Recommendations for Cordoning Earthquake-Damaged Buildings

FEMA P-2055-2 / September 2023

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Prepared by
APPLIED TECHNOLOGY COUNCIL
201 Redwood Shores Parkway, Suite 240
Redwood City, California 94065
www.ATCouncil.org

Prepared for
FEDERAL EMERGENCY MANAGEMENT AGENCY
Michael Mahoney, Project Officer (retired)
Christina Aronson, Task Monitor/Final Project Officer
Washington, D.C.

APPLIED TECHNOLOGY COUNCIL
Jon A. Heintz, Project Executive
Ayse Hortacsu, Project Manager

PROJECT TECHNICAL COMMITTEE
Stefanie Rae Arizabal
John Osteraas
Ines Pearce

WORKING GROUP MEMBERS
Francisco Galvis
Anne Hulsey
Amy Inhofer
Alan Puah
Tommy Sidebottom
Brenden Winder
Jack Wegleitner

PROJECT REVIEW PANEL
Michael Barker
Charles Eadie
David Hammond
Scott Nacheman
John O'Connell
Jonathan C. Siu
Mariam Yousuf

GRAPHICS ILLUSTRATOR
Sandesh Aher

Cover photo by Josh Marrow via EERI Learning from Earthquakes photo archive for 2014 Napa earthquake.

Preface

Following the passage of the *Disaster Recovery Reform Act* (DRRA) in October 2018, FEMA commenced work with the Applied Technology Council (ATC) under Task Order Contract HSFE60-12-D-0242 to develop a guidance document for structural integrity and livability of buildings after disasters, as requested by the 115th United States Congress (2017-2018). The resulting report, FEMA P-2055, *Post-disaster Building Safety Evaluation Guidance – Report on the Current State of Practice, including Recommendations Related to Structural and Nonstructural Safety and Habitability*, was published in 2019. In 2021, FEMA commenced work with ATC to develop a supplemental publication to FEMA P-2055 to provide guidance cordoning around damaged buildings.

The recommendations presented in this report draw from lessons learned and development included a literature review of building collapses and identified collapse and debris shadow areas, and interviews with emergency management professionals who were responsible for cordon management following two damaging earthquake events.

ATC is indebted to the leadership of the ATC-137-6 Cordon Project Technical Committee of Stefanie Rae Arizabal, John Osteraas, and Ines Pearce. The collapse shadow work was supported by Francisco Galvis, Amy Inhofer, Alan Puah, Tommy Sidebottom, and Jack Wegleitner who are members of the Structural Engineers Association of Northern California (SEAONC) Disaster Emergency Services (DES) committee and the ATC-137-6 Project Working Group. The considerations for cordon management were prepared with input from Brenden Winder, Charlie Eadie, and Anne Hulsey. The Project Review Panel, consisting of Michael Barker, David Hammond, Scott Nacheman, John O'Connell, Jon Siu, and Mariam Yousuf provided technical review, advice, and consultation at key stages of the work. Sandesh Aher prepared illustrations and sketches. The names and affiliations of all who contributed to this report are provided in the list of Project Participants.

ATC gratefully acknowledges Michael Mahoney (FEMA) who served as Project Officer on this and many other impactful publications over his 38-year career. Christina Aronson served as the FEMA Task Monitor for the project and also took over as the FEMA Project Officer. Kiran Khan (ATC) provided report production services.

Ayse Hortacsu
ATC Director of Projects

Jon A. Heintz
ATC Executive Director

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Chapter 1: Introduction

1.1 Background and Scope

Following a damaging earthquake event, it is common practice to place fencing, barricades, or cordons around damaged structures to provide safety against potential collapse or debris falling in an aftershock event or progressive collapse. However, as described in FEMA P-2055 report, Post-disaster Building Safety Evaluation Guidance – Report on the Current State of Practice, including Recommendations Related to Structural and Nonstructural Safety and Habitability, (FEMA, 2019), prepared in response to Section 1241(a) of the Disaster Recovery Reform Act (DRRA) of 2018, there is relatively limited technical guidance on how to determine the area to be cordoned. Although the 2019 document presents an existing document as best practice, it also highlights the need for further development of consensus guidelines. It is also recommended that additional guidance should include discussion about protection of not just the public way, but also adjacent buildings in potential danger from damaged structures. This report provides the initial step for gathering the information into a formal report in the hopes of discussion and future consensus approval.

The aim of this report is to present recommendations for determining the cordon area for individual damaged buildings. Considerations for managing the cordon area are also included.

This report was prepared with input from both structural engineering and emergency management professionals bringing forward lessons learned from past events. From the structural engineering perspective, the lessons learned include a review of collapsed buildings to determine potential collapse modes from visible damage for given structure types. A key assumption in the development of these guidelines is that the post-disaster building safety evaluator determining the cordon area would have the necessary certification and training meeting the criteria described in FEMA P-2055 report, consistent with the published resource types in FEMA National Incident Management System (NIMS) Resource Typing Library Tool. From the emergency planning perspective, lessons were shared directly from personnel who managed cordon areas for two major earthquakes.

This report focuses on building collapses caused by earthquakes and aftershocks. However, as illustrated by the recent apartment building collapses in Davenport, Iowa, and Miami, Florida, there are other causes of collapse for which cordoning guidance is necessary.

1.2 Target Audience

The recommendations in this document have been prepared for post-disaster building safety evaluators, as well as State and local emergency management departments and their planning staff, emergency operations center staff, and local Building Officials and building department staff.

1.3 Report Organization

This report is organized as follows:

- Chapter 2 presents the context of post-earthquake building safety cordons
- Chapter 3 presents recommendations for determining cordon area around an individual damaged building in terms of collapse and debris shadow distances
- Chapter 4 presents considerations for management of a cordon area around several damaged buildings
- Appendix A presents a summary of collapse shadow literature review

Lists of references and project participants are provided at the end of the report.

Chapter 2: Context of Cordons

2.1 Purpose of a Cordon

Aftershocks following a damaging earthquake may be strong enough to cause additional movement and collapse of buildings damaged by the main shock, potentially leading to more injuries and fatalities. For instance, the 1999 Armenia Earthquake in Colombia (M_w6.2) had an aftershock of M_w5.8 a few hours later, which caused the majority of the 1,230 fatalities from this sequence (Restrepo and Cowan, 2000). Similarly, the 2010 Canterbury Earthquake (M_w7.1) caused widespread damage in the South Island of New Zealand, but it was a large aftershock known as the 2011 Christchurch Earthquake (M_w6.2) that caused the bulk of the 185 fatalities from this sequence (Kam and Pampanin, 2011). Most recently, the 2023 Türkiye-Syria earthquake sequence consisted of an M_w7.8 mainshock and multiple aftershocks, including an M_w7.6 that occurred nine hours after the mainshock (GEER-EERI, 2023). This sequence caused more than 45,000 fatalities in Türkiye and more than 7,000 in Syria (International Medical Corps, 2023). Many of these fatalities are believed to be caused by building collapses during the aftershocks.

Mitigating injuries and fatalities in aftershocks requires a rapid disaster response strategy that includes creating safety cordons around damaged buildings at risk of collapse or generation of falling debris. The concept of a safety cordon is to evacuate the area surrounding at-risk buildings and restrict access to damaged and partially collapsed buildings. Cordon area determination relies on realistic engineering assessment of the stability and potential collapse of the building and debris, such as chimneys and parapets, falling from individual damaged buildings. Especially when the damaged buildings are tall (taller than 3 stories), cordon areas may overlap, requiring the evacuation of a larger area.

Goals and objectives are important to determine regardless if the cordon area is small and only for one building, or medium-sized with a couple of structures whose potential fall would impact other buildings, or whether it is a large cordon area established after a major earthquake that damages a central business district. The purpose of establishing a cordon area is to control public access, to prevent further casualties in a large aftershock, and isolate damaged buildings within a restricted perimeter where authorized personnel can repair, demolish, or rebuild without causing harm to people. There are high-level goals and themes that will facilitate setting up an effective cordon area as well as manage the recovery, mitigation, and rebuilding process. The basic themes of the cordon area are to be flexible, adaptable, improvisational, and keep the goals in mind while communicating well and often with stakeholders.

2.2 Existing Guidance

The key objective of a post-earthquake safety evaluation program is to speed recovery following an earthquake to get as many individuals as possible back into buildings deemed safe, while keeping individuals out of dangerous/hazardous buildings. Doing so is essential for community resilience. As described in FEMA P-2055, *Post-disaster Building Safety Evaluation Guidance* (FEMA, 2019), the process following earthquake events is well established and relies on the guidance provided in the ATC-20 series of documents, primarily ATC-20-1, *Field Manual: Procedures for Postearthquake Safety Evaluation of Buildings, Second Edition* (ATC, 2005).

The focus of the ATC-20-1 *Field Manual* and associated training is on evaluating the safety of individually damaged buildings and "tagging" those buildings with respect to their safety using green placards for lawful permitted use, yellow for restricted use, and red for prohibited occupancy. There is recognition of safety cordons in ATC-20-1 on small scale situations–chimneys and parapets–but only in the context of keeping people out of the area of potential collapse. Post-earthquake safety evaluators are advised to post a cordoned area with a red "area unsafe" placard to prevent further casualties in a large aftershock. Only with respect to landslide or rockfall issues is the possibility of danger from off-site debris considered, which can lead to red or yellow posting of an otherwise undamaged building; assessment of the threat posed by adjacent damaged buildings is not explicitly addressed. Consideration of hazards for adjacent buildings has been incorporated into post-earthquake safety evaluation training materials by the Structural Engineer Association of Northern California (SEAONC) and Structural Engineer Association of Washington (SEAW).

The 2012 training curriculum for the Safety Assessment Program (SAP) of the California Office of Emergency Services (CalOES) flagged the need for stopgap guidance for cordoning with recommendations for practices and implementation. In 2013, California Building Officials (CALBO) issued *Interim Guidance for Barricading, Cordoning, Emergency Evaluation and Stabilization of Buildings with Substantial Damage in Disasters* (2013). The CALBO *Interim Guidance* noted initial safe distances for barricades, indicating safe horizontal distances of up to 1.5 times (1.5x) the height of a building until "the nature and extent of building damage can be investigated, and shorter safe distances can be justified." This was reiterated in a subsequent bulletin posted by CALBO in 2015 following the Berkeley, California balcony collapse case. Additionally, the 2015 bulletin recommended potential cordons of entire blocks to avoid multiple collapse risks. However, the recommendations did not include explicit guidance on how shorter safe distances can be determined and the timeframes in which to do so.

The current practice of first responders, e.g., fire services, is to establish a cordon offset distance of 1.5x the building height. This conservative value is logical and acceptable for common fire emergencies, such as fires in low-rise buildings (i.e., three stories or less), as the cordon distance will in most cases be less than the width of a street and likely not affect more than the immediately adjacent buildings and only for a short period of time. However, utilizing the 1.5x rule as the cordon radius of taller earthquake damaged buildings would result in an exclusion zone as large as one-half mile in diameter (depending on the number of stories) that could be in place for an extended period of time, having an enormous impact to a densely populated urban area and hinder recovery. Figure 2-1 illustrates a simulated cordon with a radius of 1.5x building height around a 520 ft tall building in downtown San Francisco. Work by Hulsey et al. (2022) and Hulsey and Deierlein (2022) further identified that cordon delays are responsible for approximately one-third of the total downtime of office space for the first year after a simulated M_w7.2 earthquake event in the San Andreas fault.

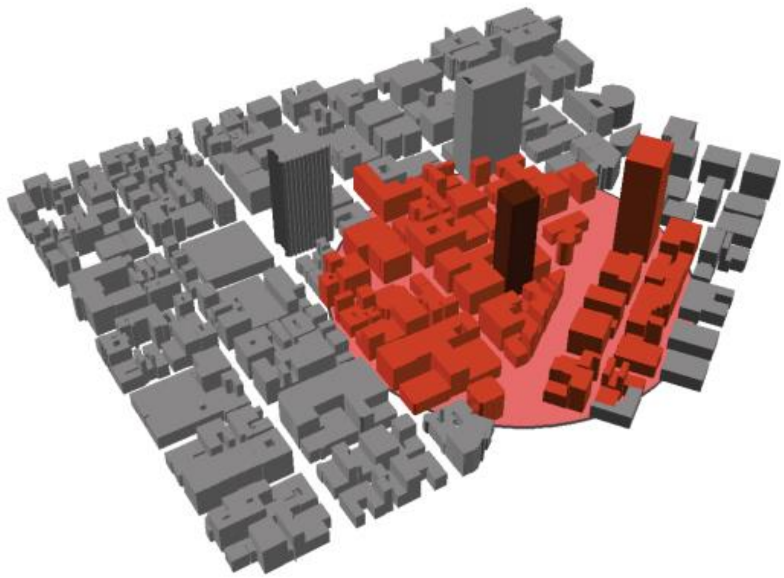


Figure 2-1 **Illustration of cordon around a 520 ft tall building at radius equal to 1.5 times the building height impacting downtown San Francisco following a simulated earthquake event (ATC, 2018).**

2.3 Cordons in Past Earthquakes

In the 1989 Loma Prieta earthquake (M_w6.9), the fatalities in Santa Cruz, California were caused by the collapse of the upper portion of the side wall of a three-story unreinforced masonry (URM) building through the roof of an adjacent single-story building. Following this, the authorities established two cordons around vulnerable areas: an outer cordon to prevent access to the general public but enable media, non-governmental organizations (NGO), and healthcare access, and an inner cordon with limited access only to authorized workers (Shepard et al., 1990).

Following the 2010 and 2011 Christchurch earthquakes, several damaged buildings resulted in the closure of the entire Central Business District (CBD) of Christchurch, New Zealand, for more than two years. The areal extent of the cordon was reduced over time to concentrate around areas where demolitions were taking place (Figure 2-2).

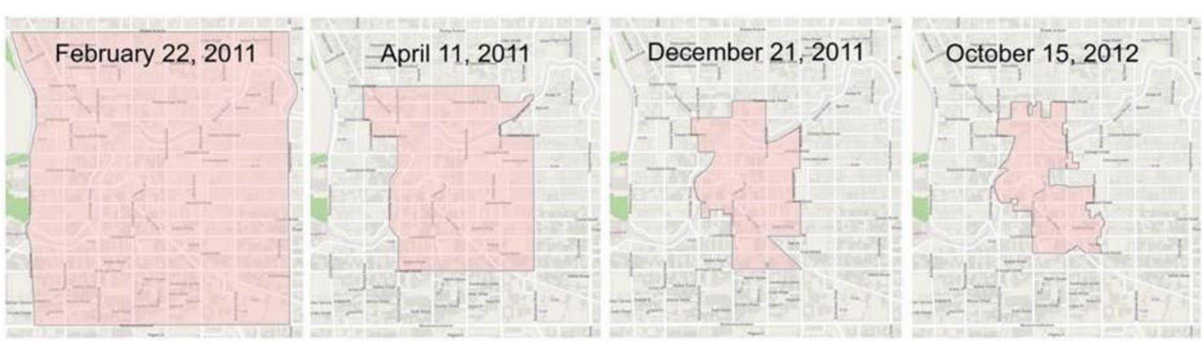


Figure 2-2 Evolution of the CBD cordon in Christchurch (Image from (Shrestha et al. 2022)).

Several follow-on studies have been conducted on the impacts of cordoning the CBD of Christchurch. Shrestha et al. (2022) document the inherent complexities of post-earthquake cordoning based on key informant interviews and conclude that while cordons are a powerful tool to restrict people's exposure to life safety risks, the complexities of cordon management increase as the duration of the cordon is extended. They conclude that cordons "should be avoided, if possible, through long term disaster risk reduction and resilience-building measures in high-risk urban environments."

Learning from New Zealand

Following the 2010-2011 earthquakes in New Zealand, the Canterbury Earthquake Recovery Authority (CERA), established the Earthquake Recovery Learning and Legacy Programme that produced a collection of 300 publicly available documents on recovery lessons and tools. The documents are available on the following website: https://quakestudies.canterbury.ac.nz/store/collection/22109

FEMA P-1024, *Performance of Buildings and Nonstructural Components in the 2014 South Napa Earthquake* (FEMA, 2015) documents the use of cordons and barricades immediately after the event and their transition to longer-term barricades. Chapter 12 of the report includes observations of initial barricades that were inadequately spaced from damaged buildings. For example, the building shown in Figure 2-3 is an unreinforced masonry (URM) building with an UNSAFE placard and significantly damaged masonry façades; however, the fence is located only several feet from the building, while the street remained fully operational.

Figure 2-3 A URM building with in UNSAFE placard with a very narrow cordon around it. (FEMA P-1024 Figure 12-1).

FEMA P-1024 also documents the impact of debris from a damaged unretrofitted URM building on adjacent structures. The building shown in Figure 2-4 was posted UNSAFE; the masonry wall on the south side of the building (right side of the figure) separated from the structure and portions of it fell into the neighboring parking lot, striking an unoccupied, parked car. In addition, stones fell off the back of the building into the alleyway that separates the building from several retrofitted URMs. As a result, four of the neighboring buildings were also posted UNSAFE due to the risk of collapsing masonry walls striking the buildings. The surrounding buildings were subsequently posted INSPECTED following the erection of wood barriers (Figure 2-5), allowing the occupants, in this case businesses, to resume operations.

Figure 2-4 Failure of URM south wall of URM building posted UNSAFE (FEMA P-1024 Figure 4-49, photo by Marko Schotanus).

2.4 Optimizing the Cordon Area

Cordoning an overly conservative area surrounding a damaged building or buildings reduces the probability of additional injuries or fatalities but impedes response and recovery actions. Thus, cordons may also increase the population displaced due to restricted access to occupiable buildings located within the cordon, as well as the ability for occupiable businesses within the cordon to resume operations. Additionally, the displaced population increases shelter needs, and the affected businesses are subjected to prolonged economic losses.

Figure 2-5 Protective barrier constructed over the rooftops of buildings to protect from falling brick. (FEMA P-1024, Figure 12-7)

The tension between the benefits and impacts of safety cordons demonstrates the need to optimize the areal extent and duration of cordons to ensure the effectiveness in protecting the public while avoiding unnecessary access restrictions to surrounding occupiable buildings. Thus, it is important to refine (typically reduce) the areal extent of the cordon over time as the stability of the at-risk building is better understood through ongoing monitoring and mitigation measures. Decrease in the probability of damaging aftershocks with time should also be considered. This is discussed in *Earthquake Aftershocks – Entering Damaged Buildings* (ATC, 1999).

Chapter 3: Recommendations for Determining Cordon Area

This chapter presents general guidance with respect to engineering assessment of the stability of damaged buildings and associated debris in determining the necessary cordon area. Summary recommendations are presented in Section 3.1. Additional discussion, photos of damaged buildings, and schematic illustrations are provided in Section 3.2.

The cordon area of a structure is determined by identifying distance, *D*, for both the potential collapse shadow of the building as a whole or significant portions thereof and the potential debris shadow for small components of the building. Figure 3-1 illustrates the units for defining shadow area.

Terminology

- **Collapse shadow:** Area to be cordoned to provide safety from potential collapse of building. Also termed **fall shadow.**
- **Debris shadow:** Area to be cordoned to provide safety from falling debris.

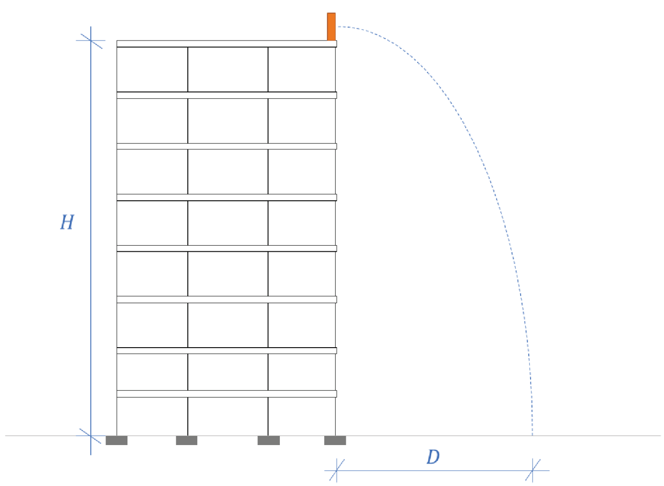


Figure 3-1 Schematic showing units for defining shadow area, *H* indicates building height and *D* indicates debris distance from face of building.

3.1 Recommendations

Cordoning of buildings should proceed in stages. Immediately following the damaging event, an initial emergency cordon distance can be established (Section 3.1.1). Determination of collapse shadow (Section 3.1.2) and debris shadow (Section 3.1.3) can be established following safety evaluation of individual buildings. Progressive collapse could occur for any of the collapse modes if gravity pulls down the whole building after additional damage from an aftershock occurs.

Following detailed evaluation and monitoring of damaged buildings, the cordon area can be reduced and eventually eliminated once shoring actions are completed, the stability of damaged structures relative to the intensity of potential aftershocks is established, and threat of additional damage/collapse is mitigated.

3.1.1 Initial Emergency Cordon Distance

The existing recommendation in CALBO's *Interim Guidance for Barricading, Cordoning, Emergency Evaluation and Stabilization of Buildings with Substantial Damage in Disasters* (CALBO, 2013) suggests providing an initial soft barrier at a distance of 1.5 times (1.5x) the building height. This distance is overly conservative, particularly for taller buildings, due to the likelihood of the cordon distance for tall buildings impairing the recovery of densely populated urban areas following a large seismic event.

Initial Emergency Cordon Distance

Immediately after the damaging event, armed only with the knowledge of obvious serious damage or visible lean of a building, an initial emergency cordon distance, *D*, equal to the height of the building above the significant damage or hinge point is prudent. However, greater resiliency can be obtained by refining the cordon area for taller damaged structures using the guidance presented herein.

3.1.2 Determination of Collapse Shadow Cordon Area

Identifying a collapse shadow area as a wedge of a full circle or limited rectangle rather than a default 360-degree radius will dramatically reduce the cordon and thus reduce the impact of the cordon on recovery. One of the key factors in the prediction of the collapse shadow is the identification of the potential collapse mode(s) of a damaged building. All buildings that suffer damage sufficient enough to pose a collapse hazard have an inherent "fatal flaw" that was exposed by the earthquake, such as unreinforced masonry, non-ductile concrete, a weak story, or a torsional irregularity. Potential collapse modes in an aftershock are a function of the nature and extent of structural damage, the structural configuration, and the stability of the damaged/partially collapsed building.

Terminology

- **P-delta forces:** The force of gravity on a leaning building generates a horizontal force in the direction of the lean that combines with lateral forces of aftershocks to push the building further out of plumb.
- **Azimuth:** Angular distance from a selected direction.

Table 3-1 relates the visible damage state of a building of a given structure type to a potential collapse mode. A collapse shadow cordon area is prescribed in accordance with the potential collapse mode. Section 3.2 presents a detailed description of each collapse mode.

Table 3-1 Recommendations for Determining Collapse Shadow Cordon Area

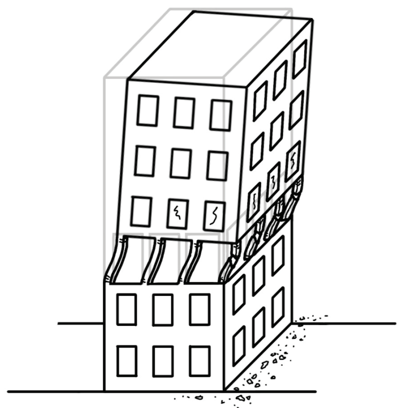
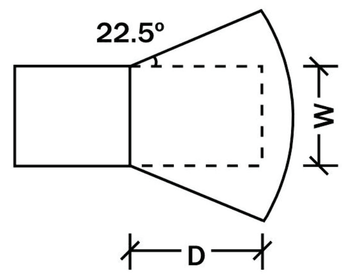
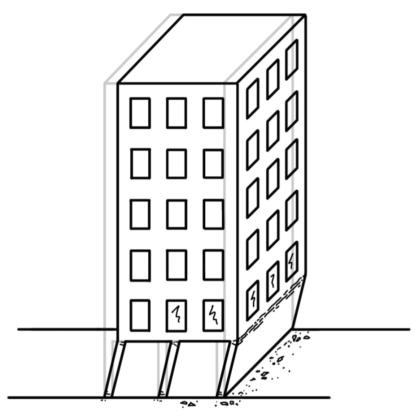
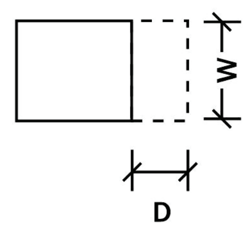
Structure Type	Visible Damage and Potential Collapse Mode	Collapse Shadow Cordon Area
Ductile concrete shear wall core, braced frame	 Visible monolithic lean; core and façade damage **See Section 3.2.1**: Monolithic Overturning	 45-degree circular wedge area, oriented along azimuth of tilt, with cordon distance *D*, where: w = building width *D* = height of building above hinge point
Frame (steel, concrete, wood)	 Story mechanism: Progressive collapse unlikely per engineering evaluation **See Section 3.2.2:** Story Mechanism	 Rectangular area, where: w = building width *D* = story height (in the direction of potential collapse)

Table 3-1 Recommendations for Determining Collapse Shadow Cordon Area (continued)

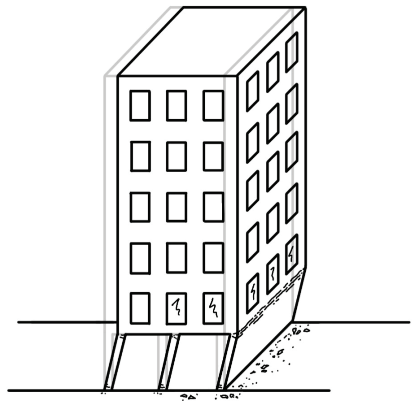
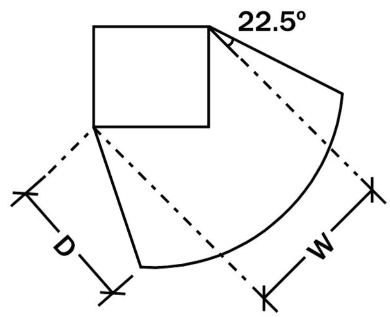
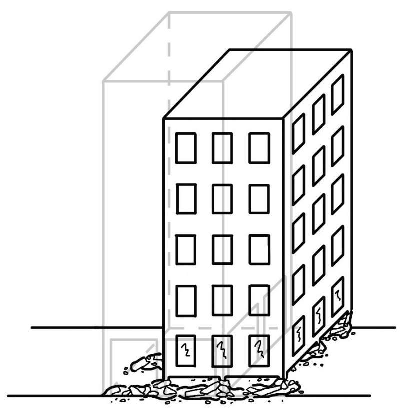
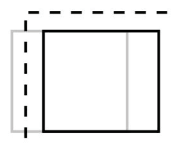
Structure Type	Visible Damage and Potential Collapse Mode	Collapse Shadow Cordon Area
Frame (steel, concrete, wood)	 Sidesway mechanism: Progressive collapse mechanism likely per engineering evaluation **See Section 3.2.2:** Story Mechanism	 45-degree circular wedge area, oriented along azimuth of tilt, with cordon distance *D*, where: *D* = height of building
Frame (steel, concrete, wood)	 Story mechanism: Stable **See Section 3.2.2**: Story Mechanism	 If stable, minimal collapse shadow.

Table 3-1 Recommendations for Determining Collapse Shadow Cordon Area (continued)

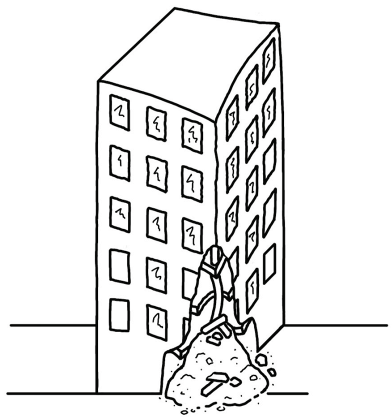
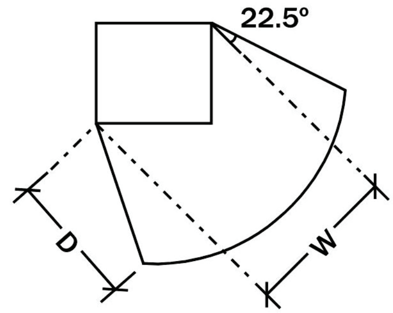
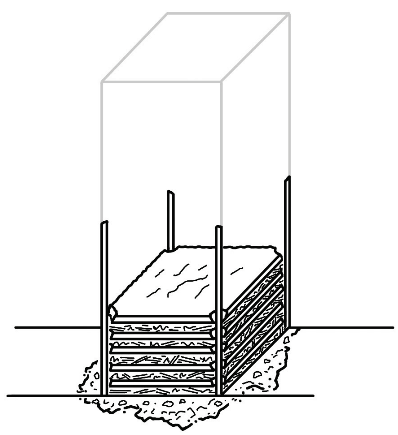
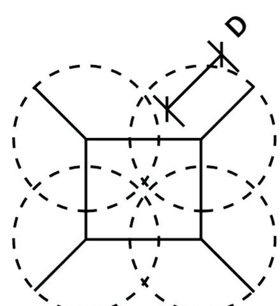
Structure Type	Visible Damage and Potential Collapse Mode	Collapse Shadow Cordon Area
Possible in all structural types with torsional irregularities	 Torsional damage **See Section 3.2.3** Torsion	 45-degree circular wedge area, oriented along azimuth of tilt, with a cordon distance *D*, where: *w* = width of building measured from opposing corners *D* = height of building above hinge point
Concrete flat slab with weak slab-column connections	 Pancake collapse, slabs collapsed; columns, walls, and/or core unbraced; monolithic overturning of remaining vertical elements **See Section 3.2.4** Pancake	 Circular area, with radius *D* where: *D* = height of unsupported vertical elements, measured horizontally from location of unsupported vertical element

Table 3-1 Recommendations for Determining Collapse Shadow Cordon Area (continued)

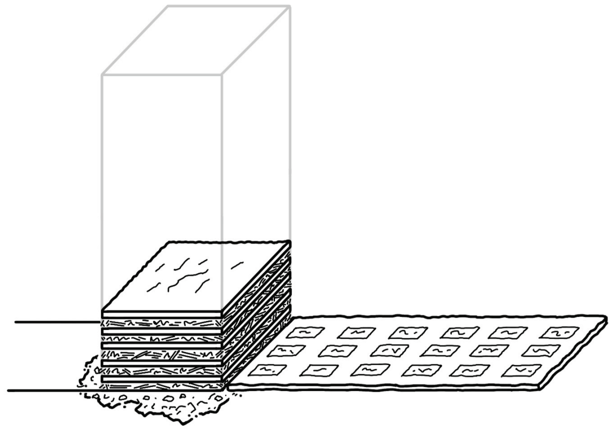
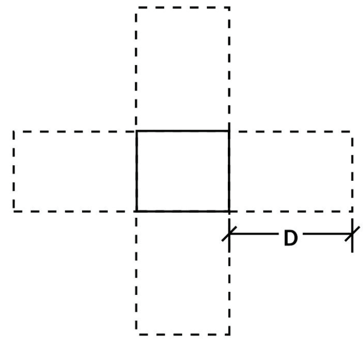
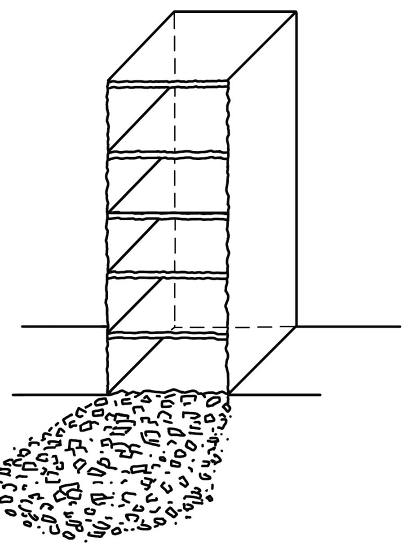
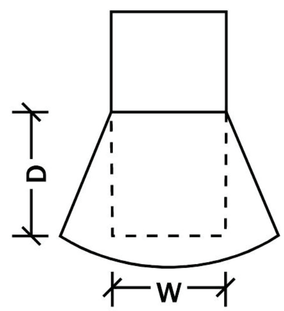
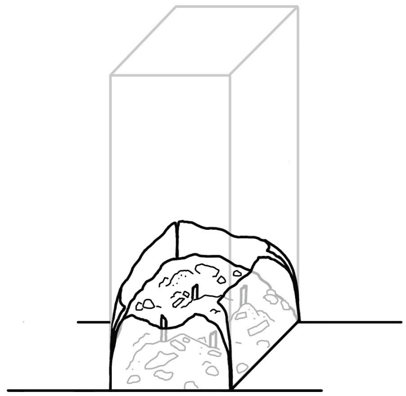
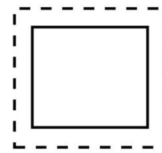
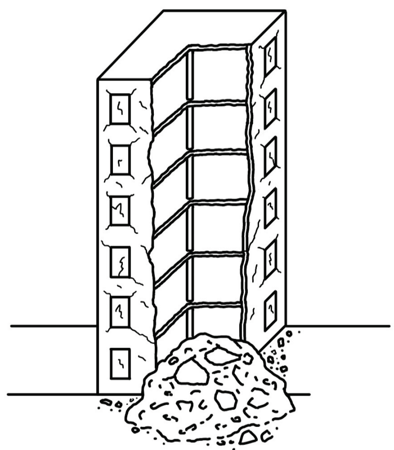
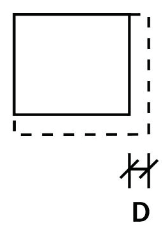
Structure Type	Visible Damage and Potential Collapse Mode	Collapse Shadow Cordon Area
Concrete tilt-up or other façade panel systems	 Damage to connection between horizontal diaphragms and perimeter wall panels **See Section 3.2.5** Wall Fall	 Rectangular area extending from each affected wall distance *D*, where: *D* = height of wall panels
Masonry walls	 Damage to connection between horizontal diaphragms and masonry façade **See Section 3.2.5** Wall Fall	 45-degree circular wedge area, oriented along azimuth of tilt, with cordon distance *D*, where: *D* = ½ height of wall panels. For shorter buildings (up to 4 stories) *D* can be approximated as the height of the building.

Table 3-1 Recommendations for Determining Collapse Shadow Cordon Area (continued)

Structure Type	Visible Damage and Potential Collapse Mode	Collapse Shadow Cordon Area
Perimeter load bearing structure	 Interior column failures with inward perimeter structure tilt **See Section 3.2.6** Implosion	 Minimal collapse shadow
Non-engineered masonry, adobe, concrete block, or precast buildings	 Partial collapse of the building as a rubble pile, or wide spread damage on most vertical supporting members **See Section 3.2.7** Rubble Pile	 Rectangular area extending from each damaged wall at distance *D*, where: $D = 0.15\ H$ (debris shadow)

3.1.3 Determination of Debris Shadow Cordon Area

A leaning damaged building can present a significant threat that demands careful assessment; however, a more widespread yet subtle threat in aftershocks is the shedding of debris from damaged buildings. This may even occur in buildings that pose no threat of collapse. For purposes of this discussion, the fall of anything other than the overall collapse of the building structure, or a significant portion of the building structure is considered debris.

The most common types of falling debris are small debris, such as masonry and glass, from building façades. Common examples of larger debris include parapets, chimneys, infill masonry walls, curtain walls, or cladding. The fall of small debris poses only a hazard to people and vehicles and can be arrested by a building roof or pedestrian protection. Larger debris have sufficient mass to damage adjacent buildings, such as collapsing the roof of a shorter building.

Falling debris from building façades is a common concern independent of earthquakes as demonstrated by the large number of temporary protective sidewalk covers that have been installed in major cities like New York City and Chicago.

Small debris shadow cordons should be established for those buildings that sustain serious visible damage to the building façade and/or shed debris onto surfaces accessible to pedestrian or vehicular traffic. If larger falling debris is a concern, the debris shadow cordon area should include adjacent structures as well. Debris shadow cordons should remain until the debris hazard is mitigated via temporary protection, such as removal or restraint of damaged elements; the structure is demonstrated to lack debris shedding in aftershocks; or, if the threat of aftershocks subsides with the passage of time.

Figure 3-2 illustrates estimation of falling debris trajectory in terms of a small initial horizontal velocity, v_0, of the falling debris from the roof level of the building, the parabolic trajectory of the falling debris, and the resulting debris shadow with a cordon distance of D.

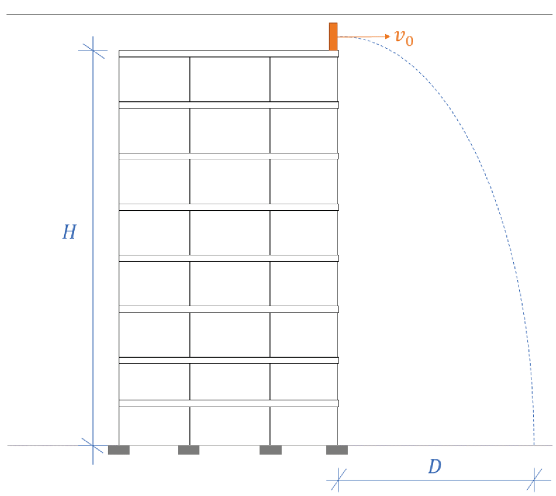


Figure 3-2 Schematic concept for falling debris analysis.

Figure 3-3 presents an estimate of the maximum horizontal distance for determining falling debris shadow from the building, R, as a function of building height, H, determined based on the following: The initial horizontal velocity is approximated as the peak floor acceleration divided by the natural frequency of the first mode of the building, both determined in accordance with ASCE/SEI 7-22. For example, for a building with *H* = 100 ft, the debris shadow distance, *D*, is recommended as 12 ft.

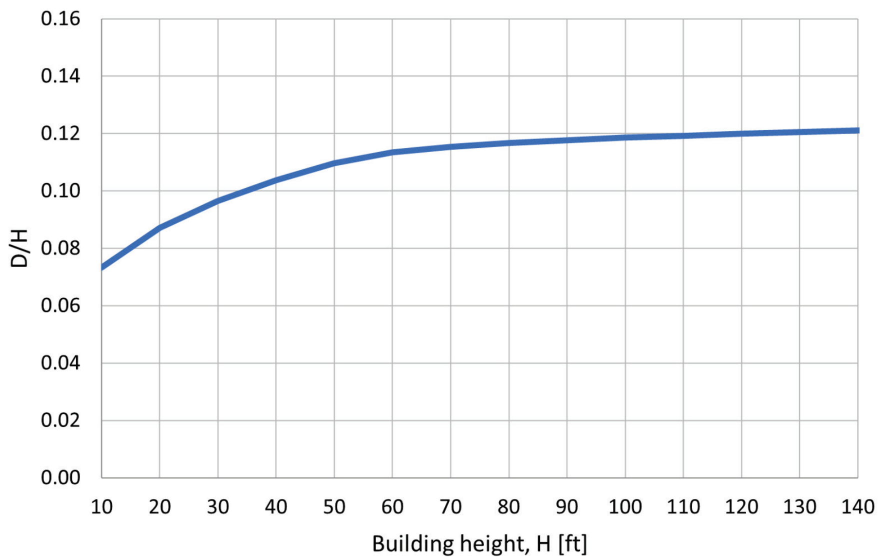


Figure 3-3 Determination of debris shadow as a function of building height.

3.2 Building Collapse Modes

The recommendations in this section are based on a literature review of information on damaged buildings and the collapse or debris shadow area around them found in the literature. It should be noted that the current literature is very limited. Appendix A presents a summary of the literature review and a database of collapse buildings reviewed.

3.2.1 Monolithic Overturning

The potential collapse shadow associated with monolithic overturning is the most troublesome for an earthquake-damaged urban area. Not only does the potential collapse shadow impact a large area (significantly with tall buildings), but the potential energy is large, meaning the collapse can cause considerable damage to adjacent buildings.

The monolithic overturning collapse mode is best illustrated by the felling of a tree (Figure 3-4): the trunk of a tree is notched facing the direction of the intended fall (thereby removing compressive strength on that side of the tree) while the back side of the tree is crosscut (thereby removing tensile strength on the backside of the tree). These cuts effectively create a hinge at the base of the tree, allowing the force of gravity to topple the tree. The collapse shadow of the tree is equivalent to the solar shadow of a tree with the sun 45 degrees above the horizon; i.e., the shadow has the width and height of the tree centered on the stump and oriented at the azimuth defined by the location of the undercut.

Monolithic overturning can occur as a result of failures in the structure or failure of the foundational soils (or as a result of soil liquefaction). Continuing the tree analogy, monolithic overturning due to structural failure occurs when the columns or foundation on the front side *(for purposes of this discussion of collapse mode, "front side" refers to the side of the building facing the fall shadow)* of a building lose their capacity to resist gravity forces and/or the columns or foundation on the backside lose their tensile capacity. Taller buildings that have sufficient shear and flexural strength in the toppling section to maintain monolithic structural integrity in a collapse, such as frames with reinforced infill masonry, braced frames, and ductile core structural systems, can experience monolithic overturning. The collapse shadow of the building will be the width and height of the building above the hinge point, centered on the front face of the building at an azimuth perpendicular to the front face.

Figure 3-4 Tree notched to define direction of fall (image from public domain).

Examples of monolithic overturning identified in the literature review include:

- Tilting of apartment buildings due to liquefaction in 1964 Niigata Japan earthquake (Figure 3-5)
- One of the five towers of the Piño Suarez building collapsed in the 1985 Mexico City Earthquake as a result of column buckling in the fourth story, crushing an adjacent tower (Figure 3-6)

- One wing of the Royal Palm Resort partially collapsed in the 1993 Guam Earthquake due to shear failure of second story columns along the front face resulting in significant residual lean (Figure 3-7)
- The Weiguan Jinlong Building overturned during the 2016 Southern Taiwan Earthquake (Figure 3-8)
- Multiple residential buildings in Gölbaşı (Türkiye) were affected by liquefaction after the 2023 Kahramanmaraş earthquake sequence (Figure 3-9)

Figure 3-5 Tilting of apartment buildings due to liquefaction in 1964 Niigata Japan earthquake (Photo Credit: NISEE).

All of the monolithic overturning collapses identified in the literature review occurred during the main shock; literature review conducted did not identify buildings that collapsed monolithically in an aftershock. This is not surprising – if a structure survives the dynamic forces of the main shock and forces associated with partial collapse, without toppling, the damaged structure has established a stable equilibrium during the main shock. Further damage and movement will likely require forces comparable to those of the main shock. Therefore, buildings that survive the main shock without residual lean are highly unlikely to sustain a monolithic overturning failure in an aftershock. The Piño Suarez building (Figure 3-6), consisting of three identical 22-story towers, provides an excellent case study (albeit for a single earthquake). During the main shock, one of the three 22-story towers collapsed, while the remaining two towers sustained similar column buckling and resulting visible residual lean; however, the two remaining towers did not collapse in the aftershocks.

It is noted that few buildings are perfect – many tall buildings may have some benign long-term lean, which does not compromise their safety.

Figure 3-6 Piño Suarez towers before and after the 1985 Mexico City Earthquake (from *Reports on the Damage Investigation of the 1985 Mexico Earthquake*, Architectural Institute of Japan, 1987; upper image photoshopped by Exponent to include all five original towers).

Figure 3-7 Partial collapse of Royal Palm Resort in 1993 Guam Earthquake due to shear failure of captive columns in soft story. Note undamaged adjacent structure along right edge of photo (Exponent/Luth).

Figure 3-8 Weiguan Jinlong building before and after the 2016 Southern Taiwan Earthquake (before: from Zaldivar et al.; after: from Xinhua via SCMP).

Figure 3-9 Residential buildings in Gölbaşı in the 2023 Kahramanmaraş Earthquake (Türkiye) (Photo Credit: Thornton Tomasetti/Galvis).

For the buildings with this collapse mode identified in the literature review, the collapse shadow was well defined with a distance equal to the height of the toppled portion (as measured from the front face of the building) and a width equal to the width of the building. The azimuth of the collapse shadow was always nominally perpendicular to the front face of the building. While a non-perpendicular collapse shadow azimuth is possible (e.g., a diagonal azimuth), no such cases were identified in the literature review.

Taller buildings with an overall visible lean should be further evaluated to assess the potential for collapse in aftershocks. Factors to consider when assessing the potential for monolithic overturning in an aftershock include the following:

- The degree of residual lean – P-delta forces increase with increasing residual lean.
- The nature and extent of damage that caused the residual lean.
- The stability of the damaged structure:
    - whether it has come to rest in a stable configuration, such as the Royal Palm Resort (Figure 3-7)
    - whether the angle of tilt increases during aftershocks or remains stable
    - whether the leaning portion of the building has sufficient structural integrity to remain intact as it topples
- The probability of a damaging aftershock, which decreases with time.

The same rationale applies to portions of buildings that may fall as rigid bodies, such as reinforced columns and shear walls protruding from partial collapses as shown in Figure 3-10, as well as reinforced chimneys.

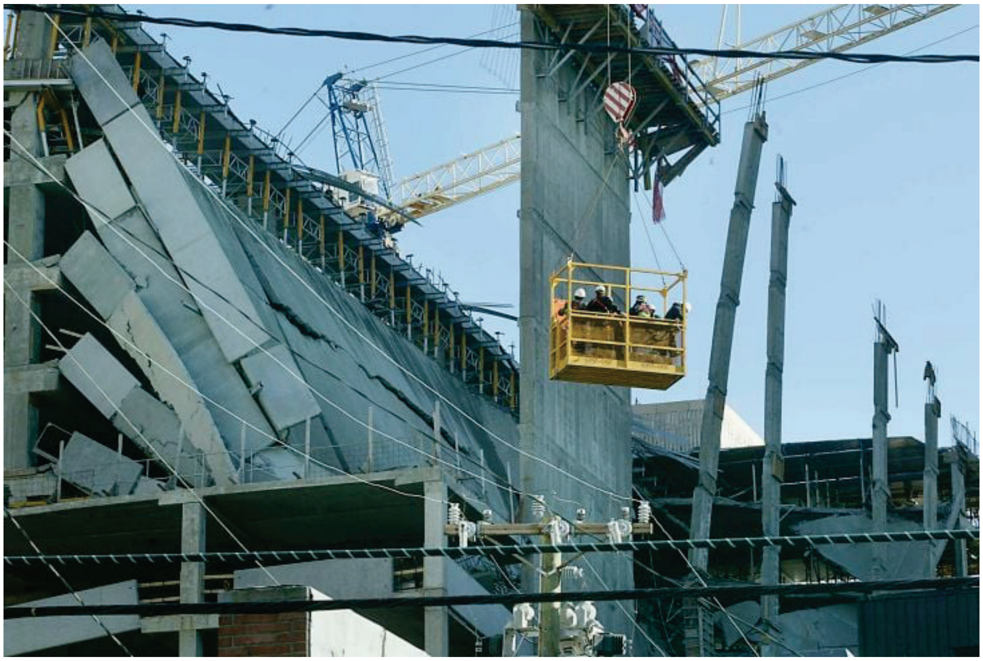


Figure 3-10 Laterally unsupported columns and shear wall following partial collapse of Tropicana Casino parking garage during construction in Atlantic City, New Jersey, 2003.

Cordon Area for Monolithic Overturning Collapse Mode

For a building with a visible lean that developed during the earthquake, a cordon area determined by a 45-degree wedge with a radius (measured from the front face of the building) equal to the height of the building above the hinge point would be prudent. Figure 3-10 illustrates the potential collapse mode and Figure 3-11 presents a plan view of the collapse shadow.

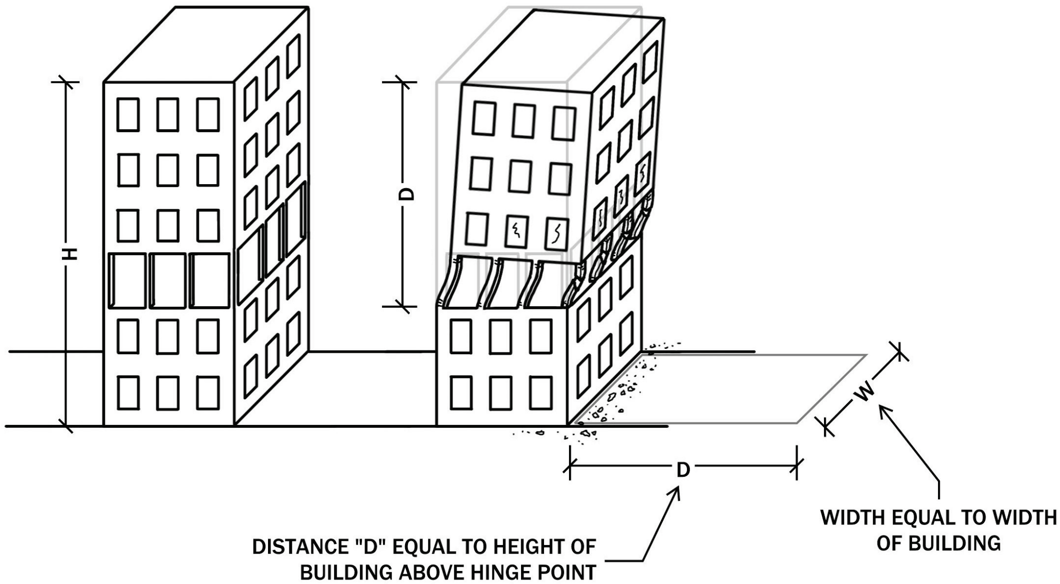


Figure 3-11 Illustration of monolithic overturning collapse mode.

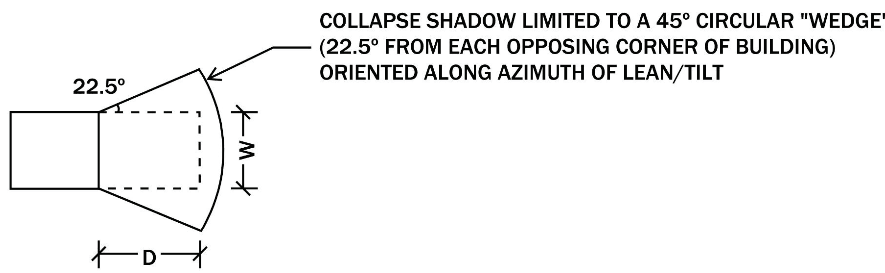


Figure 3-12 Plan sketch of recommended cordon shadow for monolithic overturning collapse mode.

3.2.2 Story Mechanism

The sidesway collapse mode is characterized by the leaning/tilting of all columns in a single story. A story mechanism may occur in any story, but most commonly occurs in the first story, where the lateral strength/stiffness of that story is less than the stories above; i.e., a weak or soft story This was particularly observed in the Marina District of San Francisco following the 1989 Loma Prieta Earthquake, as illustrated in Figure 3-13.

Figure 3-13 San Francsico soft story collapse showing leaning story after main shock (upper photo) and story collapse in aftershock (lower photo). Image from ATC-20 training materials.

The force of gravity on the portion of the building above the weak or soft story creates an additional destabilizing force (p-delta force), proportional to the degree of lean in the leaning story that can drive the story to collapse. A leaning story may have come to rest in a stable or marginally stable state after an earthquake. Aftershocks will disrupt the marginally stable state, increasing the tilt until the destabilizing force exceeds the remaining lateral strength of the weak or soft story and causes collapse.

If there are multiple weak or soft stories in a building, a cascading story collapse can occur where each weak or soft story collapses one story further away from its original position than the weak or soft story below. As shown in Figure 3-13, the second story of the building to the left is leaning and could be vulnerable to collapse in an aftershock. It is this type of potential cascading collapse that poses the greatest threat and should receive a detailed engineering evaluation to inform cordoning decisions. It is important to note that the vast majority of weak or soft story collapses occur during the main shock.

Examples of buildings with soft story damage include:

- Many low-rise, wood frame apartment buildings in the Marina District of San Francisco, California with garages in the first story were damaged in the 1989 Loma Prieta Earthquake (Figure 3-13). Some collapsed into the street in a stable configuration. Some buildings sustained residual lean, two of which collapsed in an aftershock (Figure 3-13), this is the only instance of aftershock-induced weak or soft story collapse that was identified in the literature review. Buildings that did not collapse were temporarily braced against further movement and subsequently repaired.

- Olive View Hospital in San Fernando, California, was a four-story, reinforced concrete frame building that was relatively rigid above the first story. In the 1971 San Fernando Earthquake, the first-story columns were extensively damaged, and the first story sustained a residual lean; however, the building did not collapse during aftershocks. Because the columns were well reinforced with steel hoops, they retained sufficient strength in their damaged condition to support the weight of the building and prevent collapse.

- Weak or soft story collapses occurred in the mid-stories of several buildings in the 1995 Kobe Earthquake (Japan), as shown in Figures 3-14 and 3-15.

- The first story of several buildings in Mexico City, Mexico collapsed after the 2017 Puebla-Morelos Earthquake, leaving the remaining portions of the buildings stable (albeit extensively damaged) against further collapse, as shown in the example of Figure 3-16. For the buildings identified in the literature review, the collapse shadow was well defined as a rectangle with a length equal to the height of the weak or soft story and width equal to the building width along the “front” side of the building. For buildings with potential cascading story failures, the length of the collapse shadow could extend to a length equal to the height of the building above the weak or soft story.

Most commonly, the seismic damage in buildings of this collapse type is concentrated in the weak or soft story, leaving the remaining stories relatively unscathed (such as the white building in Figure 3-13). In such a case, if collapse does occur, the remaining portion of the structure apart from the weak or soft story generally comes to rest in a stable, relatively undamaged condition, as shown in Figures 3-14 and 3-15. A building with a collapsed weak or soft story (such as the white building in Figure 3-13) is arguably more stable than the undamaged building in its original state. This is because the ‘fatal flaw” – the weak or soft story, has been eliminated, leaving the remaining portion of the building potentially more stable (due to removal of irregularities) than the original building prior to the weak or soft story collapse. Therefore, in the immediate aftermath of an earthquake, cordoning efforts should focus on buildings with residual story lean. A building that remains plumb, albeit with significant damage concentrated in a collapsed single story is unlikely to fail in a sidesway mode in an aftershock.

Figure 3-14 Third story collapse of 10-story office building in 1995 Kobe Earthquake in Japan (Source: Exponent/Osteraas).

Taller buildings with a visible residual lean in any story should be further evaluated by an engineer to assess the potential for cascading collapse of multiple stories in an aftershock. Factors to consider when assessing the potential for cascading collapse of multiple stories in an aftershock include the following:

- Degree of residual lean – P-delta forces increase with increasing residual lean
- Residual strength of the story considering the nature and extent of damage that caused the residual lean
- Stability of the damaged structure
    - whether it has come to rest in a stable configuration
    - whether the angle of tilt increases during aftershocks or remains stable
    - whether the portion of the building above the weak or soft story has sufficient structural integrity to remain intact in the event of collapse of the leaning story

- Probability of a damaging aftershock, which decreases with time

Figure 3-15 Sixth story collapse of 8-story Kobe City Hall Annex building in 1995 Kobe Earthquake in Japan (Source: EERI Slides on the Hyogo-Ken Nanbu (Kobe) Earthquake of January 17, 1995).

Figure 3-16 Residential building before and after 2017 Puebla-Morelos Earthquake (Galvis et al. 2021).

Cordon Area for Story Mechanism Collapse Mode

For a building with a visible story lean that developed during the main shock, immediate cordoning of an area defined as a rectangle with the width equal to the front face of the building and length (measured from the front face of the building) equal to the height of the building above the floor of the weak or soft story would be prudent. Figure 3-17 illustrates the potential collapse mode.

Following an engineering evaluation, if progressive collapse is unlikely, the cordon area can be reduced to equal the height of the damaged story. Figure 3-18 presents a plan view of the collapse shadow for this condition. If progressive collapse is likely, refer to guidance for monolithic collapse in Section 3.2.1. Figure 3-19 presents a plan view of the collapse shadow for this condition.

If the collapse occurs only in a weak story with no visible story lean for the structure remaining above, minimal collapse cordon is necessary. Figure 3-20 illustrates the potential collapse mode and Figure 3-21 presents a plan view of the collapse shadow.

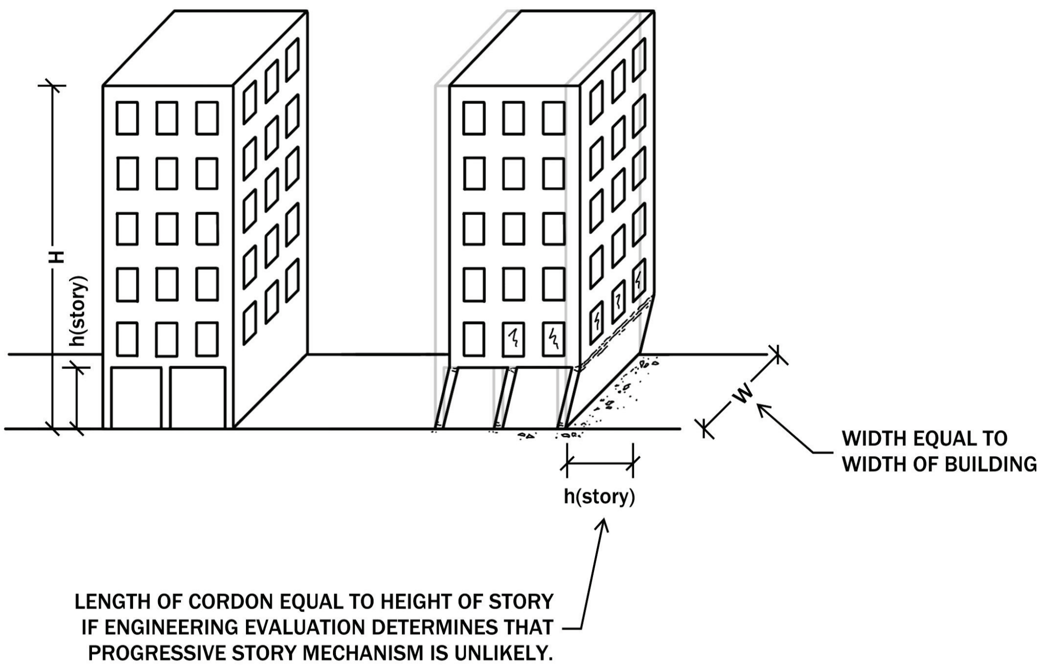


Figure 3-17 Illustration of story mechanism collapse mode.

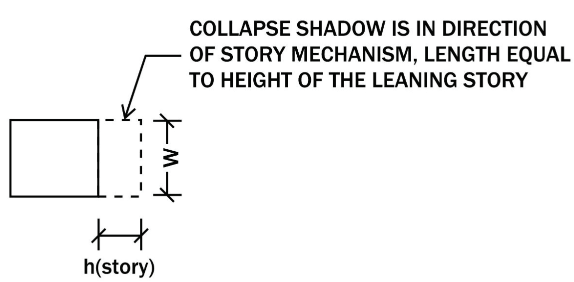


Figure 3-18 Plan sketch of recommended cordon shadow for story mechanism collapse mode, where progressive collapse is unlikely.

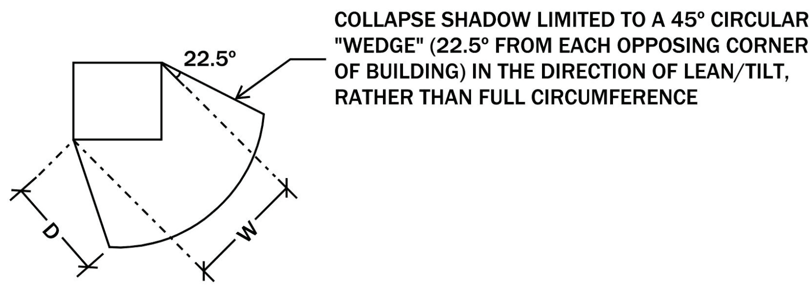


Figure 3-19 Plan sketch of recommended cordon shadow for story mechanism collapse mode where progressive collapse is likely.

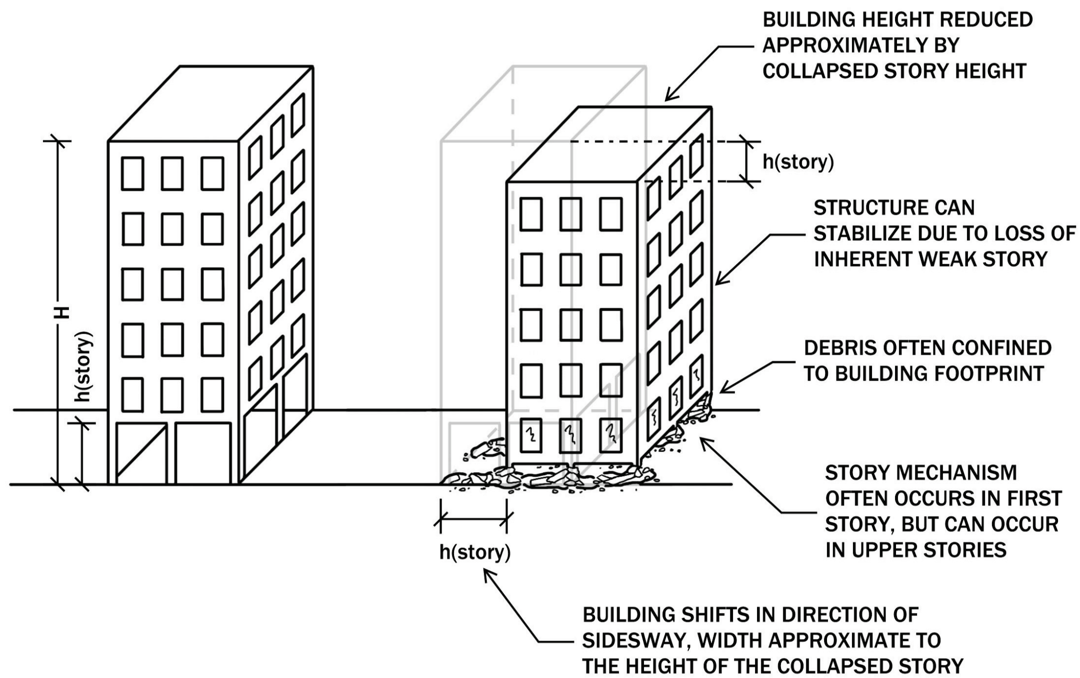


Figure 3-20 Illustration of story mechanism collapse mode for stable condition.

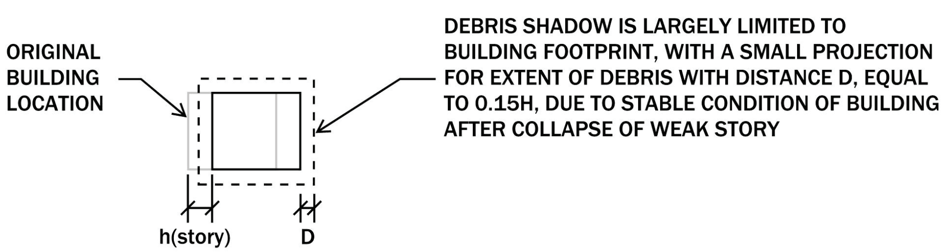


Figure 3-21 Plan sketch of recommended cordon shadow for story mechanism collapse mode, stable condition.

3.2.3 Torsion

Buildings with plan irregularities, such as a solid wall on one side and open frames on the other three sides, or corner buildings with two open street facing sides and solid walls on the remaining two sides, will have a twisting or torsional response to earthquake ground motions that will cause more extensive damage to the columns along one side or near one corner of the building- often resulting is a diagonal tilt, as shown in Figure 3-22. The direction of collapse of a building with torsional damage will be in the direction of the tilt towards the area with the more extensive damage to columns on the open faces. The potential collapse mode may be monolithic overturning for taller buildings or tend towards a rubble pile for shorter buildings.

This collapse mode caused many partial collapses of corner buildings in the 1995 Kobe Earthquake in Japan (Figure 3-22) and in the 2010 Maule Earthquake in Chile (Figure 3-22).

Figure 3-22 Corner building collapse in 1995 Kobe Earthquake in Japan (Exponent/Osteraas).

Figure 3-23 Story collapses at the 10th, 14th, and 18th floors of the Torre O'Higgins Building in 2010 Maule, Chile Earthquake (from Dragovich & Harris NEHRP presentation).

Cordon Area for Torsion Collapse Mode

For buildings with a height less than their width, collapse can be expected to remain largely within the footprint of the building, requiring a minimal cordon area.

For taller buildings, the collapse shadow may extend in the direction of the building tilt as far as the height of the building, above the most severely damaged story, measured from the back wall(s) of the building or center of an eccentric core. Figure 3-24 illustrates the potential collapse mode and Figure 3-25 presents a plan view of the collapse shadow.

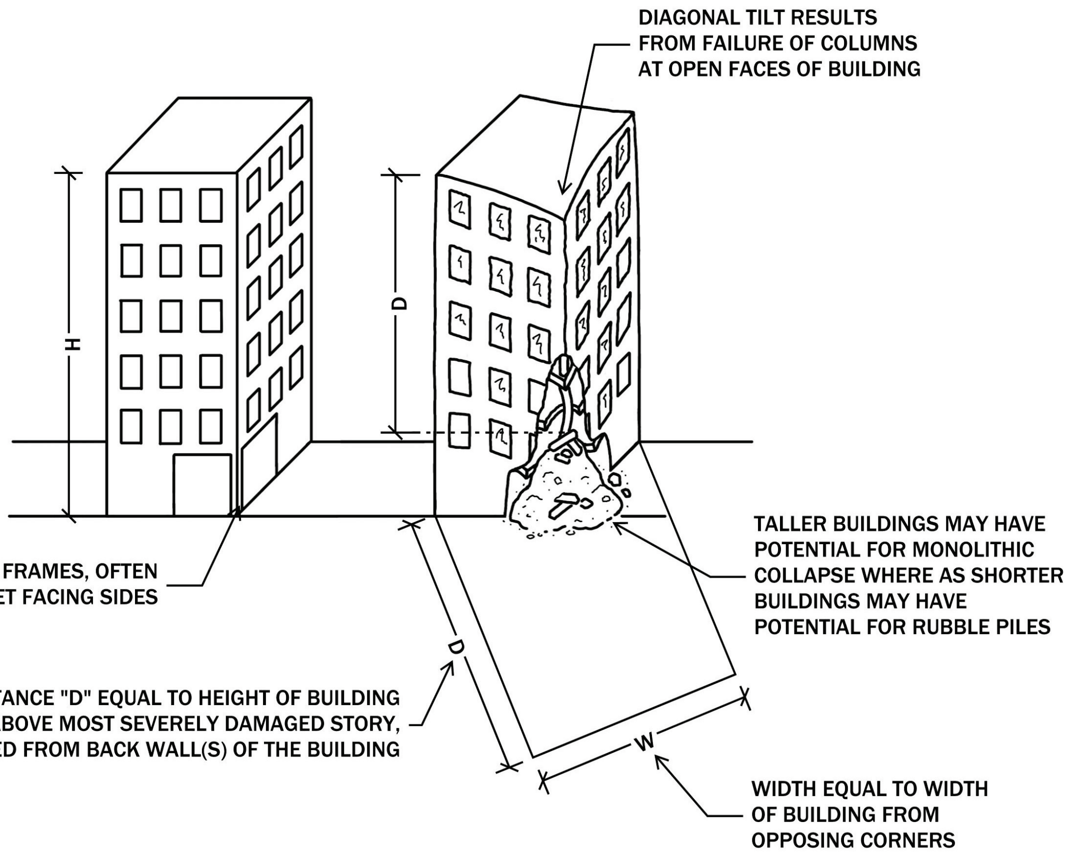


Figure 3-24 Illustration of torsion collapse mode.

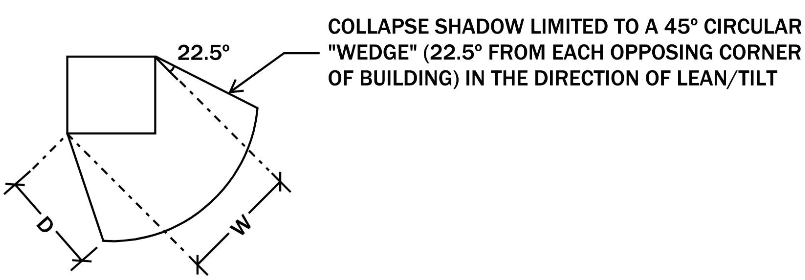


Figure 3-25 Plan sketch of recommended cordon shadow for torsion collapse mode.

3.2.4 Pancake

Buildings with flat concrete floor plates and fragile slab-to-column connections will typically collapse in a pancake fashion, where the floor slabs slide down the columns and generally end up stacked one upon the next at the ground level. Pancake collapses tend to be all or nothing. In the event of a partial pancake collapse, the remaining portion of the structure may be vulnerable to collapse in an aftershock- although, the collapsed slabs should generally stay within the building footprint. Remaining columns extending above the collapsed slabs may pose a collapse hazard outside the building footprint.

Examples of buildings that sustained pancake collapses include:

- Macy's department store floor collapse in the 1994 Northridge Earthquake (Figure 3-26)
- Collapse of L'ambiance Plaza in Bridgeport, Connecticut in 1987 (Figure 3-27). Note, this collapse occurred during the construction of the building.

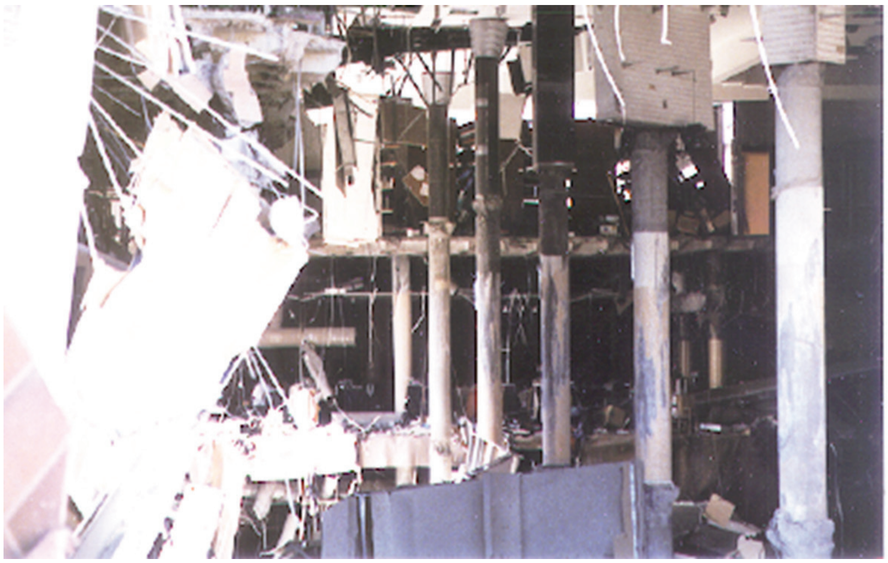


Figure 3-26 Punching shear failure of floor slabs in Macy's store in Los Angeles, California in the 1994 Northridge Earthquake (Exponent/Osteraas).

Figure 3-27 L'Ambiance Plaza collapse during construction, Bridgeport, Connecticut, 1987 (Exponent/Peraza).

Cordon Area for Pancake Collapse Mode

Cordoning is generally only necessary with respect to vertical elements (columns and shear walls) that protrude from the collapsed slabs due to the hazardous potential for a monolithic collapse outside the building footprint. Figure 3-28 illustrates the potential collapse mode and Figure 3-29 presents a plan view of the collapse shadow.

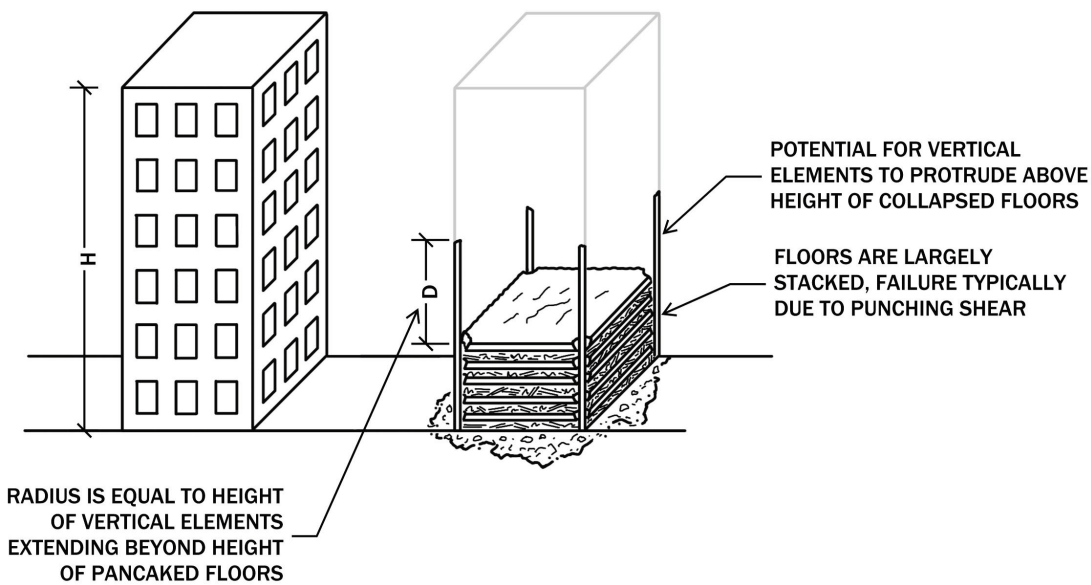


Figure 3-28 Illustration of pancake collapse mode.

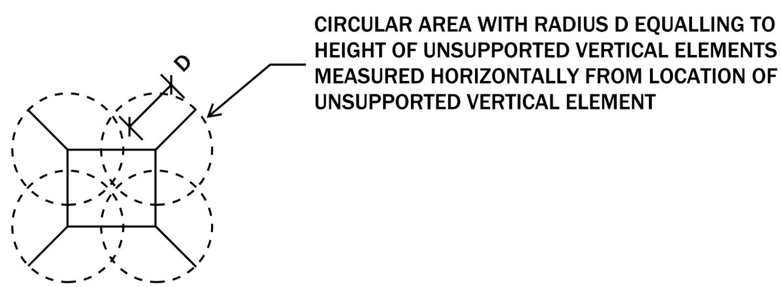


Figure 3-29 Plan sketch of recommended cordon shadow for pancake collapse mode.

3.2.5 Wall Fall

The wall fall collapse mode occurs in taller buildings that shed their skin as the structure within collapses in a pancake fashion. The prime example of this collapse mode was observed with the World Trade Center towers WTC1 and WTC2, where the perimeter column “trees” and the floor slabs had a mutually beneficial relationship. As the floor slabs collapsed in a pancake mode, the perimeter column trees fell away from the building in a partial monolithic collapse fashion, crushing or impaling surrounding buildings. The azimuth of these failure shadows was perpendicular to each face of each tower, thus eight debris lobes in total; four for each building. The maximum length of these lobes-measured from the face of the building, was approximately 700 feet relative to an overall building height of 1,386 feet (110 stories); about 50% of the building height. This type of collapse can occur for curtain walls, reinforced masonry walls, or infill masonry where the connections between the curtain wall/masonry and the structure are inadequate or damaged in an earthquake.

The tilt-down collapse mode derives its name from the tilt-up construction process, where reinforced concrete panels are cast horizontally on the building floor slab then tilted up into position around the building perimeter. The walls have a mutually beneficial relationship with the upper floors and roof diaphragm: the walls carry the gravity loads and in-plane seismic loads from the floors and roof, while the floors and roof hold the wall panels in a vertical position out of plane. When the connection between the walls and roof/floors is lost, the wall panels fall away from the building and the roof/floors collapse (Figures 3-30 and 3-31).

Figure 3-30 Warehouse in Kahramanmaraş after the 2023 Kahramanmaraş Earthquake (Türkiye). (Photo Credit: Thornton Tomasetti/Galvis).

Tilt-up construction is only used for low-rise buildings (1-4 stories). The collapse shadow of buildings with tilt-up wall panels is always a rectangle perpendicular to the building wall, with length equal to the panel height, starting at the face of the building, and width equal to the width of the collapsed wall

Figure 3-31 Collapse of tilt-up walls in the 2010 Maule, Chile Earthquake (ATC-20 training slides).

Cordon Area for Wall Fall Collapse Modes

Cordoning around buildings is necessary in cases where the connection between walls and roof/floors has failed or has been compromised, or where panels are tilted out of plumb but not collapsed.

Figure 3-32 illustrates the potential collapse mode for a building with an unreinforced masonry wall and Figure 3-33 presents a plan view of the collapse shadow.

Figure 3-34 illustrates the potential collapse mode for a building with tilt-up walls and Figure 3-35 presents a plan view of the collapse shadow.

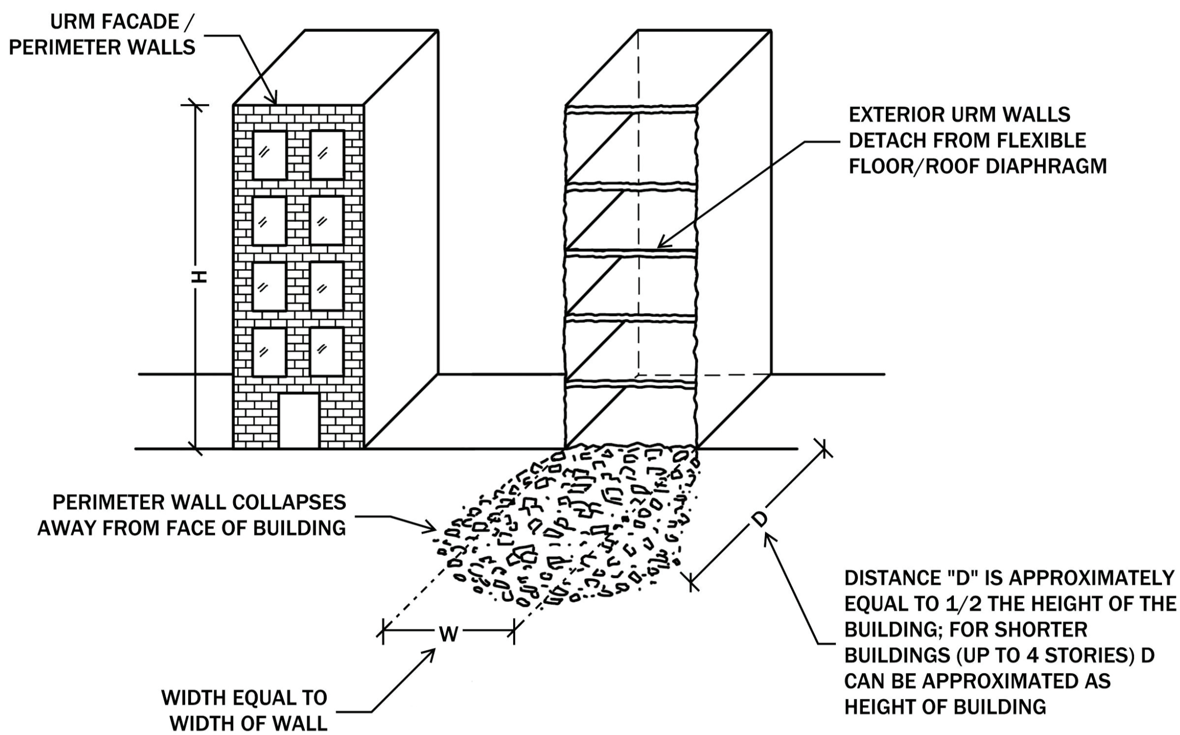


Figure 3-32 Illustration of wall fall collapse mode with URM wall.

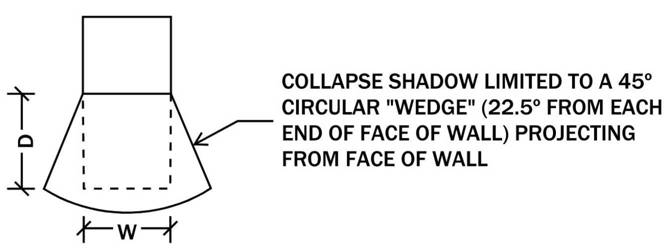


Figure 3-33 Plan sketch of recommended cordon shadow for wall fall collapse mode with URM wall.

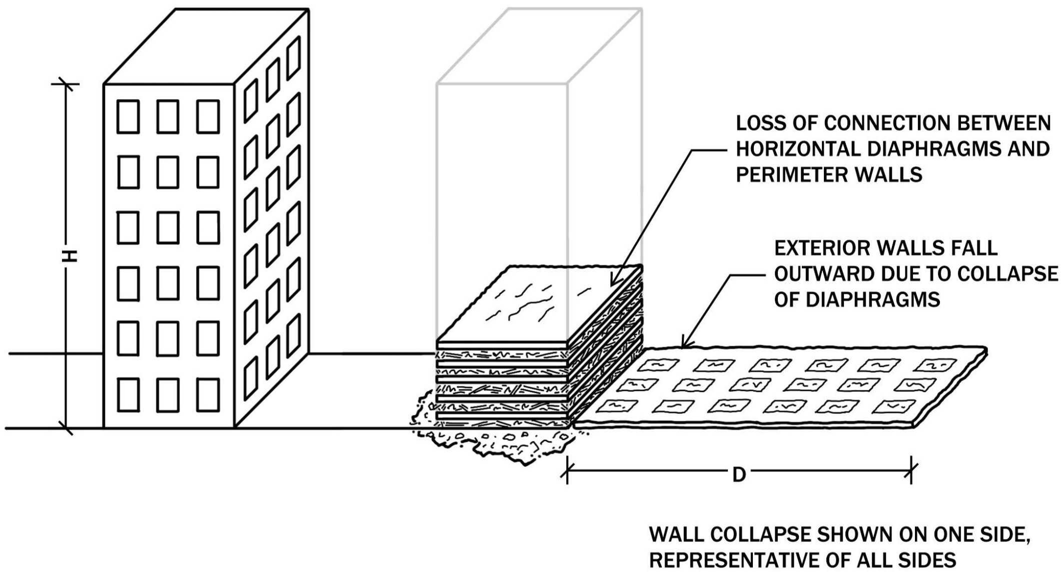


Figure 3-34 Illustration of wall fall collapse mode with tilt-up wall.

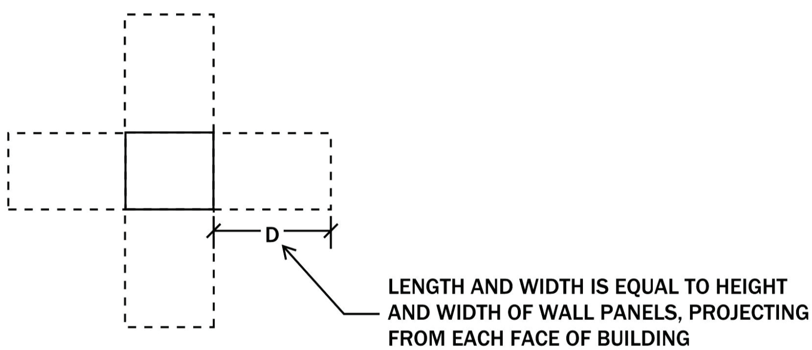


Figure 3-35 Plan sketch of recommended cordon shadow for wall fall collapse mode with tilt-up wall.

3.2.6 Implosion

The implosion collapse mode occurs in buildings that are well-connected between the roof/floors and perimeter walls when the interior columns collapse and pull the building perimeter inwards such that all debris falls within the building footprint.

Example of a building that sustained implosion collapse is:

- Northridge Campus parking garage collapsed in the 1994 Northridge Earthquake (Figure 3-36)

Figure 3-36 Parking garage damage at Northridge CSU in the 1994 Northridge Earthquake (Exponent/Shusto).

Cordon Area for Implosion Collapse Mode

This type of collapse poses no public safety concern outside the building footprint unless the collapse shadow of unsupported columns extends outside the building footprint, in which case minimal cordon area is required. Figure 3-37 illustrates the potential collapse mode and Figure 3-38 presents a plan view of the collapse shadow.

If unsupported columns extend outside of the building footprint, see guidance for monolithic overturning in Section 3.2.1 and pancake collapse in Section 3.2.4.

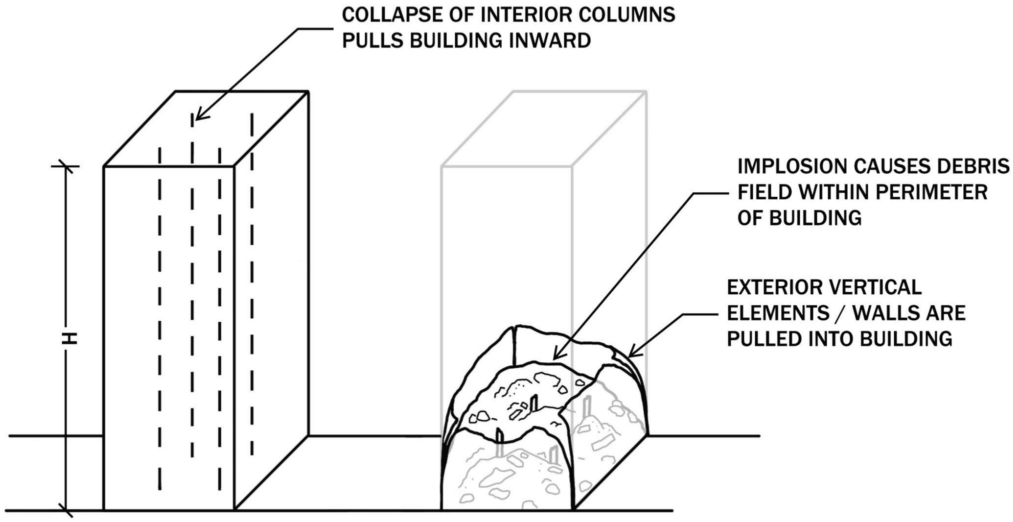


Figure 3-37 Illustration of implosion collapse mode.

Figure 3-38 Plan sketch of recommended cordon shadow for implosion collapse mode.

3.2.7 Rubble Pile

Buildings that are weak and poorly intra-connected, such as adobe, unreinforced masonry, and precast concrete, have little capacity to resist lateral loads caused by ground shaking or P-delta effects associated with tilting of a damaged building. Once cracks develop in the masonry or adobe or when precast members slip off their supports, there is no secondary load path to hold the components together. Thus, weak and poorly intra-connected buildings generally collapse into a rubble pile (Figure 3-39) that does not extend significantly beyond the building's footprint.

Figure 3-39 Adobe dwelling in Arsuz after the 2023 Kahramanmaraş Earthquake (Türkiye) (Photo Credit: Thornton Tomasetti/Galvis).

Cordon Area for Rubble Pile Collapse Mode

The cordon shadow is based on potential shifting of the debris and the debris shadow of any remaining building components. Minimal cordon area is necessary, with *D* less than building height. Figure 3-40 illustrates the potential collapse mode and Figure 3-41 presents a plan view of the collapse shadow.

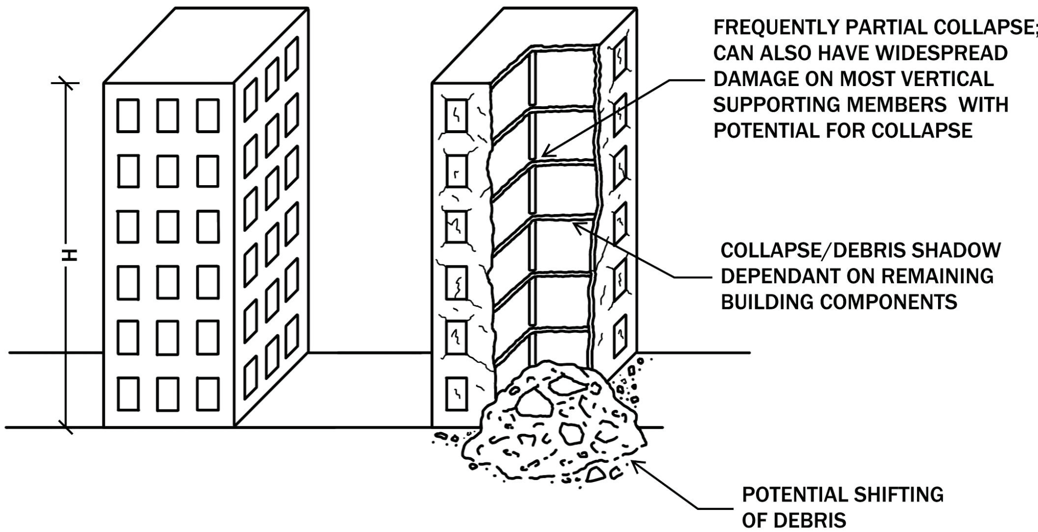


Figure 3-40 Illustration of rubble pile collapse mode.

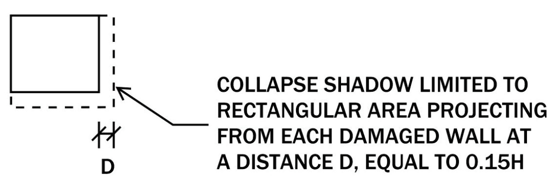


Figure 3-41 Plan sketch of recommended cordon shadow for rubble pile collapse mode.

3.2.8 Cascading Collapses

There is a possibility that a building collapsing due to monolithic overturning could impact a second building, causing its collapse (and potentially others) like dominoes. While the collapse shadow of the first building may be well defined, the potential collapse shadows of the downstream buildings are less defined. Thus, a cordon zone for a single damaged tall building could grow considerably.

An example of a cascading collapse occurred at the Piño Suarez complex (Mexico City, Mexico 1985) (Figure 3-6) where a 22-story tower collapsed onto an adjacent 15-story building, causing its collapse. If the first tower to collapse had been located at the other end of the line of towers, all three towers may have collapsed.

The literature review did not find documentation of a cascading collapse extending beyond the adjacent building. While theoretically possible that several buildings could collapse in a domino style, the probability of that occurrence is deemed to be relatively low. Emergency cordoning based on the presumed cascading collapses is not recommended in the absence of engineering guidance. In the rare event that detailed evaluation of a leaning, damaged building identifies a realistic concern of cascading collapses, expanded cordoning should be considered.

Chapter 4: Considerations for Managing a Cordon Area

Where establishing cordons around individual buildings results in multiple adjacent buildings to be cordoned off, a specific cordon area can be established. Because lessons from recent major disasters have proven that a pre-disaster plan can lead to a community's quicker recovery and reduce long-term economic impact, this chapter provides key considerations for implementing a cordon area in the post-disaster environment. These can be customized to fit a jurisdiction's needs and build upon well-established emergency management practices and procedures.

This chapter presents best practices that were compiled based on experiences from two earthquake events: the Mw 6.2 2011 Christchurch, New Zealand, which resulted in a large cordon area that lasted 857 days in the Central Business District (CBD) of Christchurch displacing 6,000 businesses (Chang et al., 2014), and the Mw6.9 1989 Loma Prieta Earthquake that resulted in a 9-block cordon area displacing 600 businesses for about 30 days in downtown Santa Cruz, California.

4.1 AHJ Response to Damaging Earthquakes

In an emergency such as the aftermath of an earthquake, model building codes in the United States give the AHJ the authority to declare buildings unsafe and to be vacated [Section 116 of *International Building Code* (ICC, 2021)]. AHJs generally use this authority to activate an emergency response and conduct safety evaluations for buildings within their jurisdiction in accordance with the procedures for post-earthquake building safety evaluation. Some AHJs have established triggers for activating their emergency response, such as a specified earthquake magnitude, or the issuance of an emergency declaration by the local jurisdiction. AHJs typically report aggregated evaluation results to policy makers through their local emergency management agency or emergency operations center as part of the jurisdiction's overall emergency response. This is further discussed in FEMA P-2055 (FEMA, 2019).

It is noted that AHJs are likely already short on staff resources within their departments to evaluate a large number of buildings following a damaging earthquake. Experience has also shown that even large building departments may have difficulty responding to moderate events, because they cannot cease operations in their normal, everyday work of regulating construction through issuing permits and conducting inspections to focus entirely on post-earthquake efforts. Thus, many AHJs preplan a series of steps to acquire the necessary additional resources to conduct building safety evaluations as established by their emergency management procedures.

Dependent on the jurisdiction's laws, regulations, and policy, an AHJ could consider adding the potential of cordon area management to its pre-disaster plans and keeping the concepts for actions and activities within a cordon area similar to approvals needed for a large construction site, such as sidewalk protection and street barricading. Including cordon area management concepts in the plans could reduce delays in establishing cordoned areas to protect lives. Experience in New Zealand has shown that it is critical to establish clear communications quickly to affirm cordon authority for businesses, owners, residents, and tenants in order to eliminate confusion and support safety. Each jurisdiction can preplan in its Comprehensive Emergency Management Plan (CEMP), if applicable, or determine in the moment where that responsibility lies.

The following items pertaining to cordon area management have likely already been addressed in the existing post-earthquake building safety evaluation plan or as part of the jurisdiction's overall emergency response and could be adjusted as necessary:

- Pre-identification of existing building database
- Processes for damaged buildings information intake and management including documentation, coordination, and validation processes. FEMA P-2055 provides an overview of post-earthquake information collection efforts.
- Communication and coordination plans and strategy including media policies
- Operating policies and procedures including planning for aftershocks
- Policies regarding upgrades during repairs or after demolition
- Policies regarding removal of private property from damaged buildings
- Mutual Aid Agreements including Emergency Management Assistance Compact (EMAC). This is discussed in detail in FEMA P-2055.

Santa Cruz: Managing Limited Access into the Cordon Area

Part of the damage experienced in the M_w6.9 1989 Loma Prieta Earthquake in the San Francisco Bay area resulted in a 9-block cordon area in downtown Santa Cruz, displacing 600 businesses for about 30 days. Businesses and owners pleaded for access to retrieve cash registers, files, and belongings that were in damaged, or damaged-adjacent, buildings. When rescues were completed, the Incident Command (IC) was shifted from the fire and public works departments to a city planner who coordinated with the Downtown Association, volunteers, businesses, individuals, and other city departments to create an access system for many of these businesses and residents to enter the cordon area briefly, accompanied by safety personnel.

AHJs may be able to take advantage of grants to aid in planning for and implementing post-disaster building safety evaluation activities. Section 1206 of the Disaster Recovery Reform Act provides some funding for Building Code Administration and Enforcement Reimbursement for 180 days after a major disaster declaration through FEMA's Public Assistance Program. Additionally, other grants provide funding for building code activities included within FEMA's Building Resilient Infrastructure and Communities (BRIC) and Hazard Mitigation Grant Program (HMGP) grants.

4.2 Additional Considerations as Cordon Area Size Increases

In the case of a building leaning over an adjacent building, an AHJ may already have the policy to post the adjacent building UNSAFE or RESTRICTED USE, even if undamaged, depending on whether the entire building or only a part of the building is exposed. The placards cannot be removed or changed until the hazard is mitigated in some way. If the event is large and widespread, with many pockets of multiple smaller cordoned areas with two or more buildings affecting each other, the following items have been identified from previous earthquake event experiences for consideration by an AHJ.

Dedicated Office

The reason for establishing a cordon office is to formalize the authority, structure, and hierarchy as necessary to streamline the implementation of cordon area management. The specific timeline, purpose, and decision-making structure for the cordon office could be detailed and include access processes, mitigation of additional hazards, e.g., weather events, and security practices. Establishing a cordon office may help with informed decision making for what may become additionally complex and customized. A cordon office can provide flexibility to allow for situational adaption and flexibility to bring in relevant partners as needed which may be different from the main disaster response and recovery.

Documentation

Recordkeeping at the very early stages after a disaster can be especially difficult because it is oftentimes manual before any systems are in place. An AHJ may have already pre-identified disaster response record keeping processes and platforms that could potentially be adapted for cordon area management. Tracking written records, pictures, videos, receipts, reports, letters, documentation of decision-making, and persons involved would increase likelihood of complete documentation and provide efficiency of use. Thorough record keeping can help identify and present lessons learned as well as provide documentation to assist stakeholders in legal or insurance determinations.

Communication and Coordination

The importance of communication and coordination is a top priority in the post-earthquake environment. As the extent of the cordon area is revised, an additional level of transparency is required to ensure decisions are made with all information intact. Further, communicating the demolition timing of one building may inform the schedule for planned repairs in neighboring buildings where people and equipment are working. Coordination for pedestrian and vehicular traffic and emergency vehicle routes may increase around a cordoned area. Historic preservation policies and needs of socially vulnerable populations may require additional focus. Partnership with local non-profits, volunteers, external stakeholders, government agencies, as well as other specific entities, can be facilitated.

Santa Cruz: Lessons Learned

After the M_w6.9 1989 Loma Prieta earthquake, the City of Santa Cruz was overwhelmed and had limited staff resources. Focus during the first 48 hours was to get everyone out, and residents and businesses complied willingly. In total, one-third of the buildings had to be demolished, one-third were undamaged, and the last one-third were in between. There was a rush to demolish buildings early in the recovery, which made for challenging circumstances while the cordon was still being established.

To help many of their local businesses recover in the immediate aftermath of the earthquake, the City recognized that it was overwhelmed and assisted businesses by sharing responsibilities with non-profits and others, enlisting the help of volunteers. After signing waivers, some volunteers were assigned roles to remove requested items from many of the damaged businesses, such as the Bookstore Santa Cruz, where the work was completed quickly. Hundreds of volunteers donated thousands of hours, helped many businesses, assisted with communications, and were critical in the operation of the cordon area.

4.3 Considerations for Large Cordon Areas

If an AHJ is planning for “The Big One,” consideration of the unique complexities of cordoning at a much larger scale may be desired. As the U.S. has not had a major earthquake requiring a large cordon area, this section of the report has been developed for consideration from New Zealand’s experience during the recovery from the 2010- 2011 Canterbury earthquake sequence, which affected the City of Christchurch and killed 185 people. As described in Underwood et al. (2020), cordons were established after both September 2010 and February 2011 earthquakes, with the September cordon remaining in place for only 1 week before being narrowed to individually unsafe buildings whereas the February earthquake cordon remained in place until June 2013, after being gradually reduced over time with 33 different phases of change to the cordon extent. They add that the cordon was established initially for public safety but was kept in place to allow for effective building demolition and repair works.

Many of the activities listed in the previous section, such as access processes and security practices, can simply be increased in scale. The concept and organization of a dedicated Cordon Office may remain essentially the same. Documentation, communication, and coordination can expand and evolve. The fundamental difference will likely be the significant increase in the complexity of the overall task.

Learning from New Zealand

Following the 2010-2011 earthquakes in New Zealand, the Canterbury Earthquake Recovery Authority (CERA), established the Earthquake Recovery Learning and Legacy Programme that produced a collection of 300 publicly available documents on recovery lessons and tools. The documents are available on the following website: https://quakestudies.canterbury.ac.nz/store/collection/22109

Cordon Manager

Consideration could be given to establishing a cordon manager position who would serve as the head of the cordon office and have building official capabilities. They would be responsible for both daily cordon operations as well as the 'big picture' of the lifespan of the cordon and recovery of the impacted area.

New Zealand: An Extreme Cordon Program for an Overwhelming Scale

In New Zealand, the Canterbury Earthquake Recovery Authority (CERA was established as the cordon management authority and served as an extension of local government to facilitate decision-making with the locals. CERA had a specific purpose of recovery coordination in the damaged central business district.

After the 2011 Christchurch Earthquake, 47% of buildings in the central business district (CBD) were determined to be unsafe or required restricted access (Kam et al., 2011). Some only had superficial damage to the exterior, so were not at risk of collapse. Some undamaged buildings were at risk from damaged buildings nearby, so access to those structures was also restricted. Others were also not at risk of collapse but had enough damage that it was more cost-effective to demolish than repair. Over one thousand buildings were demolished in the CBD.

When the Canterbury Earthquake Recovery Authority (CERA) was eventually dissolved, it was observed that any tensions and issues that were left in the local community left with it, as the organization no longer existed. This took the pressure off the local AHJ, and they were not tarnished with the legacy of any complaints.

Cordon Physical Attributes

Careful consideration should be given in establishing the cordon perimeter to fully encompass the focus area with the goal of only thoughtfully decreasing the perimeter as needed. The perimeter should be revaluated after an aftershock occurs. New Zealand grieved after bus passengers were killed in an aftershock in area that had been within the original cordon perimeter. It was noted that the cordon perimeter had been reduced too soon, likely in response to pressure to reopen the city quickly. The decision to adjust the cordon perimeter is significant, so the decision framework should be thorough, rigorous, and defensible.

The Cordon Area is a 3-D Environment

Cordon management requires understanding that the cordon area is a three-dimensional environment. This can be difficult for people to understand or visualize as there are risks they cannot see above the surface, on the surface, below the ground, and in the airspace.

For large cordon areas, consideration of the physical placement of the barriers and any adjustments should be determined by including the engineering considerations in Chapter 3, as well as traffic and pedestrian patterns, business access, practical entry and egress points, emergency response access, and security. It is encouraged to gather pertinent information relevant to all stakeholders.

New Zealand: Using Crime Prevention to Help Inform Cordon Reduction

In recovering from the 2011 Christchurch Earthquake, the Canterbury Earthquake Recovery Authority (CERA) used the Crime Prevention Through Environmental Design (CPTED) model in reducing the cordon. CPTED is a crime prevention strategy based on the principle that proper design and effective use of buildings and public spaces in neighborhoods can lead to a reduction in the fear and incidents of crime, and an improvement in the quality of life for citizens. The cordon office informed the police of planned actions, and the police explained consequences of taking those actions. For example, if the cordon is moved, lighting should be improved to reduce crime potential.

Daily Operations Policies and Procedures

When planning for a large cordon area, most well-established, recovery office daily operations policies and procedures can be utilized. The following items are based on New Zealand’s experience and could be considered when customizing for a larger scale:

- Establishing formal policies and procedures to address aftershocks, including emergency vehicle access, evacuation, accountability, and communication.
- Establishing additional formal reinspection protocols in large cordon areas to identify buildings or components with additional lean or collapse.
- Including techniques and concepts from management of complex work sites, including daily information briefings that include review of additional risks from collapse, fire, aftershocks, weather, biohazards, asbestos, and demolition.

- Managing communication, education, and public messaging. This is very important for maintaining public trust and reducing confusion and frustration during the stressful time. In Christchurch, some messages were sometimes lost or diluted when redistributed or rebroadcast. Having the authority behind the CERA helped alleviate this issue.

Large Cordon Area Access Control

Controlling access to a large cordon area will likely increase in complexity from the standard emergency management plan or even a large construction site. Residents may want access to their belongings. Building owners may want access to determine whether to demolish or repair their buildings. Businesses may want access to their inventory, equipment, or other goods. Insurance adjusters may want to survey damage. Contractors need access to complete their work in demolition, clean up, repairs, and reconstruction. Equity in how access is provided, as well as how options are communicated with each of these groups, can lessen complications if managed properly. As safety is of utmost importance, only those truly needing access are granted.

A platform or system for accreditation, credentialling, and defined limited access zones may be desired as well as a dedicated cordon pass office to control entry and exit points. Consideration should be given to power and internet availability and additional staffing requirements when planning for this potential need.

Management of the cordon area may require coordination and communication between the cordon office and law enforcement daily. The credentials issued by the cordon office may be enforced by local police departments or within their mutual aid agreements if addressed by an AHJ's emergency management pre-planning activities.

New Zealand: Cordon Access

To access the CBD, contractors were required to come into the cordon pass office with identification, plans, reference checks, confirmation of required policies, e.g., safety plans, and correct gear, to get verified. This process allowed documentation of everyone working in the cordon area.

The cordon office provided each person a photo identification badge with a color code to show approved access. The Cordon Manager set access levels and colored "zones" for the entire cordon to manage where personnel were able to go. Except for cordon office staff and the police, who had unrestricted access, everyone else had restricted access. Restrictions included: daytime only, location specific, time specific, date specific, and all had an expiration date.

If a contractor badge was lost or expired, they would have to re-apply for access, and, as an added security measure, contractors had to turn in their cordon badges on their last day.

Other Unique Considerations

There is a lot at stake inside any cordon area, but it is magnified in a large cordon area.

- The number and diversity of stakeholders are just a part of the many challenges. In New Zealand, a Cordon Area Stakeholder Advisory group was established to facilitate consensus and communication not only in specific cordon area management issues, but also general recovery issues including insurance and building tenant/owner dynamics.
- The potential mental health needs of the cordon area staff should be considered and addressed.
- Embedding a small team of attorneys to address any emergent legal issues and provide advice may be beneficial.
- During the earthquake files containing medical records, legal paperwork, and financial records may be exposed. In New Zealand, CERA was able to coordinate with the impacted organization, business, or agency to resecure the sensitive information.

Appendix A: Collapse Shadow Literature Review

A.1 Literature Review

Current literature addressing the extent of building collapse shadows is scarce. Most of the available literature uses geometric relationships supported by expert judgements and limited damaged observations with the objective of estimating the reduced capacity of road networks after earthquakes (Anelli et al., 2020; Argyroudis et al., 2015; Castro et al., 2019). Recent studies are improving the estimation of the collapse shadow and debris extent using measurements of actual debris fields after earthquakes (Moya et al., 2020) or performing detailed computer simulations (Domaneschi et al., 2019; He et al., 2023; Osaragi and Oki, 2017; Sediek et al., 2021). This section provides an overview of this limited literature.

For masonry buildings, Domaneschi et al. (2019) used the applied element method (AEM) to perform a parametric study of 81 masonry building models to determine their collapse characteristics. The objective of the study was to calibrate an equation for estimating the amplification factor, ε, to the footprint area that would enclose 90% the debris spread as shown in Figure A-1.

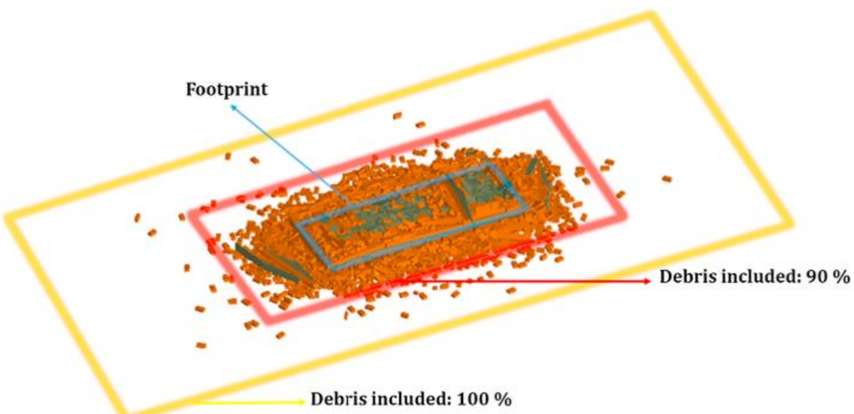


Figure A-1 Schematics of the footprint area and area enclosing debris spread from collapsed masonry buildings (Domaneschi et al., 2019).

Equation A-1 is such an equation where A_d is the debris area, A_f is the footprint area, ϵ is the amplification factor, *a* is the length on the longest side of the buildings, *b* is the length on the shortest side, h_b is the building height, and V_b is the masonry volume in the building. In this equation, ϵ is dominated by the plan aspect ratio of the building and the height of the building. In the most critical assumption for the inputs, the amplification factor is 1.80, indicating that the debris extent is equal to or lower than 80% of the building width.

$$A_d = A_f\,\epsilon^2 \quad \text{(A-1)}$$

where

$$\epsilon = 1.228+0.07869(a/b)+0.05626((A_f\,h_b^2)/(V_b\,a)$$

Moya et al (2020) performed a quantification of the debris extent produced by 851 collapsed wood-frame buildings during the M_w 6.2 and M_w7.0 Kumamoto, Japan earthquakes in 2016. This study investigated the factors influencing the extent of debris and proposed probability functions to quantify it using LiDAR data collected in the field for buildings ranging in height from 2 to 11 meters (6 to 35 feet) (i.e., from one to four stories). The scatter plot of the debris extent outside the building footprint versus building height is shown in Figure A-2, including the geometric relationship between these two variables previously proposed by Osaragi and Oki (2017). The authors found a moderate correlation between the building height and the debris extent with a significant dispersion that seems to follow a Gaussian distribution. The measurements indicate that a fraction of buildings did not produce debris extent outside their own footprint (e.g., *D* = 0) despite collapsing. Figure A-2 shows that the debris extent is lower than the building height for more than 95% of measurements including the Osaragi and Oki (2017) heuristic equation. These conclusions are useful for wood-frame construction in Japan but could be reasonably extended to wood-frame construction in other parts of the world.

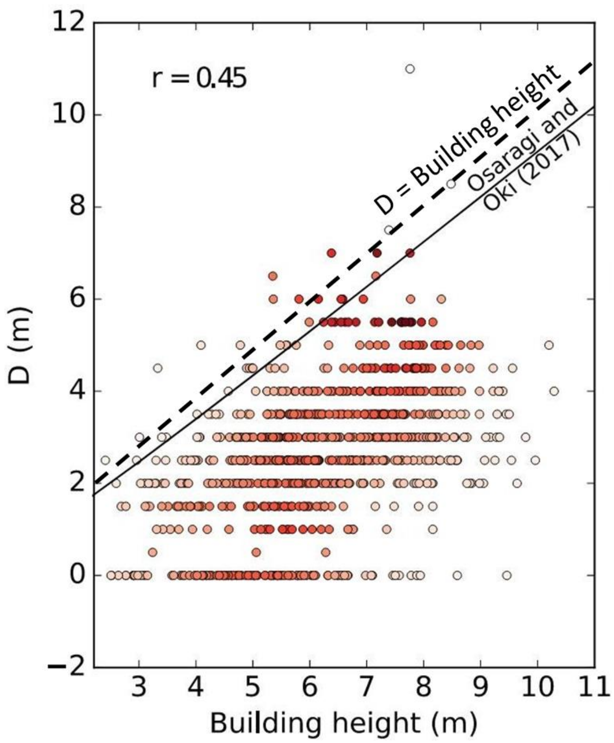


Figure A-2 **Debris distance, *D*, for wood-frame buildings in Japan after the M_w6.2 and M_w7.0 Kumamoto earthquakes in 2016 (Adapted from Moya et al., 2020).**

For reinforced concrete moment frame buildings, Sediek et al. (2021) estimated the extent of debris generation using simulations that employ the applied-element method (AEM) for an estimation of the process of a building collapsing. Their approach for collapse mode simulation was validated by comparing the analytical results with a shaking table test of a reinforced concrete moment frame (scale 1:5) tested to total collapse. They simulated 4-, 8-, and 12-story reinforced concrete frame archetypes from FEMA P-695 (FEMA, 2009). The effect of potential falling debris from the exterior enclosure was also considered. The generated database of collapses and debris fields informed the development of a collapse classification focused on two aspects: (1) mode (aligned or skewed as shown in Figure A-3) and (2) direction (positive or negative).

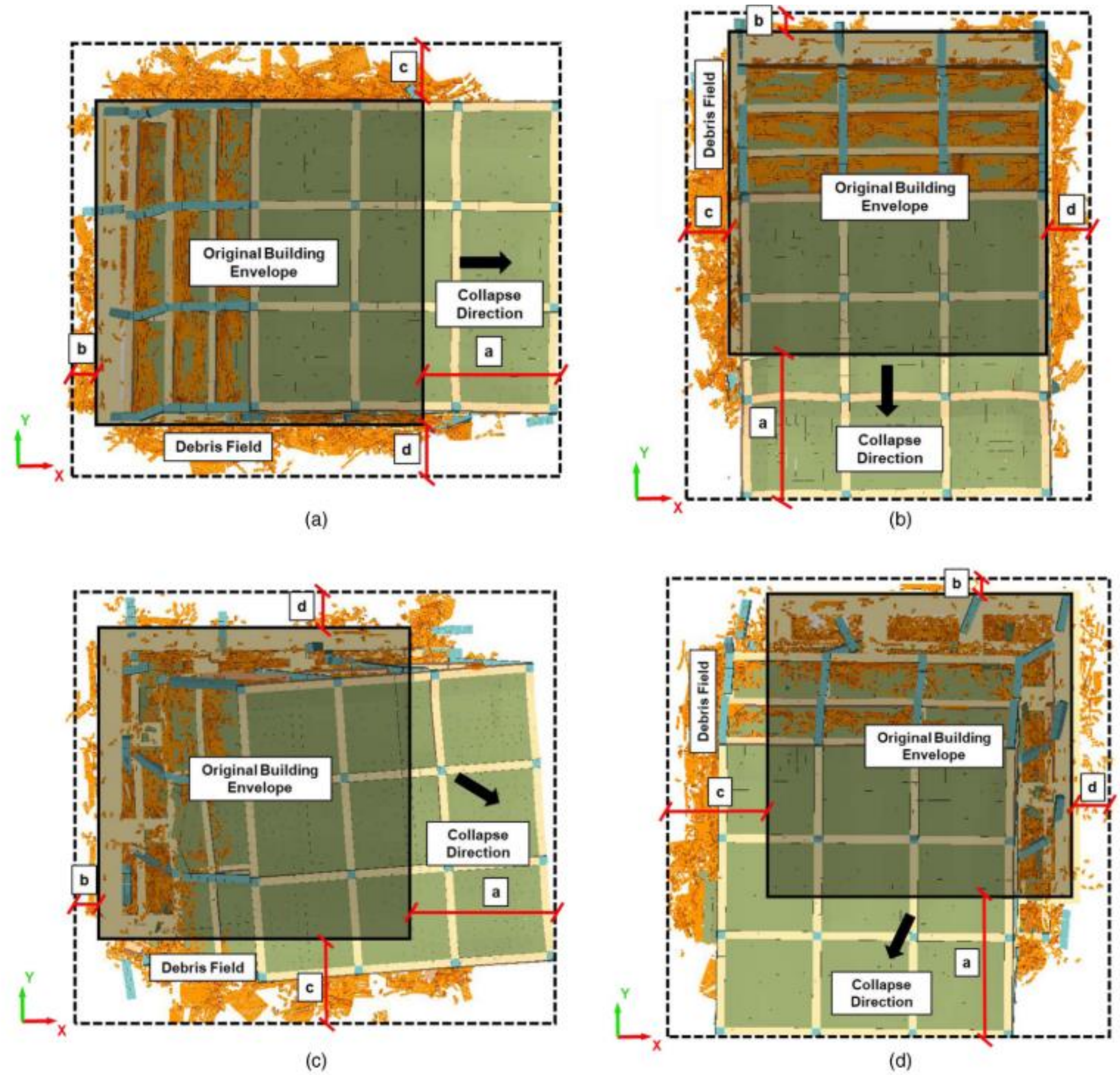


Figure A-3 **Collapse modes per Sediek et al. (2021) showing (a) collapse aligned to direction X, (b) collapse aligned to direction Y, (c) skewed collapse towards X, and (d) skewed collapse towards Y.**

Results show that, for the buildings simulated, the 90th percentile of the largest debris extension is approximately 80% of the building height depending on the collapse mode (Figure A-4). The debris are heavily concentrated in one direction for aligned collapse modes since the debris extension in the dominant direction is approximately three times larger than the debris extension in all other directions. For skewed collapse modes, the debris in the next largest direction is about 2/3 of that of the dominant direction. Aligned collapse modes were found to be more common in low-rise buildings (<4 stories) while skewed collapse modes are more common in taller buildings (8-12 stories). In all cases, the 90th percentile extent of the debris field as a fraction of building height was less than the building height, h_b, and decreased with increasing building height. The extent of the debris field on the "back" side (i.e., the side opposite the azimuth of the fall shadow) was approximately 0.2h_b. The extent of the debris field on the sides of the building was approximately 0.4 h_b.

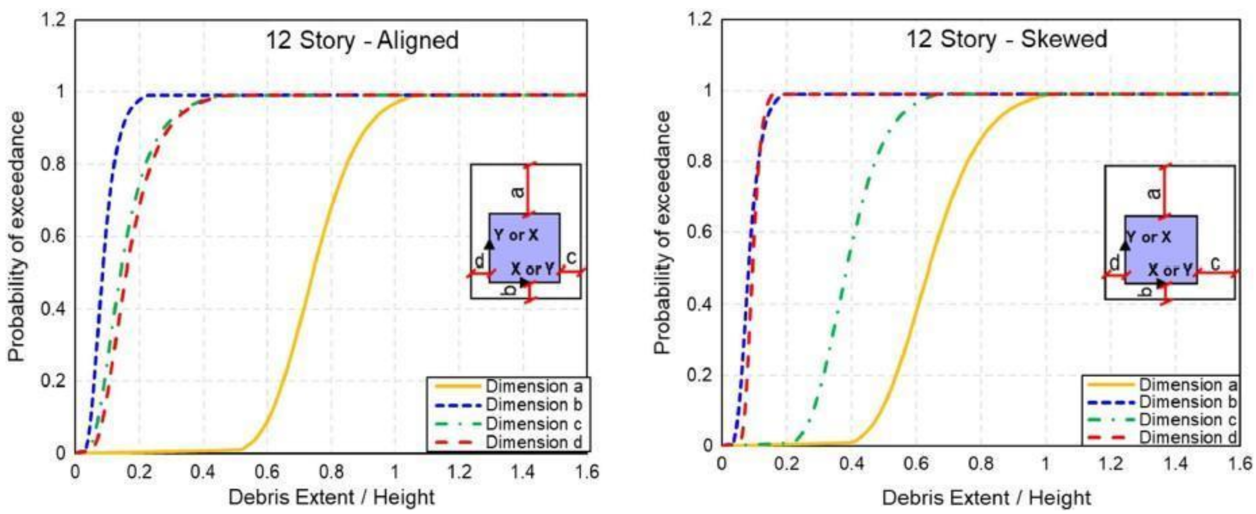


Figure A-4 Fitted lognormal cumulative density functions of the debris extent of 12-story buildings with different collapse modes (Sediek et al., 2021).

He et al. (2023) studied debris extent of regular modern reinforced concrete structures with 3, 4, and 10 stories and a rectangular footprint of 16.8m by 12.9m (55 ft by 42 ft). The study used finite element simulations in Abaqus for each building using 22 ground motions capable of producing collapse. The structural model was calibrated with previous laboratory testing of a three-story frame. The authors found that the maximum debris extent is a function of the building height and the peak ground acceleration of the ground motion as shown in Figure A-5. The results of the simulations indicate that the maximum debris extent is approximately 2/3 of the building height for strong ground motions. The authors showed that their results are aligned with estimations from simplified equations from previous studies (Argyroudis et al., 2015).

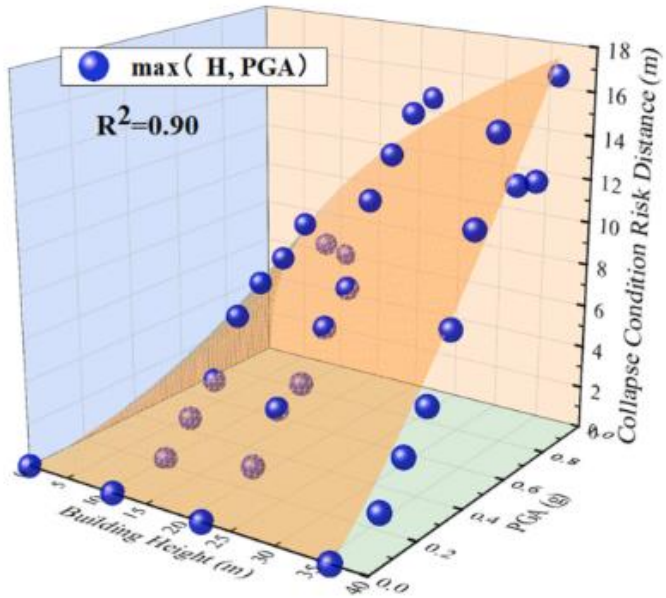


Figure A-5 Debris extent distribution for modern reinforced concrete frames per He et al. (2023)

Further, Schweier and Markus (2006) present a classification of debris extent for each type of collapse of nonductile reinforced concrete buildings for increasing the accuracy of building collapse detection from aerial video footage. Similar classifications can be found for other types of buildings, but no classification was found specifically tailored to identify the fall shadow of the potential building collapse.

A.2 Database of Collapsed Buildings

Recognizing the limitations of the literature, this study embarked on an effort to assemble a database of collapsed buildings as the basis for a rational understanding of collapse shadow for damaged structures. The database included 70 collapsed buildings documenting the event that caused the collapse, number of stories, approximate building height, notes about potential structural irregularities, a description of the structural collapse mode following the classification per Chapter 3, an approximate maximum collapse distance, and an approximate maximum debris distance. In the database, the collapse distance differs from the debris distance in the sense that the former refers as the furthest distance reached by collapses of structural members (e.g., columns, beams, slabs) while the latter includes the additional distance from non-structural components (e.g., parapets, partitions, roof equipment) that may fall further way.

The database includes collapses from the following earthquake events: Chi-Chi, Taiwan (1999); Armenia, Colombia (1999); Maule, Chile (2010); Southern Taiwan (2016); Mexico City, Mexico (2017); Hualien, Taiwan (2018); Christchurch, New Zealand (2010-2011); and Türkiye-Syria (2023). The database also includes the collapse of World Trade Center (WTC) Towers 1, 2, and 7 in the 9/11 terrorist attacks in New York City and a few collapses due to building fires, including the Windsor

Tower in Madrid, Spain (2005), the Plasco Building in Tehran, Iran (2017), and Wilton Paes de Almeida in Sao Paulo, Brazil (2018).

Database of Collapsed Buildings

The database prepared for this study is available at the following link:

https://femap2055.atcouncil.org/

The database contains mostly buildings that collapsed by story mechanism or pancake (Figure A-6) with a handful of cases in all other collapse modes.

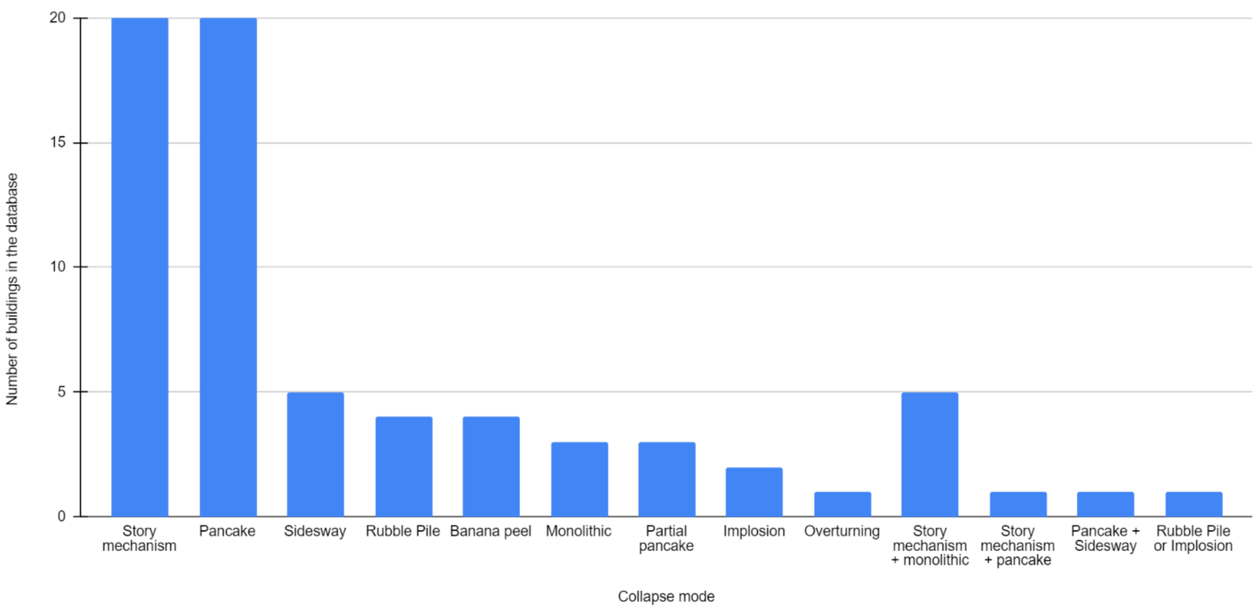


Figure A-6 Distribution of collapse modes for the buildings included in the database.

Figure A-7 shows the ratio of collapse distance and debris distance normalized by building height versus the number of stories of the buildings. All the buildings in the database had a collapse distance less than or equal to the building height, and the vast majority of cases had collapse distance less than 0.5 times the building height. The debris distance was less than 1.5 times the building height in all cases, and less than 1 times the building height in most cases. Worth noting is that debris distance includes consideration of smaller elements that although dangerous, have a much lower chance of causing injuries, fatalities or damage to surrounding buildings compared to bigger structural elements within the collapse distance.

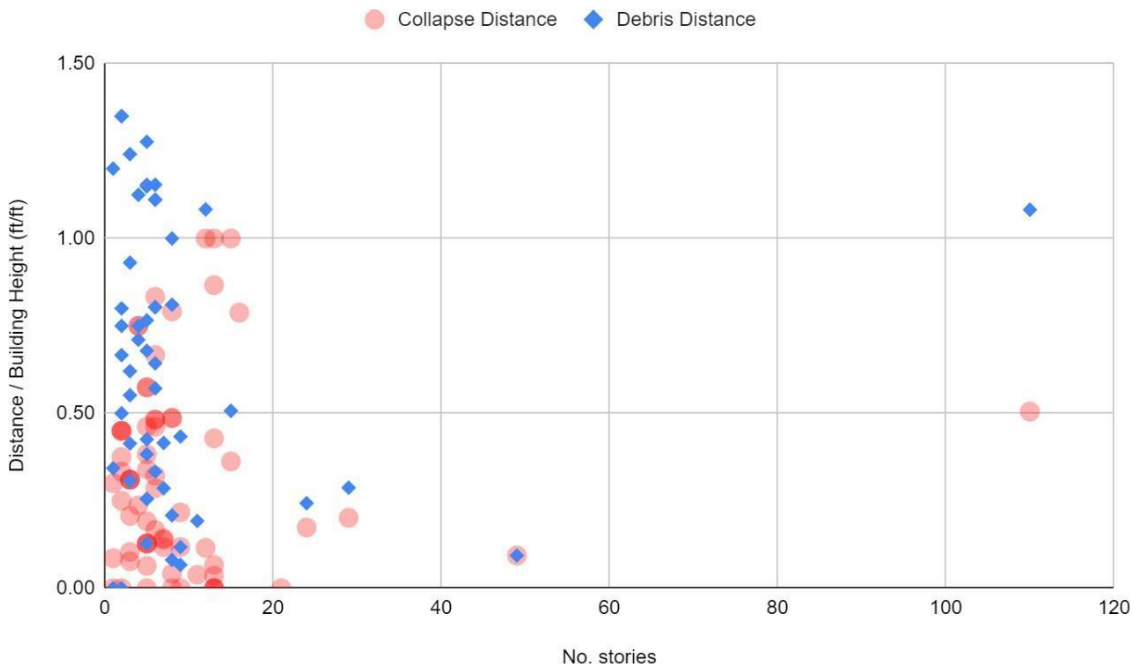


Figure A-7 Scatter plot of collapse and the debris distance normalized by the building height versus the number of stories of the buildings in the database.

This database is the first effort after Moya et al. (2020) to systematically collect and process data from past earthquakes with the intention of quantifying the fall shadow of buildings. It is recognized that conclusions drawn from 70 buildings are not representative of all the cases that an engineer may encounter in the field; thus, this database should continue to evolve to appropriately represent the multiple collapse modes of structures.

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Project Participants

Federal Emergency Management Agency

Mike Mahoney (Project Officer, retired)
Federal Emergency Management Agency
400 C Street, SW
Washington, D.C. 20472

Christina Aronson (Task Monitor/Final Project Officer)
Federal Emergency Management Agency
400 C Street, SW
Washington, D.C. 20472

Applied Technology Council

Jon A. Heintz (Project Executive)
Applied Technology Council
201 Redwood Shores Parkway, Suite 240
Redwood City, California 94065

Ayse Hortacsu (Project Manager)
Applied Technology Council
201 Redwood Shores Parkway, Suite 240
Redwood City, California 94065

Project Technical Committee

Stefanie Rae Arizabal
San Francisco
California 94111

Ines Pearce
Pearce Global Partners Inc.
5419 Hollywood Blvd Ste C-466
Los Angeles, California 90027

John Osteraas
Exponent, Inc.
149 Commonwealth Drive
Menlo Park, California 94025

Project Review Panel

Michael Barker
Windy Springs Ranch
2215 Rosedale Rd.
Laramie, Wyoming 82070

David Hammond
1062 Metro Circle
Palo Alto, California 94303

Charles Eadie
Eadie Consultants
P.O. Box 1647
Santa Cruz, California 95061

Scott Nacheman
White Birch Group, LLC
900 N. Kingsbury Street, Suite 730
Chicago, Illinois 60610

John O'Connell
11 St. Andres Road
Walden, New York 12586

Mariam Yousuf
Federal Emergency Management Agency
400 C Street, SW
Washington, D.C. 20472

Jonathan C. Siu
Jon Siu Consulting, LLC
2549 SE 16th St.
Renton, Washington 98058

Working Group

Sandesh Aher
Aher Structural Graphics
2316 Buena Vista Ave.
Alameda, California 94501

Francisco Galvis
Thornton Tomasetti
235 Montgomery St. #1050
San Francisco, California 94104

Anne Hulsey
504/11 Akepiro Street
Mount Eden, Auckland 1024
New Zealand

Amy Inhofer
Degenkolb Engineers
375 Beale St. #500
San Francisco, California 94105

Alan Puah
Mar Structural Design
2332 Fifth St. Suite D
Berkeley, California 94710

Tommy Sidebottom
ZFA Engineers
601 Montgomery St. #1450
San Francisco, California 94111

Jack Wegleitner
Degenkolb Engineers
375 Beale St. #500
San Francisco, California 94105

Brenden Winder
51 Donnington St.
Parklands, Christchurch 8083
New Zealand