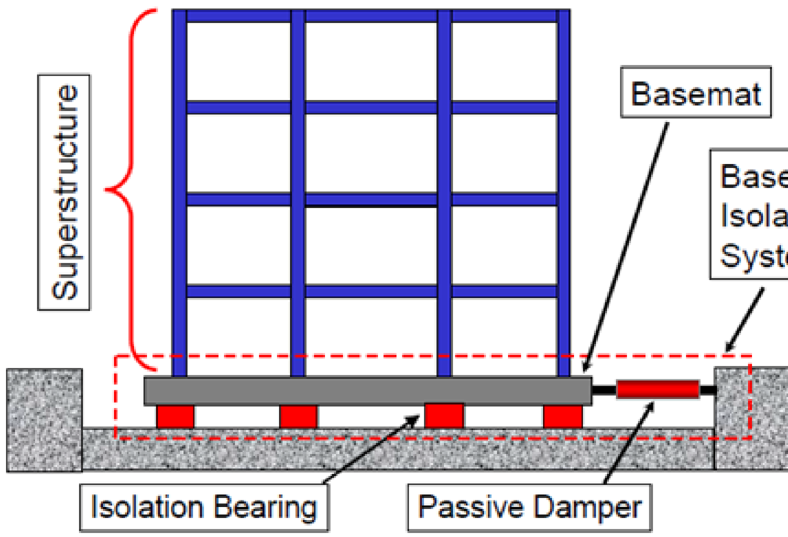



Figure 67. Basic elements of a base isolation system
Source: FEMA, 2003

One example of a structure with a base isolation system is the Utah State Capitol building in Salt Lake City (Figure 68). Another is the University of Southern California (USC) Hospital building in Los Angeles. During the 1994 Northridge earthquake, the building experienced strong motion, but performed very well. The hospital is a 7-story, braced steel frame building, and during the event, the bearings system yielded and dissipated energy. Peak roof acceleration was reduced to 0.21g, nearly 50% of the peak ground acceleration for that event (Nagarajaiah and Sun, 2000).

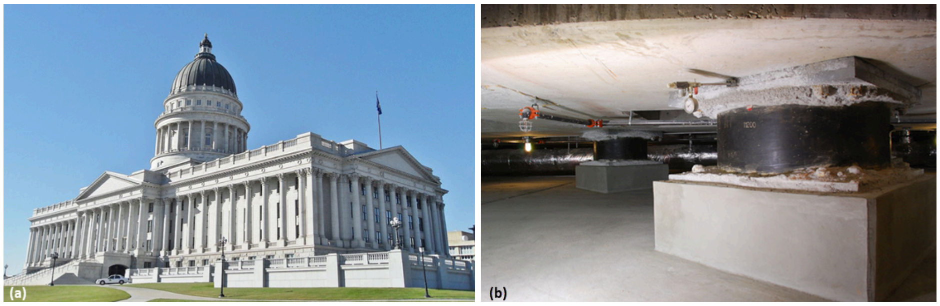



Figure 68. Utah State House: (a) Exterior and (b) Isolation bearings
Source: (a) Utah State Capitol in October 2010 by Mangman88, CC BY-SA 3.0 and (b) Base isolators under the Utah State Capitol by M. Renlund, CC BY 2.0; modified by AIR

It should be noted that base isolation only applies to engineered reinforced concrete and steel structures.

## Visco-Elastic Dampers

A common technique used in seismic retrofit or seismic design is viscous damping (or called visco-elastic damper). Viscous damping takes advantage of the high resistance of viscous fluids.

Dampers installed in a structural system can absorb energy and attenuate vibration. Damping is commonly expressed as a percentage of critical damping. A zero damped elastic system, when displaced, would theoretically vibrate at its natural period and at the same amplitude. A critically damped structure, when displaced, would return to its original position without vibration.

Figure 69 shows an example of visco-elastic dampers installed on the London Millennium Footbridge. The bridge was closed shortly after its opening, because of the consonant vibration. Engineers installed these visco-elastic dampers on the bridge to reduce the vibration amplitude.

Figure 69. Visco-elastic dampers installed on the London Millennium Footbridge
Source: Y. Yin, AIR Worldwide

In the AIR models, loss adjustment factors for this feature are based on literature studies (Mayes et al., 2004, Vargas and Bruneau, 2007) and experimental data.

## Other Energy Dissipaters

Another way to reduce or prevent vibration-caused discomfort or damage is by using a tuned mass damper, also known as a harmonic absorber. Taipei 101 (Figure 70) was constructed with such a system and has a steel pendulum suspended from the 92nd to the 87th floor (Figure 71). This 660-tonne pendulum sways to offset movements in the building due to strong wind loads or earthquake loads.

Figure 70. Taipei 101, Taipei, Taiwan
Source: Taipei101.portrait.altonthompson by A. Thompson, CC BY-SA 4.0

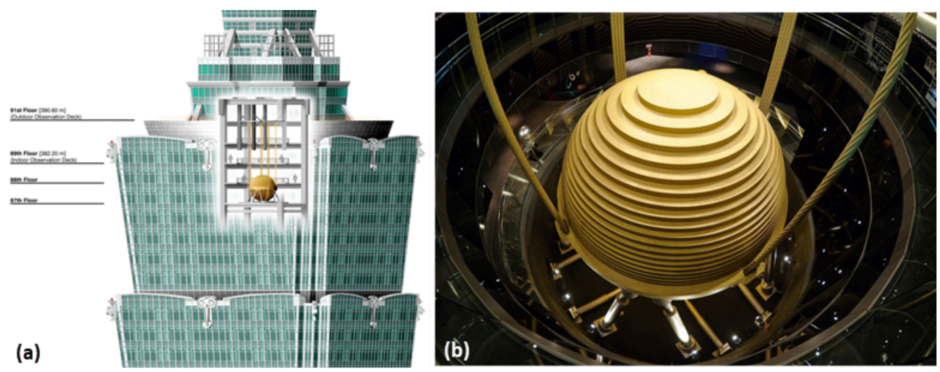


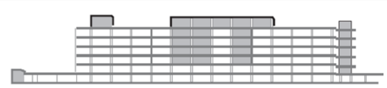

Figure 71. Taipei 101 tuned mass damper: (a) Location within the structure and (b) View of the pendulum
Source: (a) Taipei 101 Tuned Mass Damper by Someformofhuman, CC BY-SA 4.0 and (b) Taipei 101 Tuned Mass Damper 2010 by Armand du Plessis, CC BY-SA 3.0; modified by AIR

## 3.18 Structural Irregularity

While structural irregularity includes both vertical and horizontal inequalities, in Touchstone, this term refers only to vertical irregularities. Horizontal irregularities are considered separately as torsion and building shape.

Vertically-irregular buildings usually have sudden changes in mass and/or stiffness at certain floors. Touchstone considers the following vertical irregularities: vertical offset, non-uniform floor area, discontinuous shear wall, and heavy floor. Table 22 provides the valid options for Touchstone user-input for structural irregularity, with examples.

Table 22. Valid options for structural irregularity

| Value | Description | Picture/Notes |
|---|---|---|
| 0 | Unknown/default | No designation/unknown |
| 1 | Regular | This value is no longer supported. If selected, Touchstone maps to unknown/default (0) upon import. |
| 2 | Vertical offset |  Figure 72. (a) Antilia Tower, Mumbai, India and (b) SIS Building, London, England<br>Source: (a) Mumbai 03-2016 19 Antilia Tower by A. Savin, Free Art License 1.3 and (b) SIS building by L. Nevay, CC BY 2.0; modified by AIR |
| 3 | Non-uniform floor area |  Figure 73. (a) 30 St. Mary Axe and (b) 20 Fenchurch St., London, England<br>Source: (a) 30 St Mary Axe, 'Gherkin' by Paste, Public domain and (b) Walkie-Talkie - Sept 2015 by Colin, CC BY 4.0; modified by AIR |
| 4 | Discontinuous shear wall |  Figure 74. Long section, Olive View Hospital, San Fernando, California (1971). Shear walls (gray) do not extend to the ground.<br>Source: FEMA, 2006c; modified by AIR |

| Value | Description | Picture/Notes |
|---|---|---|
| 5 | Heavy floor | Example: placement of heavy equipment on higher floors. |

AIR used the analytical results from Fragiadakis et al. (2006) to determine modifiers for structural irregularities. This study analyzed the effect of vertical variation in strength, stiffness, and mass along the height of a building. AIR mapped the different modifiers (Table 22) in this category to comparable conditions in the Fragiadakis et al. (2006) study.

## 3.19 Tall One Story

This feature applies to single story buildings that are taller than typical one-story structures, such as churches, gymnasiums (Figure 75), concert halls, etc. Such buildings may be more susceptible to damage from ground shaking, as the roof of the building is higher from the ground, requiring taller columns and/or walls for support, than an average one-story structure. These elements are likely to span long lengths without bracing, which may make them more susceptible to buckling. Furthermore, taller one-story buildings may experience larger overturning forces, as the lateral forces are further away from the ground.

Figure 75. Example of a tall one-story structure: Fordham University gymnasium
Source: Fordham court 800 by Anthony22, CC BY-SA 3.0

Table 23 provides the valid user-input values for tall one story in Touchstone. This feature only applies to construction of one-story height.

Table 23. Valid options for tall one story

| Value | Description |
|---|---|
| 0 | Unknown/default |
| 1 | Height ≤ 20 ft |
| 2 | Height 20 - 40 ft |
| 3 | Height > 40 ft |

## 3.20 Tanks

Rooftop tanks are a falling hazard during an earthquake. Falling tanks are more likely to damage adjacent, shorter buildings than the structure upon which they sit. Figure 76 presents an example of rooftop tanks, and Table 24 provides the valid user-input options for Touchstone.

Figure 76. Rooftop tanks
Source: Rooftop water towers on New York apartment buildings by R. Googin, CC BY-SA 3.0, modified by AIR

Table 24. Valid options for tanks

| Value | Description |
|---|---|
| 0 | Unknown/default |
| 1 | No |
| 2 | Yes |

## 3.21 Torsion

During ground shaking, the weight of building components, such as floors, walls, and roof, contribute to the main lateral force of the structure. The force is exerted through the center of mass, usually the geometric center of the floor (in plan). If the resultant force of resistance pushes back through this center of mass, dynamic balance is maintained, as shown in Figure 77(a). However, there can be eccentricity between the resistance center and the mass center. When subjected to ground shaking, such eccentricity causes a building to rotate around its center of resistance, and experience torsion (Figure 77(b)).

In an ideal situation, earthquake resistance elements in a structure should be placed symmetrically in all directions so that no matter in which direction the floors are pushed, the structure pushes back with a balanced stiffness that prevents rotation. Of course, in practice, some degree of torsion is always present, and is addressed in building codes.

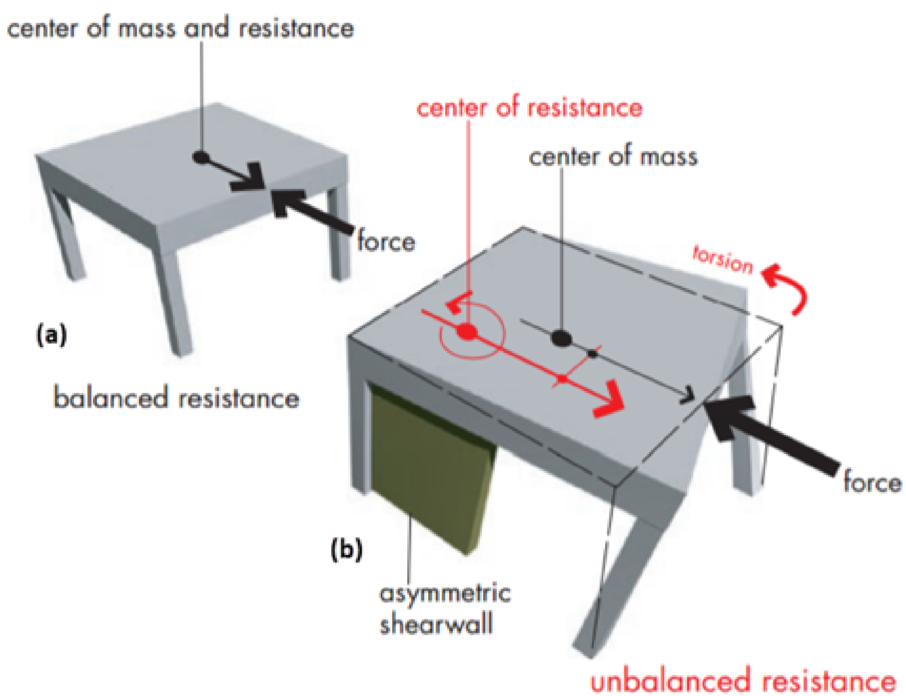



Figure 77. Torsional force illustration: (a) Symmetrical building and (b) Asymmetrical building
Source: FEMA, 2006c

A building's shape affects its torsional load. Wedge-shaped buildings and corner buildings are typical examples of structures with asymmetrical lateral load-resisting components. This leads to the induction of torsional forces when the building is shaken, which can result in significant damage. During an event, the re-entrant corner or "notch" of the building experiences local stress concentrations (Figure 78).

Please note, the torsion and building shape SRCs are highly correlated. The user should select only one of these features (torsion or building shape) to avoid double counting the loss modifier.

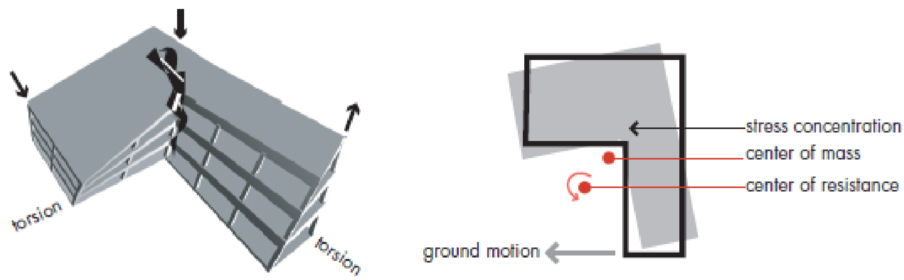



Figure 78. Torsional force acting on a corner building
Source: FEMA, 2006c; modified by AIR

Touchstone considers the following torsion secondary risk characteristics: symmetric, asymmetric, and corner building. Table 25 provides the valid options user-input values for these options.

Table 25. Valid options for torsion

| Value | Description |
| --- | --- |
| 0 | Unknown/default |
| 1 | Symmetric |
| 2 | Asymmetric |
| 3 | Corner Building |

AIR used 3D numerical models to determine modifiers of the torsion feature. To simulate torsion, the center of mass was moved, inducing rotation during lateral deflection caused by ground shaking. AIR then computed inter-story drifts and floor response accelerations when these buildings were subjected to a suite of ground motions, using the incremental dynamic analysis (IDA) procedure (Vamvatsikos and Cornell, 2002). To determine the modifier values, AIR translated differences in interstory drift into differences in loss.

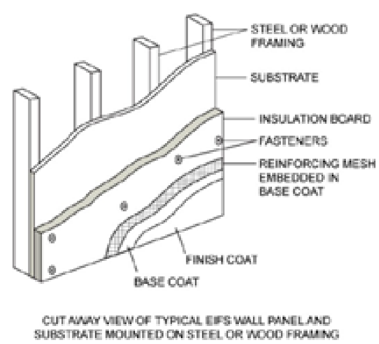
## 3.22 Wall Siding

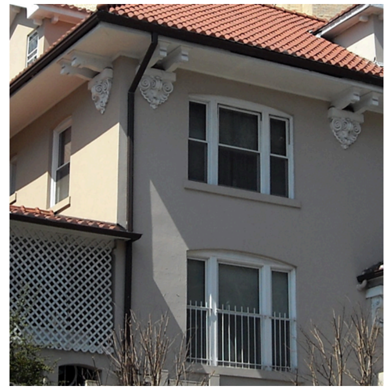
Different types of cladding materials, or wall siding, offer varying degrees of resistance to earthquake-induced lateral loads. Table 26 provides a brief description of wall siding types included in Touchstone, as well as the valid options user-input values.

Table 26. Valid options for wall siding materials

| Value | Description | Details | Pictures |
| --- | --- | --- | --- |
| 0 | Unknown/ default | No designation/unknown or no wall siding. | |

| Value | Description | Details | Pictures |
|---|---|---|---|
| 1 | Veneer brick/ masonry | Brick or masonry veneer is predominantly a decorative feature and does not bear any structural load except its own weight.<br><br>Generally, the veneer is attached to the main wall structure using wall ties, but reinforcement is not common. | <br>Figure 79. Brick veneer application<br><br>Source: FEMA, 2009b |
| 2 | Wood shingles | Wood shingle siding is a versatile option that is used on a wide variety of building structures. Wood shingles are thin, tapered pieces of wood, typically made of California redwood, western red cedar, and Atlantic white cedar. | <br>Figure 80. Example of wood shingle siding<br><br>Source: Lech - Schindelfassade 01.jpg by Basotxerri, CC BY-SA 4.0; cropped by AIR |
| 3 | Clapboards | Clapboards are long, thin, and flat pieces of wood or alternative material (e.g., fiber cement) that are used to cover the outer walls of buildings. The board edges overlap horizontally in series.<br><br>Each board is nailed or fastened to the wall structure, which increases the strength when compared to larger, lighter weight aluminum or vinyl siding panels.<br><br>Clapboard is also known as bevel siding, lap siding, or weatherboard. | <br>Figure 81. Example of clapboard siding<br><br>Source: Texture of Wooden Boards.jpg by Sadiq, CC BY-SA 3.0 |

| Value | Description | Details | Pictures |
|---|---|---|---|
| 4 | Aluminum/ vinyl siding | Aluminum/vinyl siding is relatively cheap and by far the most common siding type used in residential construction.<br>It is a lightweight panel that interlocks to adjacent panels. | <br>Figure 82. Example of vinyl siding<br>Source: Middletown, CT - Main St 20.jpg by Joe Mabel, CC BY-SA 3.0; cropped by AIR |
| 5 | Stone panels | Stone panels are a decorative siding option that is similar to a veneer.<br>They are applied to the main wall structure with plaster. | <br>Figure 83. Example of stone panel siding<br>Source: History of Stone Veneer.jpg by c avery, CC BY-SA 2.0 |
| 6 | Exterior Insulation Finishing System (EIFS) | Exterior Insulation Finishing System (EIFS) is a general class of non-load bearing building cladding systems that provides exterior walls with an insulated, water-resistant, finished surface in an integrated composite material system.<br>EIFS can be attached by mechanical fasteners or by adhesive.<br>EIFS is common in commercial applications, such as mid- or high-rise hotels and offices. | <br><br>Figure 84. Schematic example of an EIFS wall panel<br>Source: FEMA, 2011a |

| Value | Description | Details | Pictures |
|---|---|---|---|
| 7 | Stucco | Stucco is a very common exterior wall finish.<br>It is a cement plaster that is usually applied on a metal mesh with a vapor barrier and attached to the main wall system.<br>Wood-framed and masonry homes use stucco quite extensively. | <br>Figure 85. Example of stucco siding<br>Source: 2112 19th Street, N.W..JPG by AgnosticPreachersKid, CC BY-SA 3.0; cropped by AIR |

Although siding is a non-structural component, the type of siding can impact losses. Wall siding can sustain serious damage in an earthquake, resulting in significant losses. For example, consider a wood-frame building with an exterior wall of unreinforced masonry or a residence with masonry veneer siding. In an earthquake, the exterior wall may collapse, or the veneer may fall, while the wood-frame experiences little damage (Figure 86).


Figure 86. Examples of earthquake damage: (a) Unreinforced masonry during the 2014 South Napa, California earthquake and (b) Collapsed brick veneer in the 1989 Loma Prieta earthquake
Source: (a) NPS, 2016 and (b) C. E. Meyer, USGS; modified by AIR

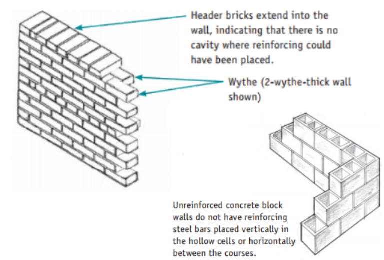
AIR computed the loss adjustment factors for different types of wall siding by establishing fragility function parameters for each type, based on published literature (Choi and LaFave, 2004; Reneckis and LaFave, 2009) and engineering judgment. AIR integrated these fragility functions with repair costs, using an approach similar to HAZUS, to obtain relative loss values. These values were then adjusted to account for the loss of the component relative to the replacement cost of the entire building.

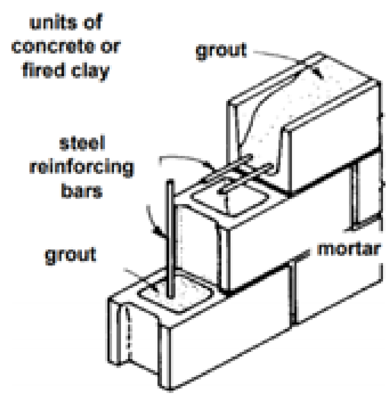
## 3.23 Wall Type

Wall type refers to the external walls of a structure. Based on the type of construction, some wall forms can contribute to increasing the lateral-load capacity of a building, while others tend to act independently when shaken.

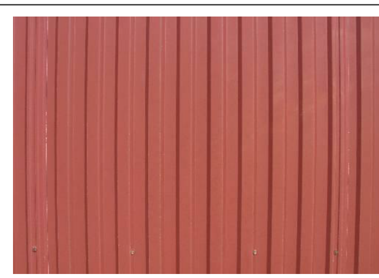
For example, unreinforced masonry walls are vulnerable in earthquakes due to a lack of shear resistance and out-of-plane force resistance. In contrast, reinforced masonry uses bricks, concrete blocks, or other types of masonry that are supported by steel rods, making these walls less vulnerable. Table 27 provides examples of the valid options for Touchstone user-input values for wall type.

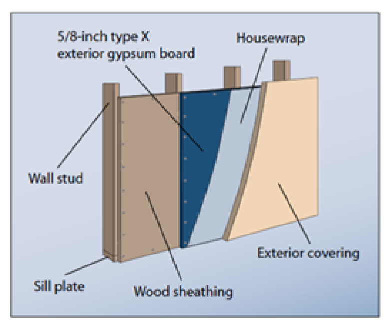
Table 27. Valid options for wall type

| Value | Description | Details | Pictures |
|---|---|---|---|
| 0 | Unknown/ default | No designation/unknown | |
| 1 | Brick/ unreinforced masonry | This option refers to brick or concrete masonry units (CMU) that are bonded together to form a wall that has no vertical reinforcement. Lack of reinforcement increases susceptibility to wall collapse or toppling due to out of plane bending. | <br>Figure 87. Example of unreinforced concrete block walls<br>Source: FEMA, 2009b; cropped by AIR |

| Value | Description | Details | Pictures |
|---|---|---|---|
| 2 | Reinforced masonry | Reinforced masonry generally refers to CMU construction rather than other types of masonry. Reinforcing is achieved with vertical rebar encased in grout at building code-specified intervals.<br><br>Reinforced masonry is better suited to resist bending. | <br>Figure 88. Example of a reinforced masonry wall<br><br>Source: Bond-beam by B. Bradley, CC BY-SA 3.0<br><br><br>Figure 89. Diagram of a reinforced masonry wall<br><br>Source: FEMA, 2013, cropped by AIR |

| Value | Description | Details | Pictures |
|---|---|---|---|
| 3 | Plywood | Plywood refers to standard 4 ft x 8 ft panels that come in various thicknesses, wood species, and quality. Plywood is typically used in residential and low-rise commercial applications in which the main structure is wood-frame construction. |  Figure 90. Example of plywood wall construction<br><br>Source: Defense.gov News Photo 101112-N-7743H-024 by Petty Officer Leif HerrGesell, Public domain |
| 4 | Wood planks | Wood planks can be used in place of plywood or OSB sheathing (see Option 5 below) to form the wall shell. They are used for aesthetic reasons if no siding is required. |  Figure 91. Example of a wood plank wall<br><br>Source: HABS CAL,36-RANCU,3D-2 by T. Olmos, Library of Congress |

| Value | Description | Details | Pictures |
|---|---|---|---|
| 5 | Particle board/ oriented strand board (OSB) | Particle board is made of compressed wood chips and shavings that are mixed with synthetic resins and formed into a usable wood panel.<br><br>Oriented Strand Board (OSB) is a similar wood product that is more common as an exterior wood construction material. OSB is typically cheaper and denser than standard plywood. Historically, OSB was susceptible to swelling and nail withdrawal when exposed to water but some current treatment and manufacturing processes have reduced this risk, making them comparable to plywood in terms of strength but at a lower cost. OSB is a very common product in timber-frame construction. | <br>Figure 92. Particle board<br><br>Source: Particle board close up-big-plane face PNr°0099 by D-Kuru/ Wikimedia Commons, CC BY-SA 3.0<br><br><br>Figure 93. Oriented strand board<br><br>Source: Oriented strand board at Courtabœuf 2011 by L. Allorge, CC BY-SA 3.0 |
| 6 | Metal panels | Metal panels form the outer shell of many industrial facilities, warehouses, and storage facilities. The main structure is usually a steel frame or light metal frame. | <br>Figure 94. Corrugated steel siding<br><br>Source: LightningVolt Corrugated Steel Siding by L. Lentz, CC BY-SA 1.0 |

| Value | Description | Details | Pictures |
|---|---|---|---|
| 7 | Precast concrete elements | Precast concrete elements are very common in low-rise commercial building construction. Walls or wall panels are pre-cast and then installed at the job site. Tilt-up concrete construction, shown in the figure to the right, is a primary example. |  Figure 95. Precast concrete<br><br>Source: Precast concrete house in construction by Self Made, CC BY-SA 3.0 |
| 8 | Cast-in-place concrete | Cast-in-place concrete is transported to the job site in the unhardened state and poured into forms, which harden to become the wall structure. |  Figure 96. Example of cast-in-place concrete construction<br><br>Source: Concrete Housing by WTF Formwork http://www.WALLTIES.com by B. Bradley, CC BY-SA 3.0; cropped by AIR |
| 9 | Gypsum board | Gypsum board, which is sometimes referred to as sheetrock, is used as an exterior wall material in wood-frame construction or in steel and concrete buildings.<br><br>It is predominantly used as an interior wall finish and is prone to water damage if the siding is breached. |   Figure 97. Diagram of a gypsum board<br><br>Source: FEMA, 2008b |

AIR constructed fragility functions for each exterior wall type based on literature (Magenes and Calvi, 1996; Tomazevic, 1996; Ehsani et al., 1999) and engineering judgments. Then, fragility functions were integrated with repair costs to obtain relative loss values, using an approach similar to HAZUS. These values were then adjusted to account for the loss of the component, relative to the replacement cost of the entire building.

## 3.24 Water Heater

Residential houses in the United States usually have a water heater tank for hot water (Figure 98). When water heaters are not properly braced, they may topple down, causing water damage to the house.


Figure 98. Hot water heater: (a) Unbraced and (b) Braced
Source: (a) Hot water heater with pipe by Tomwsulcer, CC0 1.0 and (b) Cynthia Perry, BFP Engineers in FEMA, 2011b; modified by AIR

AIR computed loss adjustment factors for the water heater feature using the results of the CUREE study (Porter et al., 2002).

Table 28 provides the valid options for Touchstone user-input values for water heater. This feature only applies to wood construction.

Table 28. Valid options for water heater

| Value | Description |
|---|---|
| 0 | Unknown/default |
| 1 | Braced |

| Value | Description |
|---|---|
| 2 | Unbraced |

# Selected References

American National Standards Institute (1984). *American National Standard for Safety Glazing Materials Used in Buildings – Safety Performance Specifications and Methods of Test*. ANSI Z97, 1-1984.

American Society of Civil Engineers (ASCE; 2007). *Seismic Rehabilitation of Existing Buildings*. ASCE/SEI Standard 41-06.

ASCE (2010). *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*. ASCE/SEI Standard 7-10.

ASCE (2016). *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*. ASCE/SEI Standard 7-166.

Applied Technology Council (2006). *Next-Generation Performance-Based Seismic Design Guidelines, Program Plan for New and Existing Buildings*. FEMA 445, August 2006.

Choi, Y. H. & LaFave, J. M. (2004). Performance of Corrugated Metal Ties for Brick Veneer Wall Systems, *Journal of Materials in Civil Engineering*, 16(3), 202-211.

City and County of San Francisco, Board of Supervisors (2013). Building Code - Mandatory Seismic Retrofit Program - Wood-Frame Buildings; Optional Evaluation Form Fee, Ordinance Enacted No. 0066-13. Retrieved from http://sfbos.org/ordinances-2013

City and County of San Francisco, Department of Building Inspection, Mandatory Soft Story Program, http://sfdbi.org/Softstory, visited on March 26, 2018.

City of Los Angeles, Department of Building and Safety (2015). *Mandatory earthquake hazard reduction in existing wood-frame buildings with soft, weak or open-front walls, Ordinance No. 18383*.

City of Los Angeles, Department of Building and Safety, *Soft-Story Retrofit Program*. Visited on March 26, 2018.

Cole, G., Dhakal, R., & Turner, F. (2012). Building Pounding Damage Observed in the 2011 Christchurch Earthquake, *Earthquake Engineering & Structural Dynamics*, Volume 41(5), 893-913.

Ehsani, M. R., Saadatmanesh, H., & Velazquez-Dimas, J. I. (1999). Behavior of Retrofitted URM Walls under Simulated Earthquake Loading, *Journal of Composites for Construction*, 3(3).

Federal Emergency Management Agency (FEMA, 2002). *Installing Seismic Restraints for Mechanical Equipment*. FEMA 412, December 2002.

FEMA (2003). *Seismic Protective Systems: Seismic Isolation*, Instructional material complementing FEMA 451, Design Examples.

FEMA (2006a). *Homebuilders' Guide to Earthquake-Resistant Design and Construction*. FEMA 232, June 2006.

FEMA (2006b). *Designing for Earthquakes: A Manual for Architects*. FEMA 454, December 2006.

FEMA (2006c). *Techniques for the Seismic Rehabilitation of Existing Buildings*. FEMA 547, 2006 Edition.

FEMA (2006d). *Design Guidance for Shelters and Safe Rooms, Risk Management Series*. FEMA 453, May 2006.

FEMA (2008a). *Openings in Foundation Walls and Walls of Enclosures, Below Elevated Buildings in Special Flood Hazard Areas in Accordance with the National Flood Insurance Program*. Technical Bulletin 1, August 2008.

FEMA (2008b). *Exterior Walls, Home Builder's Guide to Construction in Wildfire Zones*. FEMA Technical Fact Sheet No. 7, September 2008.

FEMA (2009a). *Local Officials Guide for Coastal Construction, Design Considerations, Regulatory Guidance, and Best Practices for Coastal Communities*. FEMA P-762, February 2009.

FEMA (2009b). *Unreinforced Masonry Buildings and Earthquakes, Developing Successful Risk Reduction Programs*. FEMA P-774.

FEMA (2009c). *Recommended Residential Construction for Coastal Areas. Building on Strong and Safe Foundations*. Second Edition, FEMA P-550, December 2009.

FEMA (2011a). *Principles and Practices of Planning, Siting, Designing, Constructing, and Maintaining Residential Buildings in Coastal Areas*, Fourth Edition. FEMA Coastal Construction Manual, Volumes 1 & 2, P-55, August 2011.

FEMA (2011b). *Reducing the Risks of Nonstructural Earthquake Damage – A Practical Guide*. FEMA E-74, January 2011.

FEMA (2013a). *Foundation Requirements and Recommendations for Elevated Homes, Hurricane Sandy Recovery*. FEMA Fact Sheet No. 2, May 2013.

FEMA (2013b). *2009 NEHRP Recommended Seismic Provisions: Training and Instruction Materials*, FEMA P-752, June 2013.

FEMA (2015). *Earthquake Strengthening of Cripple Walls in Wood-Frame Dwellings, South Napa Earthquake Recovery Advisory*, FEMA DR-4193-RA2, HSFE60-12-D-0242, April 2015.

Fragiadakis, M., Vamvatsikos, D., & Papadrakakis, M. (2006). Evaluation of the Influence of Vertical Irregularities on the Seismic Performance of a 9-storey Steel Frame. *Earthquake Engineering and Structural Dynamics*, 35(12), 1489-1509.

International Code Council (2009). *International Building Code*, ISBN: 978-58001-725-1, February 2009.

Liao, K. W. & Wen, Y. K. (2004). *Redundancy in steel moment frame systems under seismic excitations*, Civil Engineering Studies, Structural Research Series No. 636, University of Illinois Engineering Experiment Station, College of Engineering, University of Illinois at Urbana-Champaign, August 2004.

Liao, K.-W., Wen, Y.-K., & Foutch, D. A. (2007). Evaluation of 3D Steel Moment Frames under Earthquake Excitations. II: Reliability and Redundancy. *Journal of Structural Engineering*, 133(3), March 1, 2007.

Magenes, G. & Calvi, G. M. (1997). In-plane Seismic Response of Brick Masonry Walls. *Earthquake Engineering and Structural Dynamics*, 26(11), 1091-1112, November 1997.

Mayes, R., Goings, C., Naguib, W., Harris, S., Lovejoy, J., Fanucci, J., Bystricky, P., & Hayes, J. (2004). *Comparative Performance of Buckling-Restrained Braces and Moment Frames*. Paper 2887, Proceedings of the 13th World Conference on Earthquake Engineering, Vancouver, Canada, August 1-6, 2004.

Memari, A., Shirazi, A., Kremer, P., & Behr, R. (2014). Seismic Vulnerability Evaluation of Architectural Glass in Curtain Walls. *Journal of Civil Engineering and Architecture Research*, 1(2), 110-128, August 25, 2014.

Nagarajaiah, S. & Sun, X. (2000). Response of Base-Isolated USC Hospital Building in Northridge Earthquake. *Journal of Structural Engineering*, 126(10), 1177-1186, October 1, 2000.

National Park Service (2016). *The Seismic Rehabilitation of Historic Buildings*, Preservation Brief 41, April 2016.

National Earthquake Hazards Reduction Program (NEHRP; 2003). *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures (FEMA 450)*, 2003 Edition, Building Seismic Safety Council of the National Institute of Building Science.

NEHRP (2012). *Seismic Design of Reinforced Concrete Mat Foundations, a Guide for Practicing Engineers*, NEHRP Seismic Design Technical Brief No. 7, Report 12-917-22, August 2012.

Porter, K. A., Beck, J. L., Seligson, H. A., Scawthorn, C. R., Tobin, L. T., Yong, R., & Boyd, T. (2002). *Improving Loss Estimation for Woodframe Buildings*, CUREE-Caltech Woodframe Project, Element 4, Economic Aspects, May 2002.

Pourzanjani, M. (2010). Seismic Design of Concrete Parking Structure Ramps. *Structure Magazine*, July 2010.

Reneckis, D. & LaFave, J. M. (2009). *Seismic Performance of Anchored Brick Veneer*, Newmark Structural Engineering Laboratory Report Series, No. NSEL-016, August 2009.

Rogers, C. A., Tremblay, R., Yang, W., & Martin, E. (2004). *Ductile Design of Steel Roof Deck Diaphragms for Earthquake Resistance*. Paper 1997, Proceedings of the 13th World Conference on Earthquake Engineering, Vancouver, Canada, August 1-6, 2004.

Sarkisian, M., Korista, S., & Abdelrazaq, A. (1995). *Jin Mao Tower's Unique Structural System*, Shanghai International Seminar for Building Construction Technology, Shanghai, China, 1995.

Tomazevic, M., Lutman, M., Capuder, F., & Petkovic, L. (1996). *Seismic Behaviour of R.C. Shear-Walls: An Experimental Study*. Paper 381, Proceedings of the 11th World Conference on Earthquake Engineering, Acapulco, Mexico, June 23-28, 1996.

Vamvatsikos, D. & Cornell, C. A. (2002). Incremental Dynamic Analysis. *Earthquake Engineering and Structural Dynamics*, 31(3), 491–514, March 2002.

Vamvatsikos, D. (2009). National Technical University of Athens, School of Engineering, personal communication.

Vargas, R. & Bruneau, M. (2007). Effect of Supplemental Viscous Damping on the Seismic Response of Structural Systems with Metallic Dampers. *Journal of Structural Engineering*, 133(10), October 2007.

Wen, Y. K. & Song, S. H. (2003). Structural Reliability/Redundancy under Earthquakes. *Journal of Structural Engineering*, 129(1), 56-67, January 2003.

Zhou, F. L., Xu, Z. G., & Liu, W. G. (2003). *World Housing Encyclopedia Report, China, Multi-Story Isolated Brick Masonry Building with Reinforced Concrete Floors and Roof*, Earthquake Engineering Research Institute, International Association of Earthquake Engineering, June 17, 2003.

# About AIR Worldwide

AIR Worldwide (AIR) provides risk modeling solutions that make individuals, businesses, and society more resilient to extreme events. In 1987, AIR Worldwide founded the catastrophe modeling industry and today models the risk from natural catastrophes, terrorism, pandemics, casualty catastrophes, and cyber incidents. Insurance, reinsurance, financial, corporate, and government clients rely on AIR's advanced science, software, and consulting services for catastrophe risk management, insurance-linked securities, longevity modeling, site-specific engineering analyses, and agricultural risk management. AIR Worldwide, a Verisk (Nasdaq:VRSK) business, is headquartered in Boston with additional offices in North America, Europe, and Asia. For more information, please visit www.air-worldwide.com.

AIR®
A Verisk Business