Earthquake Safety Implementation Program
The City and County of San Francisco

RECOMMENDATIONS FOR MITIGATION OF CHIMNEY HAZARDS

ESIP Task A.4.g
September 28, 2015

Applied Technology Council

Cover image (left): Chimney damaged in 2014 South Napa earthquake (photo from www.californiawinefan.com)

Recommendations for Mitigation of Chimney Hazards in San Francisco (ESIP Task A.4.g)

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September 2015

Summary

In every California earthquake, from San Francisco in 1906 to South Napa in 2014, chimneys have routinely been among the first building components to fail, often dangerously, sometimes fatally.

San Francisco does not yet have a program to improve chimney-related earthquake safety. Even owners ready to do voluntary retrofit will not find guidance pre-approved for use in San Francisco; they are likely to receive inconsistent information when they ask architects, contractors, or building officials about the risk and how to address it. Other jurisdictions, notably Los Angeles, have published generic details and regulations, but they are focused on repair, not retrofit, and they do not apply to many San Francisco conditions.

This report was developed for the San Francisco Earthquake Safety Implementation Program (ESIP) under Task A.4.g of *CAPSS Earthquake Safety Implementation Program Workplan 2012-2042* (Kornfield et al., 2011) and describes the earthquake risks posed by San Francisco's masonry chimneys. It presents background data to inform the development of mitigation policies and offers recommendations based on those findings.

Four chimney types are prevalent in San Francisco:

- **Patent flue.** Over 100,000 patent flues serve typical San Francisco houses, duplexes, and apartment buildings. Built of a ceramic flue with a sheet metal enclosure, patent flues are vulnerable to earthquake damage but are much less subject to dangerous collapse than brick masonry chimneys. If used while damaged, they can pose fire and health hazards.
- **Setback house masonry chimney.** A few thousand detached or "setback" San Francisco houses have masonry chimneys. Most are unreinforced, and most are vulnerable to partial or total collapse – much more so than the houses themselves – even if nominally anchored to floor or roof framing. In most cases, the safety and property risks are borne largely by the house's owner and tenants.
- **Apartment building boiler masonry chimney.** Approximately 1,000 apartment buildings, representing about 10,000 housing units, have

simple unreinforced masonry chimneys to vent boilers. These chimneys pose risks to safety and property. In addition, damage to boiler chimneys can also disable a building's heating system, delaying reoccupancy and recovery of the city's multi-unit housing stock.

- **Victorian rowhouse masonry chimneys.** Approximately 45,000 unreinforced masonry chimneys remain on the city's iconic Victorian rowhouses. Most are three stories tall and located on a side wall near the front of the building. All are vulnerable to costly damage; those not enclosed by siding and those that still extend more than a few feet above the roof are the most vulnerable to partial or total collapse.

Policy recommendations and approximate mitigation costs, if available, for each chimney type are presented in Table S-1.

Table S-1 Summary of Recommendations for Four Prevalent Chimney Types in San Francisco

Patent Flue

Recommendation: Through ESIP, the city should prepare advisories for a postearthquake messaging campaign reminding building owners to have their chimneys inspected by qualified professionals before use.

Setback House Masonry Chimney

Recommendation: Through ESIP, the city should encourage voluntary retrofit by adopting prescriptive details based on repair schemes already in use elsewhere and by gathering applicable building regulations into a user-friendly bulletin. The recommended retrofit involves replacing as much of the heavy masonry as possible with a metal flue and light-framed enclosure.

Approximate mitigation cost, per chimney: $15,000 to $25,000 depending on size, complexity, and extent of masonry removal.

Table S-1 Summary of Recommendations for Four Prevalent Chimney Types in San Francisco (continued)

Apartment Building Boiler Masonry Chimney

Recommendation: Through ESIP, the city should encourage voluntary replacement for safety and loss reduction. The city should also consider mandatory, triggered, or strongly incentivized voluntary replacement for purposes of citywide housing recovery.

Approximate mitigation cost, per chimney: $10,000 to $15,000 depending on size and location of chimney, not including possible costs of associated boiler upgrade.

Victorian Rowhouse Masonry Chimney

Recommendation: Through ESIP, the city should encourage voluntary retrofit as for the setback house chimneys. ESIP should also work with the Planning Department and with preservationists to develop appropriate retrofit details. For perhaps 1,500 chimneys located adjacent to streets or sidewalks, the city should consider mandatory or triggered retrofit for public safety.

Approximate mitigation cost, per chimney: $25,000, with variation for historic preservation approaches to be determined.

Preface

The risks from future earthquakes in San Francisco have been well documented in the work conducted for the Community Action Plan for Seismic Safety (CAPSS). This work led the way to the development of a 30-year program to be implemented by the San Francisco Earthquake Safety Implementation Program (ESIP). In 2014, the Applied Technology Council (ATC) was awarded a contract to provide seismic safety and engineering consulting services to ESIP. This document is the first in a series of reports to fulfill the tasks identified in this contract under the ATC-119 project.

Thor Matteson, Brian McDonald, and David Bonowitz were the lead researchers and writers of this report. The Applied Technology Council is indebted to the leadership of David Bonowitz and Laura Samant, Co-Team Leaders on the ATC-119 project. Their affiliations are provided in the list of Project Participants.

The Applied Technology Council thanks the following for the generous donation of their time and expertise: Mark Caldwell and Kevin McKee (Okell's Fireplace), Hugh Cruickshank (Fireplace Safety Services), Scott Bailey (Willson Bailey Construction), and Pat McGuire (property owner).

ATC also gratefully acknowledges the staff of the City and County of San Francisco Earthquake Safety Implementation Program: Patrick Otellini (Director of Earthquake Safety and Chief Resilience officer), Stacey Lee (Program Manager), Micah Hilt (Planner), Jeno Wilkinson (Program Assistant) and Laurence Kornfield (Special Assisstant to the City Administrator), and Christopher Rojahn (ATC Director Emeritus) for ATC Project Management and Amber Houchen for ATC report production services.

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Chapter 1

Introduction

1.1 Project Background

In early 2000, the San Francisco Department of Building Inspection (DBI) began work on the Community Action Plan for Seismic Safety (CAPSS) which resulted in a wide-ranging 10-year program of studies and recommendations involving staff, citizens, and experts to develop a basis for earthquake risk reduction and response policy decision-making by the City and County of San Francisco.

One of the primary products of the CAPSS project was the ATC-52-2 report, *Here Today—Here Tomorrow: The Road to Earthquake Resilience in San Francisco, A Community Action Plan for Seismic Safety* (ATC, 2010b). Based on the ATC-52-2 report, the City and County of San Francisco developed the *CAPSS Earthquake Safety Implementation Program Workplan 2012-2042* (Kornfield et al., 2011). The *Workplan* "outlines a 30-year program, based on the extensive CAPSS analysis and community supported recommendations that will reduce San Francisco's most significant earthquake impacts. [Many of the plan's elements are] scheduled to start soon so that results can be achieved in time to reduce likely earthquake impacts" (Kornfield et al., 2011). Accordingly, the Earthquake Safety Implementation Program (ESIP), under the oversight of a Director of Earthquake Safety, was established within the City Administrator's office in 2012 with the purpose of carrying out the 30-year *Workplan.*

1.2 Project Scope

In July 2014, ESIP awarded a contract to the Applied Technology Council (ATC) to provide technical expertise in selected tasks from the 2011 *Workplan*. Under this contract, ATC is conducting work on the following eight tasks:

> This report is one out of eight Task Reports prepared by the ATC-119 project.

- Develop chimney mitigation and repair guidelines and standards (Reference: *Workplan* Task A.4.g)
- Develop evaluation criteria for non-ductile concrete buildings (A.6.c)
- Conduct study of fire-related initiatives (A.6.i)

- Develop evaluation and retrofit standards for desired performance goals (A.6.h)
- Conduct study of retail sector (A.6.g)
- Develop standards and criteria for mandatory retrofit for concrete tilt-up buildings (A.3.b)
- Develop technical guidelines, standard plans, and program to support voluntary seismic retrofit of 1- and 2-unit dwellings (A.6.b)
- Develop standards for triggered evaluation for 3-unit wood buildings (A.2.a)

1.3 Report Scope and Organization

This report is a final deliverable from work conducted under *Workplan* Task A.4.g. The scope of Task A.4.g evolved over the conduct of the work to present earthquake risks posed by San Francisco's chimneys along with policy recommendations to ESIP.

Chapter 2 presents an inventory of the types of chimneys prevalent in San Francisco and their association with different types of wood-frame residential buildings. The three chimney types most prevalent in San Francisco are not found in large numbers elsewhere. These are patent flues, tall Victorian chimneys, and apartment house boiler chimneys.

Chapter 3 presents a review of the past performance of the different chimney types, as well as current estimates of their failure rates. Probability of failure, or fragility, is hard to quantify with precision, but every analysis confirms that masonry chimneys are more vulnerable than the structures to which they're attached and more vulnerable than other conditions, such as "soft story" buildings, for which the city already mandates or incentivizes retrofit.

Chapter 4 summarizes available mitigation approaches as they apply to San Francisco's chimney types, with a brief assessment of costs and benefits. The most common guidelines currently in use were developed for repair, not retrofit. They are usable, but will need to be adapted for retrofit and for San Francisco conditions. In general, the consensus best approach for retrofit of masonry chimneys is to remove as much of the masonry as possible. For many Victorian chimneys, historic preservation goals will need to be considered as well.

Chapter 5 synthesizes the findings in the previous chapters and recommends four actions or policies for further development by ESIP. The recommendations correspond to the four common San Francisco chimney types. Although not an exhaustive list, these four types comprise the vast majority of the city's vulnerable chimneys, and each presents a unique combination of construction, risk, and mitigation potential.

Chapter 2

Inventory of San Francisco Chimneys and Flues

An inventory conducted for this project based on sidewalk surveys and satellite imagery found that the dominant chimney types in San Francisco are particular to the city's dense, early twentieth century housing stock.

2.1 Terminology

This report uses terms as defined in the *San Francisco Building Code* (The City and County of San Francisco, 2015), which in turn relies on definitions from the *California Building Code* (ICC, 2013) and the *International Building Code* (IBC) (ICC, 2012). The definitions in 2015 IBC have been slightly revised from previous editions; no California or San Francisco amendments are expected. The following terms are defined in the 2015 IBC:

- **Chimney.** A primarily vertical structure containing one or more flues, for the purpose of carrying gaseous products of combustion and air from a fuel-burning appliance to the outdoor atmosphere.
- **Masonry chimney.** A field-constructed chimney composed of solid masonry units, bricks, stones, or concrete.
- **Metal chimney.** A field-constructed chimney of metal.

By this definition, a chimney is distinct from the flue or flues it contains. Neither the IBC nor the CBC provides a definition of flue.

Conventional practice has varied, over time and by locale, from these code definitions. Among laymen, practitioners, and even building officials, the word "chimney" can mean a masonry chimney, distinct from a metal or otherwise lightweight component; it can mean both the box-like enclosure and the metal or ceramic flues within; it can include or exclude the firebox; it can apply only to fireplaces but not other appliances such as stoves or boilers; and it can refer just to wood or coal-burning devices, but not to gas or oil.

In San Francisco, a **patent flue** is commonly used either instead of a lined chimney, as a vertical extension of a masonry chimney, or as a flue within a decorative chimney. The patent flue, so called because its design was covered by a registered U.S. patent, was mentioned in the 1906 San Francisco Building Law as an acceptable alternative to the traditional brick flue and was used during the rebuilding that followed the 1906 earthquake. It is formed from a stack of mortared ceramic tube sections about one inch thick, surrounded by an air gap of approximately one inch, and an outer sheet metal jacket (Figure 2-1a). The patent flue usually bears on a masonry pad built up from either a masonry firebox or set on a steel plate directly over conventional wood floor joists (Figure 2-1b). Within the building, the flue is meant to be strapped to adjacent wall studs every few feet. Above the roof, the ceramic liner stops 1 to 2 feet below the top of the tubular metal jacket. Since a patent flue is not a structure that contains a flue, it is not itself considered a chimney by the building code definition.

(a)

(b)

Figure 2-1 Patent flue exposed during renovation showing: (a) the cross section consisting of a ceramic liner and two light metal casings separated by an air gap; (b) installation on a masonry pad (probably with a masonry firebox below) and a strap anchor (white arrow) about four feet above the floor to attach the flue to the wall (inadequately connected in this case). (Photos courtesy of Jim Deasy)

In addition to the IBC's generic and comprehensive definitions, this report makes the following distinctions and clarifications:

- A chimney is distinct from the flue or flues it contains, unless it is an unlined masonry chimney and is thus acting also as a masonry flue.
- A brick or masonry chimney can serve fireplaces, incinerators, or other appliances burning any type of fuel.

- A chimney generally means the portion above the lowest firebox. Thus, in a two-story structure with a firebox on each floor, the brick chimney can include portions around and even below the second floor firebox.
- For the purposes of this report, a patent flue is not a chimney.

2.2 Patent Flues

In San Francisco, the vast majority of flues used (originally or currently) to vent fireplaces, incinerators, boilers, and other appliances are relatively lightweight patent flues.

Figure 2-2 shows typical San Francisco residential buildings with patent flues without masonry chimneys. The common location in plan indicates a typical fireplace or heater along the side wall in the front living room or parlor. In Figure 2-2b, the boxy structures around the patent flue give the appearance of a masonry chimney but are typically wood framed.

2.3 Masonry Chimneys

San Francisco's relatively few masonry chimneys may be categorized with three main types, each of which corresponds to a particular building type:

- Setback house
- Apartment building
- Victorian rowhouse

2.3.1 Setback House

Pre-1950 single-family dwellings set back on all sides from lot or property lines (as shown in Figure 2-3) are relatively rare in San Francisco, but they account for nearly all of the traditional masonry chimneys of the type addressed by existing prescriptive retrofit approaches (discussed in Chapter 3). ("Setback house" is not a conventional architectural term. This report uses it to distinguish larger detached houses, many in a shingle or Tudor style, from detached houses or single-family rowhouses with very little separation from their neighbors, such as those shown in Figure 2-2.)

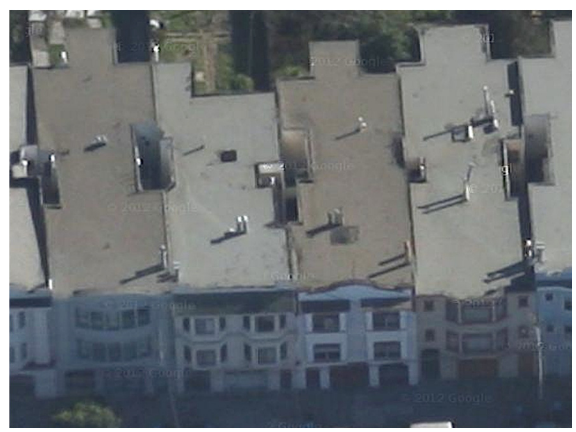
Since model building codes began requiring vertical steel reinforcing in brick chimneys only around 1950, nearly all of these setback house chimneys are expected to be of unreinforced masonry, though some may have been reinforced, anchored to the building frame, or retrofitted after the 1989 Loma Prieta earthquake. Though all unreinforced masonry chimneys share some key attributes, the expected performance of these chimneys may vary more than that of the other chimney types described in this report because the

(a)

(c)

(b)

(d)



(e)

Figure 2-2 Typical San Francisco residential buildings with patent flues: Two story-dwellings in (a) through (c); three-story rowhouses in (d) and (e). (Photos from Google Maps, 2015)

houses vary significantly in style and massing. Chimney detailing and construction quality may also vary by neighborhood, as certain parts of San Francisco were developed at different times, with tradesmen of different nationalities and traditional masonry practices (McKee, 2015). Still, amplehistoric evidence shows extensive damage to unreinforced masonry chimneys of all shapes and sizes, with and without rod bracing, at or away from the roof ridge, and inside or outside a cornice or fascia board (see Chapter 3).

(a)

(b)

(c)

(d)

Figure 2-3 San Francisco single-family “setback” houses with masonry chimneys. Note the variety of building styles, chimney styles, and chimney locations relative to a sidewalk, a roof eave or rake, or the roof ridge. Location relative to the roof ridge determines the height of the chimney extension above the roof. Not shown are cases of chimneys within the interior of the building footprint.

2.3.2 Apartment Building

Most wood-frame multi-unit apartment buildings in San Francisco do not have fireplaces in each unit. Instead, they were built (many in the 1920s and early 1960s building booms) with radiator systems fed by a central boiler. The boiler is frequently vented with a flue just outside the ground floor utility room. Commonly, the flue combines a masonry chimney for the first or first two stories with a lighter weight flue for the remaining height above. It is unclear why the masonry chimney is only partial height; at least a few full-height chimneys of this type exist, so it is possible that some of the partial-height chimneys might have been taller when originally built.

Figure 2-4 shows three examples of this chimney type. Not every building has such a chimney, but where they do exist, they appear remarkably uniform, including in many cases a nominal steel anchor strap (often loose) at the second floor level.

(a) (b) (c)

Figure 2-4 San Francisco apartment buildings with masonry chimneys. Note the uniformity of style, including, at (b) and (c) a nominal steel anchor strap at the second floor level.

2.3.3 Victorian Rowhouse

San Francisco's many Victorian (or Edwardian) rowhouses account for the majority of the city's masonry chimneys. Despite substantial chimney damage in the 1906 earthquake (see Chapter 3), tens of thousands of these unreinforced chimneys remain.

For purposes of characterizing the damageability and falling hazard, one might categorize a multistory Victorian chimney by its location within the building plan (perimeter or interior), its construction relative to the building framing (restrained or unrestrained), and its location relative to adjacent occupied areas (private or public). The height above the roofline is likely also a risk factor, but this can vary from case to case.

(a) (b)

Figure 2-5 Victorian buildings with front and rear masonry chimneys.

Many Victorian rowhouses have more than one masonry chimney, as shown in Figure 2-5. One chimney, commonly located along a perimeter side wall near the front of the building, serves parlor fireplaces. Others, located in the “back of house” and typically in the interior of the space away from a side wall, serve appliances, such as gas stoves or furnaces. A Victorian single-family house will often have only the rear appliance chimney. Victorian era buildings can also have a mix of flues, for example a patent flue serving the parlor fireplaces and a brick chimney for the back of house appliances.

Although a three-story unreinforced brick chimney is prone to earthquake damage in either plan location, the perimeter location probably represents the greater falling hazard. First, the perimeter chimney is probably less well restrained by the wall and floor framing. Second, if located at the building eave, as opposed to near the building ridge, the chimney is likely to extend farther above the roofline (though the examples in Figure 2-5 show relatively small extensions).

Figure 2-6 shows two nearly identical buildings, each with a typical perimeter chimney serving the front parlor, one restrained by the exterior wall sheathing (Figure 2-6a), and one that breaks the wall line and is restrained only by the cornice at the roof level (Figure 2-6b). In concept, a chimney entirely enclosed, or restrained, by the wall sheathing will be less of a falling hazard; even if damaged, the cracked or falling bricks are kept in place. A cornice or fascia board alone, as shown in Figure 2-6b, might be thought to provide partial restraint, and perhaps some resistance to total collapse, but such a detail is not sufficient to prevent severe or total damage. In any case, any benefit from a cornice or fascia will depend on the construction details and the quality of aged materials.

(a) (b)

Figure 2-6 Victorian rowhouses with perimeter masonry chimneys: (a) restrained within the exterior wall sheathing; (b) unrestrained.

> A damage-prone chimney next to a street or sidewalk poses a "public risk." This is different from a "private risk" that affects only the occupants of one or two private buildings.

Figure 2-7 illustrates a potential difference in risk posed by similar chimneys, one adjacent to a public street or sidewalk (Figure 2-7a) and one adjacent to a courtyard or private access between buildings (Figure 2-7b). A "public" risk is most often presented by a building on a corner lot, but Figure 2-5a shows that midblock buildings can also be adjacent to public or regularly occupied spaces. (In the case of Figure 2-6a, a gas station is located on the corner lot.)

Even a "private" risk, such as that illustrated in Figure 2-7b, is not entirely that of one building owner. A falling hazard between two buildings affects also the property of the neighboring building and the safety of tenants in both buildings. Still, this is reasonably considered a different level of risk than that posed by a chimney directly adjacent to a street or sidewalk.

Though it is not considered good practice among chimney experts to change flue types mid-height, after the 1989 Loma Prieta earthquake, many Victorian chimneys were removed or braced, or had their top sections lowered and replaced by lightweight flues (McKee, 2015). Figure 2-8 shows examples of an original full height chimney and a lowered chimney.

(a) (b)

Figure 2-7 Victorian buildings with unrestrained perimeter masonry chimneys: (a) chimney posing a public risk; (b) chimney posing a private risk.

(a) (b)

Figure 2-8 Victorian buildings with original and retrofitted perimeter masonry chimneys showing: (a) original rod bracing; (b) lowered and replaced with lightweight flue.

Also, nominal rod bracing of the masonry stack, as shown in Figure 2-8a, was sometimes provided even with the original construction (Lawson et al., 1908,

p. 358) but is no longer recommended or considered effective (ASCE, 2014; FEMA, 2015).

2.4 Inventory of Chimneys and Flues

Developing an accurate count of chimney types in San Francisco is challenging because even the best inventories of San Francisco buildings, developed by the Community Action Plan for Seismic Safety (CAPSS) (ATC, 2010a and 2010b), focus on structural systems and materials, not nonstructural features, such as chimneys or flues. Further, CAPSS relied on data from the San Francisco Planning Department that group all pre-1934 buildings without separating Victorian or Edwardian era structures. Planning data also generally count housing units or parcels, not buildings (San Francisco Planning Department, 2014). In addition, without a compiled set of permit records going back to 1989, a thorough accounting of past chimney mitigation projects is not possible. Nevertheless, the order-of-magnitude figures given in Table 2-1 and explained in the following sections for selected San Francisco chimney and flue types can be considered a starting point for a discussion of policy recommendations.

2.4.1 Patent Flues

San Francisco has about 124,000 single-family houses that account for about a third of the city's 376,000 total housing units (San Francisco Planning Department, 2014). In addition, the city's duplexes number about 19,000 buildings (ATC, 2010a and 2010b). By observation, the vast majority of these 140,000 buildings, as well as many of the multi-unit apartment houses, have at least one patent flue serving a fireplace or other appliance. Accordingly, a count of 100,000 patent flues is conservatively low, intended only as an order of magnitude estimate.

2.4.2 Setback House Chimneys

Setback houses old enough to have unreinforced brick chimneys are rare in San Francisco. They exist in relatively small enclaves, such as Ingleside Terrace, Laurel Village, and St. Francis Wood, and are otherwise scattered among the older neighborhoods, such as Haight Ashbury and Pacific Heights. CAPSS building counts are broken down by districts much larger than these enclaves. Data from the Planning Department identify single-family dwellings, but group these houses with the tens of thousands of rowhouses in the Richmond and Sunset districts. Others have mapped the median age of San Francisco buildings (NTHP, 2014) but do not distinguish occupancy or size. Thus, a clear count of these particular houses is not readily available.

Table 2-1 Approximate Inventory of Prevalent San Francisco Chimney and Flue Types

Chimney or flue type	Characteristic building types	Approximate citywide count
Patent Flues	• Two-story (1 unit) house-over-garage rowhouse, 1920s – 1940s • Three-story (2 unit, typically) rowhouse, 1910s – 1940s • Multi-unit buildings, all sizes and ages	100,000+
Masonry Chimneys		
1. Setback house	Single-family detached houses, set back from property lines, typically pre-1950	1,000 – 3,000
2. Apartment building	1920s – 1950s multi-unit buildings	500 – 1,000
3. Victorian rowhouse	• Three-story (2 or 3-unit), corner or midblock • Single-family dwellings	45,000 where: Interior, restrained: 15,000 Perimeter, restrained: 10,000 Perimeter, unrestrained: 20,000 where: public-adjacent: 1,000 – 1,500

A detailed analysis combining these data sources might arrive at a useful order of magnitude estimate of the number of setback houses, but even that would not provide a reliable estimate of the number of masonry chimneys serving them. As an order of magnitude, the number is likely closer to 1,000 than 10,000.

2.4.3 Apartment Building Boiler Chimneys

This chimney type is observed primarily in relatively large (10 units or more) pre-1950 apartment buildings. The city's current "soft story" retrofit program has identified 6,000 to 7,000 wood-frame buildings with five or more units each. Of these, approximately 5,000 have a structural vulnerability subject to the retrofit mandate (ESIP, 2014). Based on a review of the first 300 or so permit applications, about two-thirds of these were built before 1950, and about a third of those, or about 1,400 buildings, have 10 or more units. As this chimney type is not found in every such building, a rough estimate of 500 to 1,000 chimneys is appropriate. Assuming 10 units per building, this chimney type affects about 10,000 housing units citywide.

2.4.4 Victorian Rowhouse Chimneys

The city has approximately 30,000 remaining Victorian and Edwardian buildings. About 48,000 were originally built, but many were demolished over the years (Wikipedia, 2015). Practically all of these buildings were originally built with at least one brick chimney, but some had two or more. A rough estimate assumes each building has one perimeter chimney, and about half have a second interior chimney, for a total of about 45,000 chimneys. Since many Victorians are 2- or 3-unit buildings, the performance of these chimneys will have a direct effect on at least 60,000 housing units citywide.

Of the 30,000 perimeter chimneys, some are within the wall framing or sheathing and thus “restrained.” A rough initial estimate assumes one-third of the perimeter chimneys are restrained, and two-thirds unrestrained. The most critical subtype – unrestrained, perimeter chimneys adjacent to public spaces – thus comprises only a fraction of the total chimney count, estimated as fewer than one in thirty, or about 1,000 to 1,500.

Chapter 3

Risk, Past Performance, and Fragility of Chimneys and Flues

3.1 Risks from Chimneys and Flues

The immediate safety and property risks posed by masonry chimneys in earthquakes are well documented. With a resilience-based perspective, however, it is important also to think about broader effects related to response and recovery. Table 3-1 lists the different risks associated with the chimney and flue types described in Chapter 2.

Table 3-1 Earthquake Risks Associated with Chimney and Flue Types in San Francisco

Chimney or flue type	Approximate count	Public falling hazard	Private falling hazard	Roof/wall framing damage	Adjacent property damage	Demolition or repair cost	Habitability loss: Heat	Habitability loss: Egress	Subsequent fire/health risk	Historic resource loss
Patent flue	100,000+					Some	Some		Strong	
Setback house	1,000 – 3,000		Strong	Strong	Some	Strong		Some	Strong	Some
Apartment building boiler	500 – 1,000		Strong	Some		Strong	Strong	Some	Strong	
Victorian rowhouse: Restrained	25,000		Some	Some		Strong	Some		Strong	Some
Victorian rowhouse: Unrestrained, private exposure	20,000	Some	Strong	Strong	Strong	Strong	Some	Some	Strong	Some
Victorian rowhouse: Unrestrained, public exposure	1,000 – 1,500	Strong	Some	Strong	Strong	Strong	Some		Strong	Strong

No significant risk

Some association between chimney or flue type and risk

Strong association between chimney or flue type and risk

Table 3-1 distinguishes, nominally, between risks to the property owner and risks to tenants or to the public. The risk types in Table 3-1, from left to right, cover safety, financial cost, and habitability or recovery issues:

A resilience perspective considers losses related to response and recovery, not just safety.

- **Subsequent fire/health risk.** This is the risk of using a damaged flue or chimney some time after the earthquake, not the risk of a fire directly or immediately due to earthquake shaking. As this risk applies to every flue and chimney type, a seismic safety program should include considerations for postearthquake inspections.
- **Demolition or repair cost.** The direct cost of repairing or replacing a damaged brick chimney, typically borne by the building owner, can be substantial for each masonry chimney type. For a perimeter chimney, this work can usually be done with little impact on continued use or occupancy of the building. Repair of interior chimneys can be more complicated.
- **Roof or wall framing damage.** This is usually related to the collapse of the top part of the chimney onto the roof framing. Framing damage can also occur when chimney strap anchors overload ceiling or roof members. This type of damage is rarely life threatening itself, and once the remaining masonry is removed, repairs are usually feasible without completely disrupting occupancy. Relative movement of the chimney and the adjacent wall or roof can also lead to roofing damage and subsequent leaks.
- **Public or private falling hazard.** These are the earthquake safety risks most commonly associated with brick chimneys. They are significant for all of the unrestrained masonry chimney types. Even restrained chimneys pose a falling hazard if the unrestrained extension above the roofline breaks apart (in probably the most common failure mode) and falls or slides to the ground. If an apartment building boiler chimney is located in a sparsely occupied lightwell or storage area, it might represent a lesser safety risk. In many cases, however, the chimney is adjacent (or even attached) to a rear exit stair in the same lightwell and thus might represent the same safety risk as a setback house chimney adjacent to a driveway or rear yard.
- **Habitability loss: Egress.** This risk, related to the falling hazard, arises when a chimney is damaged but does not fall. In such a case, the adjacent areas are roped off for safety during the aftershock period or until the remaining masonry can be removed. In most cases, this has little effect on continued occupancy, but if the restricted area is a code-required egress, as in the case of many apartment buildings, it can inhibit

full recovery of a building's legal habitability. Where the egress hazard affects a public way, it can interfere with sidewalks, traffic, or other public accommodations until the dangerous condition is eliminated, but it probably does not affect the reoccupancy of the building in question.

Perhaps the two most interesting points suggested by Table 3-1 involve conditions specific to San Francisco's buildings and chimneys; these risks have not been considered by past efforts that focused on suburban house chimneys:

- The unrestrained Victorian rowhouse chimneys with public exposure (adjacent to streets or sidewalks), while relatively few, represent an appreciable risk to public safety. A few other building types might present similar public risks (as shown in Figure 2-3c and d). A restrained chimney might also present a similar public risk if the portion above the roofline is inadequately braced and anchored.
- Apartment building boiler chimneys represent only a small or moderate safety risk but could pose a significant risk to housing habitability if damage to the chimney means a loss of heat or hot water to an entire building, or if chimney collapse renders required egress stairs unusable.

3.2 Past Performance

Postearthquake reconnaissance efforts have counted chimney damage in many past events, but neither contemporary nor recent analytical models have been able to predict specific damage patterns with much reliability. Of the chimney types described in Chapter 2, robust performance data from actual earthquakes exist only for the setback house and Victorian rowhouse chimneys.

Performance data for Victorian homes comes almost entirely from the 1906 earthquake (but see also EERI (2014) regarding damage to historic chimneys in the Napa earthquake). Already in 1906, several damage scales recognized that masonry chimney failure (along with plaster cracking) was common and would occur more frequently, and at lower shaking intensities, than structural damage in either wood or masonry buildings (Lawson et al., 1908, p.222). Indeed, among the wood-frame buildings that dominated San Francisco in 1906, the most common damage came from their masonry chimneys (Tobriner, 2006).

Chimney damage was extensive throughout San Francisco and Peninsula cities in 1906, even where structural damage was relatively rare. One contemporary engineering study claimed "the effect of the earthquake was to shake down about 95 per cent of all the chimneys within the area affected"

(Himmelwright, 1906), and another noted chimney collapses – especially failure at the roofline – "everywhere … even where there was no other damage" (Sewell, 1907). However, both of these reports made only passing observations about wood residential buildings, focusing instead on "fire proof" steel and concrete structures. The famously thorough Lawson et al. report (1908) made distinctions by neighborhood and still noted widespread chimney failure:

> "[O]ver a large part of [San Francisco], far the larger part, the [structural] damage was slight both in amount and character. Almost everywhere chimneys were thrown down or badly broken, but in a few small localities most of the chimneys withstood the shock. … No district … exhibited any destructive effects of a more violent kind than the fall of chimneys. … The tops of Telegraph Hill and Russian Hill are districts in which a large part of the chimneys withstood the shock. This was also the case with the upper slopes of the chert hills about the head of Market Street, at the center of the area. … San Bruno Mountain, however, was about as near to the zone of faulting as Point Lobos, where most of the chimneys were thrown. … The general fall of chimneys … characterizes the northeastern half, or possibly two-thirds, of the city and county … In the Western part of the city proper, the Richmond district, the Sunset district, and Golden Gate Park, there are several places where chimneys were quite generally destroyed and houses were shifted slightly on their foundations."

From these descriptions, one might wonder how thousands of Victorian chimneys remain today. Perhaps the city's many lowered chimneys, as shown in Figures 2-5, 2-7 and 2-8, explain the discrepancy, or perhaps some of the damaged chimneys were rebuilt. In any case, it is unclear whether the remaining Victorian rowhouse chimneys are as vulnerable as those that were widely damaged in 1906. Without ground motion data, it is impossible to know whether the tops of 1906 chimneys were vulnerable even to small shaking or whether the remnant actually survived what would be considered a "design basis" demand today.

In San Francisco, many of the chimneys in question are of the tall Victorian rowhouse style described in Chapter 2. Throughout the Peninsula and South Bay, however, much of the housing stock comprised one- or two-story wood frame houses closer to the setback house type. In these cases too, the Lawson report notes extensive damage. Town by town, the losses were described the same way: near total failure of brick chimneys, even while the wood frame houses performed well. According to Lawson et al.(1908, p.246, p.257, p. 279) in Belmont, "over four-fifths of the houses lost their chimneys." In San Mateo, "nearly every brick chimney in town was shaken down." Near

Burlingame, many houses were "badly wrecked, due to the falling of extra heavy chimneys thru the roofs." In Palo Alto, "chimneys were mostly knocked down, those that remained standing being for the most part in the centers of the houses," and "all brick chimneys along the upper part of [Page Mill and Alpine] road were thrown down." In Newark, "nearly all brick and tile chimneys in the village were broken off, [though] most of the frame dwellings showed no effects of the shock." Similarly in Milpitas, "nearly all chimneys were here thrown down [though] there are no brick buildings in the village and the destruction [of buildings] seems insignificant." Toward San Jose, "about 90 percent of the chimneys were thrown down," and in Calaveras Valley, "all the brick chimneys were thrown down [though] no damage to houses is reported."

Overall, 88 percent of examined chimneys throughout the Peninsula "fell," and many with and without fallen "tops" also "were injured or cracked at the base or somewhere within the house," while some "crumbled away entirely" (Lawson et al., 1908). Better performance was associated, anecdotally, with:

- Location within the interior of the house
- Bearing on "shelves within the house," as opposed to a separate foundation on soil
- "Low, solid structure above the roof," often enclosed by wood framing or braced with iron rods. Today, rod bracing of heavy brick chimneys is no longer considered effective (ASCE, 2014; FEMA, 2015; see also Chapter 5)
- The use of cement and lime mortar, as opposed to just lime. The report noted, however, that while cement inhibited crumbling, cracking at the roofline could still occur, and the cement mortar would cause the cracked portion to fall as a solid unit. The same concern would later be voiced about masonry chimneys reinforced with steel corner bars.
- The use of iron stovepipes, terra cotta chimney pots, or concrete instead of brick masonry.

Although brick chimneys were observed to be highly vulnerable, reliable damage predictors and critical ground shaking levels remained elusive. This was only partly due to a lack of strong motion data. At three identical one-story houses on adjacent lots in Palo Alto, one chimney remained standing while the other two fell (Lawson et al., 1908), demonstrating the sensitivity of response and foreshadowing the difficulty of an analytical approach to chimney evaluation and mitigation.

In the 1989 Loma Prieta earthquake, shaking levels in San Francisco were far lower than either those in 1906 or those used for the design of new buildings today. Thus, the city's post-1906 chimney types, including the apartment building boiler chimneys and most setback house chimneys, have not yet been tested by an actual event. Communities closer to the 1989 epicenter did see the usual types of chimney damage, however, and every major west coast earthquake since 1971 has confirmed the poor performance of brick chimneys, with and without reinforcing.[1]

3.3 Fragility Estimates

Efforts to quantify the risks identified in Table 3-1 in terms of fragility (that is, probability of failure) have found limited success, as the earthquake response of chimney structures is complex and sensitive (FEMA, 2012c; Krawinkler et al., 2012). First, the strength and ductility of key components, such as mortar, wall or roof ties, rod bracing, and reinforcing bond or development, are not reliably known for existing chimneys often a century old. Second, nonlinearity in cracking, rocking, sliding, or mortar crushing can occur at low shaking intensities and early in the ground motion record. Third, although damage has been recorded in many past earthquakes, little research has been done to inventory the observed damage modes or to link them to measured ground shaking. Fourth, the dynamic characteristics of chimneys differ dramatically from the light-framed residential structures to which they are (sometimes nominally) attached, leading to complex interactions. Finally,

[1] 1971 San Fernando: About a 35 percent chimney damage rate among pre-1930 houses in two Glendale neighborhoods. Severe damage pervasive among pre-1930 chimneys in a survey of about 12,000 houses throughout the affected area. 1992 Landers and Big Bear: Preliminary estimate of 2,600 chimneys "destroyed" in affected area of about 11,000 total buildings (9,000 residential) while only 20 residences "detached from their foundations" (EQE, 1992). Code official estimate of 4,500 fireplaces and chimneys "damaged," including substantial damage to poorly built reinforced masonry chimneys (Samblanet, 1992). 1994 Northridge: About a 24 percent damage rate in a set of 233 chimneys of all types, subjected to a range of shaking levels. Throughout the city of Los Angeles, about 30,000 permits taken for chimney repair. Among pre- and post-1940 chimneys, "high damage and collapse" in peak ground acceleration of 0.25g and higher, with all pre-1940 chimneys having at least cracking damage at PGA of 0.45g or higher (Graf, 2008). 2000 Yountville: Hundreds of brick chimneys damaged, some collapsed; of 41 patients treated by Queen of the Valley Hospital, the only in-patient admission was due to falling chimney masonry (Eidinger et al., 2000). 2001 Nisqually: About a 3 percent rate of visible damage in a survey population of about 60,000 chimneys. About a 33 percent rate of visible damage among 84 chimneys in Olympia. 2003 San Simeon: About a 24 percent damage rate in a survey of 97 chimneys. 2010 Humboldt County: At least 78 chimneys in Eureka yellow-tagged, indicating remaining risk (EERI, 2010). 2014 South Napa: "[M]any residential masonry chimney failures were reported throughout Napa and the surrounding region [involving] both crumbling of masonry and toppling of entire chimneys. Many masonry chimneys … north of downtown Napa had been removed or replaced before the earthquake, possibly due to damage from the 2000 Yountville earthquake" (EERI, 2014). Unless noted otherwise, all of the foregoing summaries are from FEMA (2012c).

even if certain damage modes were more predictable, their association with non-physical losses, such as repair costs or loss of habitability, remains under-studied.

For mitigation programs, the main implication of this complexity is that simple, reliable evaluation tools based on traditional engineering methods are not available. Evaluation methods will rely either on prescriptive checklists and rules of thumb, or on relatively abstract probabilistic relationships derived from rough data.

Nevertheless, observations of past performance do reveal a number of distinct failure modes, and analysis can shed some light on their fragility relative to each other and to normative measures of seismic risk.

Analytical prediction of masonry chimney damage is difficult.

FEMA P-58/BD-3.9.7 (FEMA, 2012c) presents models of sliding (or distinct cracking) and toppling failure for masonry chimneys. It provides models of each chimney as an idealized rigid block, either "freestanding," bearing on the ground and otherwise not attached (or loosely or inadequately attached) to the adjacent one-story house, or "rooftop," anchored firmly to the structure at the roofline. Thus, for freestanding chimneys, both the sliding and toppling failure modes are probably more representative of reinforced masonry than unreinforced, because unreinforced masonry tends to disintegrate into a pile before tipping or sliding as a cohesive unit. For rooftop chimneys, both modes are more representative of unreinforced masonry, which can break at the roofline, except that masonry disintegration due to weak mortar was not modeled. Figure 3-1 illustrates these basic failure modes for freestanding chimneys and Figure 3-2 illustrates these for rooftop chimneys.

Table 3-2 summarizes the values presented in FEMA P-58/BD-3.9.7, including the fragility given a peak ground acceleration (PGA) between 0.4g and 0.6g. This PGA range represents the design basis demand for new construction in San Francisco: 0.4g throughout most of the city, increasing to 0.6g in western neighborhoods closer to the San Andreas fault. (It is also roughly the range of accelerations felt in San Francisco in 1906.)

Toppling is often, but not always, preceded by sliding/cracking. Thus, although Table 3-2 shows that in each of these idealized cases, the chimney is more prone to sliding than toppling (higher probability values), toppling might be thought of as a subset of the sliding cases. Also, the models did not account for the mortar failure or general disintegration of unreinforced chimneys documented after many earthquakes (see Figure 3-1); such material failures would certainly lead to falling hazards even if toppling of an intact unit were avoided.

(a)

Note failure/pullout of ties to ceiling framing. (Source: City of San Leandro)

(b)

Crumbling of multi-story chimney. Note ineffectiveness of roofline “restraint.” (Source: EERI)

(c)

Similar to San Francisco boiler type. Note strap anchor just above crumbled lower section. (Source: FEMA)

(d)

Sliding/cracking damage at firebox (plus rooftop toppling). Napa, 2014. (Source: californiawinefan.com)

Figure 3-1 Masonry chimney damage below the roof line, modeled with "freestanding" models: (a) toppling; (b) and (c) crumbling or disintegration of unreinforced or ineffectively reinforced masonry; and (d) sliding or cracking.

Table 3-2 also allows a comparison of two different 15-ft tall chimneys, one freestanding for 15 feet above grade and one anchored at the 10-ft roofline and extending five feet above it. The values suggest that the 5-ft rooftop extension is less prone to toppling than the 15-ft tall freestanding chimney (13 versus 60 percent) but is just as prone to sliding failure at the roofline (90 versus 88 percent), due to the acceleration imposed by the response of the one-story house itself.

(a)

Toppling through roof framing. Christchurch, 2011. (Source: stuff.co.nz)

(b)

Sliding/cracking at roofline, leaving potential falling hazard. Napa, 2014. (Source: Eilis Maynard)

(c)

Rooftop crumbling leaves falling hazard. Napa, 2014. (Source: ABC7news.com)

Figure 3-2 Masonry chimney damage at the roof line, modeled with "rooftop" models: (a) toppling; (b) sliding or cracking; (c) crumbling or disintegration of unreinforced or ineffectively reinforced masonry.

Table 3-2 Probability of Failure of Idealized[1] Masonry Chimneys at Peak Ground Acceleration between 0.4g and 0.6g (FEMA, 2012c)

	Freestanding[2] (Height above ground)			Rooftop[3] (Height above 10-ft roof)	
	11 ft	15 ft	19 ft	5 ft	9 ft
Toppling[1]	17% - 47%	32%- 60%	37%- 65%	3%- 13%	11%- 42%
Sliding[1]	30%- 78%[4]	43%- 88%	46%- 79%[4]	54%- 90%	95%+

NOTES:

1 "Idealized" means that each chimney is modeled as a rigid block of uniform cross-section for which resistance to toppling is provided by gravity alone, and resistance to sliding is provided by friction along its base (a slide of 1/16 inch represents sliding or cracking failure).

2 "Freestanding" means bearing at grade level along the outside perimeter of the building (that is, unrestrained) and not attached, or loosely or inadequately attached, at the roofline. Toppling or sliding failure occurs at the base.

3 "Rooftop" means bearing at grade level along the outside or within the building and rigidly attached to the structure at the roofline, with no additional restraint or bracing of the height above the roofline. Toppling or sliding failure occurs at the roofline.

4 These values, not reported in FEMA (2012c), were provided by the ongoing ATC-58-2 project.

In all cases, the fragilities given in Table 3-2 are quite high, generally indicating a probability of failure between 40 and 90 percent for a design-basis demand.[2] For comparison:

- For a new building, the probability of collapse in an extreme event is presumed, conservatively, to be 10 percent. Thus, the chimney fragility in a design basis event is four to nine times that of a new building in a larger event.
- The collapse fragility of an existing San Francisco "soft-story" building has been estimated as 21 to 64 percent in a magnitude-7.2 San Andreas event, which is somewhat smaller than the design basis for new construction (ATC, 2009a and b). Thus, the chimney fragility is about the same, perhaps a bit higher, than for this building type that has already justified a mandatory retrofit program. A soft-story building collapse certainly has worse consequences than a chimney collapse, but a soft-story retrofit also has much higher costs than chimney mitigation.

In brief, the risks posed by chimneys have been documented repeatedly, and their fragility can be quantified as significantly higher than that of new

[2] The FEMA P-58 (FEMA, 2012b) methodology utilizes FEMA P-58/BD-3.9.7 but reduces the analytical findings to a generic fragility relationship for all unreinforced masonry chimneys. For PGA of 0.4g to 0.6g, the generic values are 35% to 61% for toppling, 59% to 81% for cracking/sliding.

construction, and perhaps as high or higher as some of the city's riskiest buildings.

Of the chimney types described in Chapter 2, the FEMA P-58 models most closely represent the setback house chimneys. The Table 3-2 data, however, is for one-story houses; two-story houses would be expected to have even higher chimney fragilities due to the greater height of the freestanding chimney and higher potential roof acceleration of the taller house.

Apartment building boiler chimneys have uniform cross sections and are generally unrestrained by the building assuming the nominal tie at the second floor is loose or inadequate. Those that do not crumble would therefore appear to be well represented by the FEMA P-58 freestanding model (these models go upto 19 feet).

Victorian rowhouse chimneys, however, are not well represented by the freestanding model, as even those that are not restrained by wall framing are almost always anchored (perhaps unintentionally, and perhaps inadequately) by a fascia board or molding at the roofline. The extensions above the roof, however, are probably well represented by the rooftop model, the difference being that many Victorian rowhouses are three stories tall, while FEMA (2012c) assumed only a one-story building. The rooftop data in Table 3-2 may be taken as an initial fragility estimate for the extensions above the roof, subject to modification to capture the effects of a taller structure and the effects of weak mortar, both of which can be expected to increase fragility and falling hazards. Of course, unreinforced masonry chimneys are also known to disintegrate, or crumble, regardless of anchorage or restraint, as shown in Figures 3-1b, c, and Figure 3-2c.

Chapter 4

Prescriptive Mitigation Approaches

As described in Chapter 3, the detailed response of a masonry chimney is hard to model with reliability. Assessment tools therefore continue to rely on basic prescriptive checklists, such as those in ASCE/SEI 41-13 (ASCE, 2014) asking questions such as: Is it reinforced? Is it anchored at floor and roof levels? Is the height above the roof less than twice the width? These prescriptive assessments suggest equally prescriptive mitigation standards, but few mitigation tools have been developed, particularly for special cases like San Francisco's tall Victorian chimneys. Rather, the leading mitigation tools were developed as guidelines for repair (FEMA, 2012a). Applying these tools in pre-earthquake mitigation will require some adjustments, as well as an understanding of their limits.

The focus of this report is on mitigation, as opposed to repair. Without widespread mitigation, San Francisco will eventually need repair provisions as well, and the documents described in this section will almost certainly be pressed into service. A mitigation perspective, however, focuses on the particular subcategories of risk, identified in Table 3-1 that might be worth addressing in advance. It will allow San Francisco to anticipate the issues that arise postearthquake (such as aftershock safety, expedited permitting, and housing reoccupancy) and those that deserve policy attention unhurried by post-earthquake urgency, (such as cost-sharing, retrofit incentives, and historic preservation). Chapter 5 offers policy recommendations from this mitigation-based perspective.

> Applying repair guidelines to mitigation will require some adjustments for San Francisco conditions, as well as an understanding of the guidelines' limits.

4.1 Current Prescriptive Provisions

Jurisdictions with prescriptive chimney provisions generally adopted them after damaging earthquakes: Napa did so after the 2000 Yountville earthquake (Napa-A, B, and C), Seattle after the 2001 Nisqually earthquake (Seattle, 2004), and San Luis Obispo after the 2003 San Simeon Earthquake (San Luis Obispo, 2004). The Napa and San Luis Obispo provisions in particular are based on provisions adopted by the city of Los Angeles after the 1994 Northridge earthquake. The Los Angeles provisions have been updated for code coordination purposes (Los Angeles, 2014) but remain essentially the same today as they have been since at least 2001. The earlier version bore the stamp of the Los Angeles Regional Uniform Code

Program (LARUCP), indicating that it was used or accepted by jurisdictions throughout greater Los Angeles. The most recent repair provisions, developed by FEMA after the 2014 South Napa earthquake prescribe the same basic approach as Los Angeles (FEMA, 2015).

The Los Angeles and FEMA repair provisions call for replacing a portion of the damaged masonry chimney with a metal flue and a steel stud-framed enclosure (generally factory-built) to be anchored to each floor and roof level and braced to the roof framing if it extends above the roofline more than four feet. A hallmark of the Los Angeles provisions is that they distinguish between reinforced and unreinforced chimneys:

- Damaged unreinforced masonry is to be removed down “to the throat of the nearest undamaged firebox.”
- Damaged reinforced masonry need only be removed to the next lowest roof, floor, or firebox.

The Napa provisions (Napa-B, C) allow for a wood-framed enclosure as an alternative to steel and also provide details (Napa-A) for a chimney within the interior of the building.

Consider, for example, the unreinforced masonry chimneys shown with the setback houses in Figures 2-3a and b. These are conventional-appearing chimneys of the type most clearly contemplated by the Los Angeles prescriptive repair provisions, with defined “throat” locations at the top of second floor fireboxes. For each of these chimneys, a prescriptive retrofit based on the Los Angeles provisions would involve removal of the masonry down to the top of the throat, about five feet above the second floor and replacement of the removed portion with a metal flue and light-framed enclosure. Applying these provisions to retrofit, the second floor firebox would remain in place, unanchored even at the second floor level.

Consider next the chimneys shown in Figures 2-3c and d and the Victorian rowhouse chimneys in Figures 2-6 and 2-7. As these do not have pronounced “throats” or “shoulders,” it is unclear how much masonry would need to be removed to reach the highest firebox. Even so, as with the previous cases, the Los Angeles provisions would not require anchorage to the second or third floor framing.

Finally, consider the apartment building boiler chimneys shown in Figure 2-4. Here, there is no firebox, so application of the Los Angeles provisions for retrofit would require either removing the entire masonry stack or simply anchoring it at the second floor level.

Thus, the scope of the Los Angeles and similar provisions would need to be better defined for San Francisco chimneys, but the intent to remove at least the topmost sections of unreinforced masonry is clear.

By contrast, the Seattle (and also Burbank (2008)) provisions allow damaged masonry to be replaced with reinforced masonry. Seattle explicitly makes a risk-based judgment: "[B]ecause earthquakes are less frequent in Seattle than in parts of California, DPD does not feel it is necessary to remove all unreinforced masonry chimneys." The prescriptive Seattle provisions also apply to chimney alterations, not just repairs.

4.2 Mitigation Considerations

Applying the available prescriptive repair provisions to pre-earthquake retrofit will require some adjustments for San Francisco conditions. The mitigation context also offers an opportunity to consider options that might not be available during the rush to repair. Lower cost alternatives for minimum safety improvements are also worth considering, though they will likely be less effective for mitigating financial and recovery risks.

The first question is whether to leave any masonry in place once the decision to retrofit has been made. Some of the prescriptive repair provisions require thorough anchorage of the remaining masonry to the building's wood framing at floor and roof levels (Los Angeles, 2014; Seattle, 2004; Burbank, 2008). However, FEMA 547, *Techniques for the Seismic Rehabilitation of Existing Buildings*, (FEMA, 2006) adds a caution about how to angle the steel anchor straps to ensure a rigid anchorage, as shown in Figure 4-1.

A strong and rigid anchorage will certainly help prevent toppling failure and could help to hold the masonry together if it does crack. The more tightly the existing chimney is anchored to the framing, however, the more it becomes a de facto part of the building's lateral system, and this illustrates a shortcoming of prescriptive retrofit solutions. If the chimney itself is rigid enough, it can affect the overall structural response, complicating mass and torsional properties, and inhibiting otherwise beneficial flexibility of wall and floor diaphragms. If held tightly to the structure, the chimney is forced to resist interstory deformations, possibly leading to damage near the base or below the anchor point, as shown in Figure 3-2.

There is little doubt that thorough anchorage is a net benefit for a retrofit that leaves the existing masonry in place. Still, without a reliable analytical approach, these prescriptive solutions will remain problematic. For these reasons, the growing consensus is that the best mitigation approach to non-conforming masonry chimneys, especially of unreinforced masonry, is simply to remove as much of the masonry component as possible and, if a functional chimney is needed, to replace it with a lightweight flue and a light-framed enclosure (FEMA, 2015).

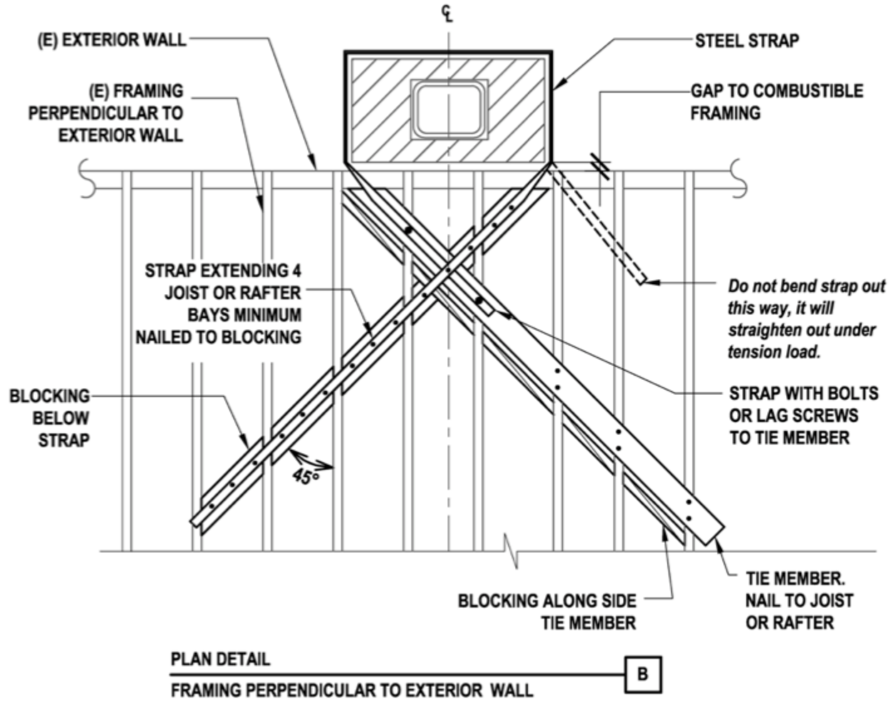


Figure 4-1 Anchorage of an exterior masonry chimney from FEMA 547 Figure 5.4.6-2B (FEMA, 2006).

Rational arguments might be made to keep an unreinforced masonry chimney in place. One is that the cost of repair might be less than the cost of mitigation, especially where the masonry is restrained behind exterior or interior finishes. Another is that the masonry is sometimes an historic resource worthy of protection. While rational, each of these arguments must acknowledge that substantial earthquake damage is possible, even likely, so that if the masonry is to remain in place, any substantial safety risk should still be mitigated, and the building should still be made capable of recovering while the chimney is being repaired or replaced.

Another consideration for mitigation proponents involves the desirability of a traditional wood-burning fireplace. If a firebox is removed as part of a voluntary retrofit, current *San Francisco Building Code* Section 3111 would prohibit reinstallation of a wood-burning unit, requiring an environmentally friendly appliance instead (except for certain historic cases) (San Francisco, 2015). This can create a disincentive to retrofit for some owners. (Paradoxically, if the masonry firebox were damaged in an earthquake, the code would allow it to be rebuilt as wood-burning.) In the case of a first-story firebox, keeping the masonry is not far different from the Los Angeles or

FEMA prescriptive repair. In the case of an upper story firebox, as shown in Figures 2-3b or c, 2-6, or 2-7, the desire to keep a wood-burning fireplace might prompt an owner to leave a relatively tall stack of masonry in place.

Additionally, the detailing of the light-framed enclosure that would replace the masonry might be more extensive than the prescriptive Los Angeles or FEMA provisions would suggest. Both Los Angeles and FEMA contemplate a chimney whose footprint is entirely outside the plan of the house. In practice, as shown in Figures 2-3a and d, and Figures 2-5 through 2-8, San Francisco chimneys frequently disrupt, or intersect with, the perimeter wall framing. Also, many San Francisco buildings – even many setback houses – have tight lot lines and are closer to their neighbors than fire codes for new construction would allow. In both of these cases, the building code might require the inside of the light steel-frame enclosure to be sheathed or taped for fire safety, changing the prescribed detail and increasing the cost of retrofit (Bailey, 2015).

The safety issue is perhaps already covered for chimneys behind sturdy finishes and with minimal extensions above the roof (for examples, see Figure 2-5). If not, enclosure of exposed masonry and lowering of the chimney extension are feasible, lower cost solutions. But enclosure or partial removal will not work for exposed ornamental chimneys at the perimeter of historic Victorian rowhouses, like those in Figures 2-7 or 2-8. For historic preservation, FEMA 547 suggests filling the chimney or the space between the masonry and the flue with concrete and reinforcing steel; this holds the masonry together, preventing a complete crumbling failure and mitigating the falling hazard. This solution adds weight to the chimney, however, and requires even more robust anchorage to roof and floor framing, possibly affecting the building's overall performance, as noted above. An alternate approach involves building a steel exoskeleton or cage around the outside of the chimney to hold large chunks of cracked masonry in place. This solution will affect the appearance of the chimney, although the steel could be painted to match the often-painted exposed brick. This is also more reversible than concrete infill, and not inconsistent with principles of historic preservation that prefer to make modern alterations, including safety improvements, sensitive to but visually distinct from the historic fabric (Look et al., 1997).

A low-cost mitigation to reduce some losses due to rooftop toppling (see Figure 3-1) involves strengthening roof and attic floor framing with sturdy plywood sheathing (CSSC, 2005; FEMA, 2015). Some references have also suggested limiting use or access to areas adjacent to chimneys. While probably wise during a period of expected aftershocks, this is an impractical long-term solution.

4.3 Mitigation Benefits and Costs

4.3.1 Benefits

The benefit of any mitigation can be quantified as the cost of damage avoided. Without a reliable analytical model, the benefits of chimney retrofit cannot be quantified in the same way as structural retrofit, but the fragility data in Table 3-2 do offer a general understanding in terms of reduced fragility.

Consider the unreinforced masonry chimneys shown in Figure 2-3a and b, for which prescriptive retrofits were described earlier in this Chapter. Assuming a retrofit design demand with a peak ground acceleration of 0.4g:

- If the chimney in Figure 2-3b is unrestrained, with a freestanding height greater than 19 ft (two full stories, plus an attic, plus a small extension above the roof ridge), Table 3-2 suggests an overall existing fragility of at least 46%, with a high likelihood that if damage occurs, it will involve toppling as well. As noted in Chapter 3, these figures do not include consideration of overall crumbling failure; if this chimney is actually well anchored at the second floor and roof levels, its small extension above the ridge would lower the toppling fragility, but with weak mortar it would still be vulnerable to crumbling failure.
- The chimney in Figure 2-3a is more restrained by its roof framing, but with an extension of about 5 feet above the roof, Table 3-2 suggests an even higher fragility, 54%, due to potential roof acceleration effects.

Assume either of these chimneys is retrofitted by removing the portion above the second floor firebox and anchoring the remaining masonry to the second floor. Only the portion remaining above the second floor will be subject to failure, as a quasi "rooftop" condition, assuming the remaining masonry has mortar strong enough to resist crumbling. Yet Table 3-2 indicates that the fragility will still be high, 54%, as the unanchored second floor firebox is little different from an unanchored extension above the roof (with the possible mitigating effect of only being able to topple in one direction).

These estimates should not be considered precise or specific to the chimneys in Figure 2-3; however, they nevertheless suggest a highly damageable condition, even after retrofit, as long as the masonry above the second floor anchorage remains in place. Even so, there is some benefit to having cracking damage in only the remaining 10 or 15 feet of masonry, as opposed to a potential toppling failure from 20 feet over a yard, sidewalk, or driveway. Translating this benefit into dollar terms requires a case-specific understanding of which risks from Table 3-1 might apply – loss of life, damage to roof framing or property below, or loss of a functional chimney.

4.3.2 Costs

Costs[1] of pre-earthquake chimney retrofit are not well documented. Even post-earthquake repair costs, for which ample permit records exist, are not well studied or specific.

Earthquake repair permit data from the city of Los Angeles includes about 30,000 records of work done after the 1994 Northridge earthquake using the Los Angeles provisions described above. While the potential scope of those provisions is known, the permit records are not linked to the nature of each repair, so the recorded costs range from $300 to $16,000. The data show no correlation with estimated peak ground acceleration, which ranged from about 0.2g to about 0.8g (FEMA, 2012c).

Repair cost data for 27 chimneys at properties insured by the California Earthquake Authority, compiled after the San Simeon earthquake, show no correlation with ground motion. While the costs are not linked to damage or repair scope, they do cluster into two groups: about one third at $2,500 or less, and the balance ranging from $6,500 to $18,000 (FEMA, 2012c).

Based on these findings, the FEMA P-58 *Seismic Performance Assessment of Buildings* methodology (FEMA, 2012b) assumes the cost to replace a damaged masonry chimney with a framed chimney to be between $6,000 and $15,000, depending on the chimney height. (Refer to fragility classification B3031.002a through B3031.002c, escalated from 2013 costs in FEMA (2012c))

The *Homeowner's Guide to Seismic Safety* (CSSC, 2005) gives a cost range from $2,500 to $15,000 for mitigation ranging from simple removal to replacement with a light-framed firebox and chimney.

For a single-family house in San Francisco, one Bay Area contractor provided an estimate of $22,500 to replace a two-story unreinforced masonry chimney with a metal flue and light-framed enclosure from the top of the second floor firebox, *not* including strap anchors from the remaining masonry to the second floor framing (McGuire, 2015). This solution would remove about 15 feet of masonry and leave about 15 feet of masonry in place, unrestrained, at the first and second stories adjacent to the house's front entrance.

[1] All costs reported in this section are 2015 costs, escalated using the Bureau of Labor Statistics' Consumer Price Index Inflation Calculator.

Since voluntary mitigation is likely to involve a larger scope of work than many nominal repairs, retrofit cost will probably be closer to the upper ends of the foregoing repair cost ranges. Further, the retrofits most likely to justify policy mandates or triggers (as opposed to voluntary work) will also probably be of more thorough scope. Therefore, for a retrofit based on the 2014 Los Angeles or 2015 FEMA provisions – replacement of the masonry with a metal flue and a light-framed enclosure from the top of the lowest firebox – a reasonable first estimate of cost would be $15,000 to $25,000. Retrofit of setback house chimneys might fall anywhere in that range. Retrofit of apartment building boiler chimneys, which are relatively simple components with little aesthetic or historic value, would likely be at the low end of that range. Retrofit of tall, perimeter, unrestrained Victorian rowhouse chimneys would likely be at the high end of the range, but alternative approaches designed for historic preservation would require separate cost data entirely.

Chapter 5

Summary and Policy Recommendations

5.1 Summary of Findings

San Francisco houses and multi-unit residential buildings have over 100,000 patent flues. They represent relatively little risk in terms of safety during an earthquake. However, the ceramic liners are prone to earthquake damage, and damaged flues can lead to fires and can expose residents to toxic combustion by-products. Therefore, any patent flue that has undergone strong earthquake shaking should be inspected before being used, and repaired or replaced, as needed.

There are a few thousand setback houses with masonry chimneys in San Francisco, most of them unreinforced and inadequately anchored. The sizes, styles, configurations, and subsequent deficiencies and risks vary significantly, but ample experience in past earthquakes has shown them to be highly vulnerable to damage in San Francisco's design-level ground shaking – much more so than the wood-frame structures to which they are attached. The risks posed by these chimneys are largely private, borne by the owners and tenants of the houses in question, but they include falling hazards, structural damage, and substantial repair costs. Prescriptive details originally developed for damage repair are adaptable to retrofit but will need to clarify the minimum scope required for any specific incentive or performance objective. Prescriptive provisions would generally contemplate replacing the masonry chimney with a metal flue and a light-framed enclosure from the top of the lowest firebox, while anchoring the remaining masonry to the existing floor framing. This scope of retrofit can be expected to address the worst falling hazards, but it will not protect unreinforced masonry with weak mortar from crumbling. The cost of such a prescriptive retrofit might range from $15,000 to $25,000, depending on the homeowner's architectural and functional choices.

About 1,000 apartment buildings, mostly built between 1920 and 1940, use unreinforced masonry chimneys at perimeter walls to vent boilers or other appliances. In addition to the falling hazard to tenants, failure of these chimneys would represent a potential loss of heat and habitability for days to weeks (and in some cases a loss of required egress) that could slow the recovery of the city's housing stock. Because these chimneys have no aesthetic or historic value, are relatively simple in configuration, are often no more than two stories tall, and are typically built entirely outside and independent of the building's wood siding, complete replacement with a modern flue and an appropriate enclosure is expected to cost up to $15,000, though there might be additional costs associated with upgrading the affected mechanical equipment.

San Francisco has about 30,000 Victorian rowhouses, and practically each one has at least one unreinforced masonry chimney. The tops of many of them (that is, the extensions above the roofline) were damaged and removed after either the 1906 earthquake or after Loma Prieta in 1989, but the remaining portions, often three stories tall, are vulnerable to failure by toppling, sliding and cracking, or crumbling due to weak mortar.

Many of the Victorian rowhouse chimneys are located within the interior of the building plan or are otherwise restrained from hazardous collapse by interior or exterior wall finishes. These cases represent a lower safety risk but a substantial repair cost for owners. Repair cost is compounded if the chimney is still used to vent a working fireplace or appliance. Because of the wall finishes, retrofit might be expensive relative to the benefit, especially if the archaic chimney is no longer used. If the chimney extends more than a foot or two above the roofline, however, replacing that portion with a metal flue extension will mitigate much of the safety risk and potential roof damage.

At least half of the remaining Victorian chimneys are located along the building's perimeter wall adjacent to a lightwell, driveway, or courtyard. These cases represent a private or semi-private safety risk, whether or not they are nominally restrained by cornices or fascia boards at the roofline. If the tops have not been lowered already, they also represent a risk of structural and roofing damage. As with the unreinforced setback house chimneys, prescriptive retrofit by removal or replacement is feasible, with a conservative rough cost of $25,000, but any masonry left in place might still be vulnerable to crumbling due to weak mortar. Chimneys subject to historic preservation might require different retrofit solutions, with possibly higher costs.

A subset of about 1,000 to 1,500 unrestrained perimeter chimneys, while small, represents a substantial public risk akin to that posed by unreinforced brick parapets (though less severe or extensive). These are the cases of perimeter chimneys adjacent to public sidewalks, streets, or parking. At minimum, tall extensions above the roof should be lowered. Because of the public risk, a strong case can be made for mandatory risk reduction for the full chimney height.

5.2 Policy Recommendations

The purpose of this report is to compile, analyze, and present background data that will inform policy development in a later phase or by others. Nevertheless, the summary items above suggest a number of actions or policies for further consideration by ESIP and city agencies. Each of the four policy recommendations below represents a judgment-based consideration of the public effects of private risk. Implementation of any of these actions or policies should involve a review by the City Attorney of potential liability – both the city's and the building owner's – associated with both current and mitigated conditions.

Recommendation 1: Prepare for post-earthquake chimney inspections

The Department of Building Inspection (DBI), working with private sector consultants, should prepare advisories (and regulations as needed) to ensure that every vulnerable chimney and flue is inspected after a damaging earthquake before being put back into use. The cost of this work would be borne by building owners, but the city should benefit from a timely messaging campaign, the cost of which might be shared by vendors and contractors. The campaign could involve annual reminders, included with property tax notices or boiler inspection forms, but a post-earthquake campaign would likely be more effective. The days and weeks after a damaging earthquake provide multiple opportunities to give advice on repair, both through the media and through city-managed response and recovery efforts. A campaign in October or November after the earthquake would provide effective reminders as cold weather approaches.

Recommendation 2: Encourage voluntary mitigation

DBI should adopt, by administrative bulletin, prescriptive provisions for voluntary mitigation of common hazards, particularly those that pose only limited public risk to safety or habitability and therefore do not warrant retrofit mandates or triggers. The provisions would give owners a useful standard for negotiating with contractors, would provide DBI with a basis for permit approval and inspection, and could be established as the criteria for possible incentive programs. DBI should prepare advisories to notify owners of the availability of the voluntary provisions and to encourage their use. Two sets of prescriptive provisions are recommended:

1. For reinforced or unreinforced masonry chimneys that extend above the roofline by more than two times the least chimney width, the provisions

would call for removal of the masonry down to one foot above the roof and either capping the unused shaft or replacing the chimney with a metal flue braced to the roof framing. (Installation of plywood to protect existing framing from falling masonry could be noted as a non-preferred, but possibly less expensive interim or partial solution.)

2. For reinforced or unreinforced masonry chimneys located along perimeter wall lines of setback houses or rowhouses, the provisions would be similar to those recommended by FEMA and already in use for repair in other California jurisdictions (see Chapter 4). They would call for removal of the masonry down to the top of the lowest firebox (or to the top of the upper firebox as a non-preferred option), either capping the unused chimney or replacing it with a metal flue and factory-built steel enclosure, braced as needed to the roof framing, and anchorage of the remaining masonry to each level of floor framing. (A similar alternate detail can be developed for interior chimneys, but these often require a more customized solution for purposes of architectural coordination and constructability.)

In both cases, the prescriptive provisions will need to anticipate questions regarding wood-burning appliances, currently addressed in the *San Francisco Building Code* Section 3111 (San Francisco, 2015), and proper fire safety for enclosures abutting or near existing wood framing.

Recommendation 3: Mandate or trigger mitigation of public risks

This mitigation strategy addresses the city's most direct and severe chimney-related risk. It would apply to the same conditions addressed by Recommendation 2 where the chimneys are directly adjacent to public property or private property offering a public accommodation, such as a shop or restaurant. The mitigation provisions could be the same as the prescriptive provisions described above, but it is likely that additional criteria will be needed to address historic preservation issues. If a mandate is not achievable, a mitigation trigger could be based on architectural renovation, disproportionate damage in a small event (a concept already defined in the *San Francisco Building Code*), condominium conversion, or creation of an accessory dwelling unit (ADU).

Recommendation 4: Mandate or trigger replacement of apartment building boiler chimneys

The purpose of this mitigation strategy would be to avoid housing loss due to inadequate heating in buildings that could otherwise be reoccupied after an earthquake. Given the nature of these chimneys, the work would involve complete removal of the masonry chimney/flue and replacement with a lightweight flue (with enclosure as needed) suitable to the mechanical equipment in question. In some cases, the existing lightweight flue that extends from the top of the masonry to the roof might need to be replaced or upgraded as well.

The mandate would apply to multi-unit residential buildings of a certain size and age, perhaps pre-1978 buildings with five or more units for coordination with the city's current soft-story program. Through the soft-story program, DBI has already compiled contact information for the owners of more than 6,000 buildings that probably include all the wood-frame buildings that have chimneys of this type. If not mandated, a trigger could be based on upgrade of heating or hot water systems, general architectural renovation, disproportionate damage in a small event, condominium conversion, or creation of an ADU. Whether mandated or triggered, mitigation could begin as a voluntary add-on, eligible for pass-through and PACE (Property Assessed Clean Energy) financing, during mandatory soft-story retrofit.

References

ASCE, 2014, *Seismic Evaluation and Retrofit of Existing Buildings*, ASCE/SEI 41-13, American Society of Civil Engineers, Reston, Virginia.

ATC, 2009a, *Here Today—Here Tomorrow: The Road to Earthquake Resilience in San Francisco, Earthquake Safety for Soft-Story Buildings*, ATC 52-3 report, prepared for San Francisco Department of Building Inspection under the Community Action Plan for Seismic Safety (CAPSS) Project, Redwood City, California.

ATC, 2009b, *Here Today—Here Tomorrow: The Road to Earthquake Resilience in San Francisco, Earthquake Safety for Soft-Story Buildings*, *Technical Documentation,* ATC 52-3A report, prepared for San Francisco Department of Building Inspection under the Community Action Plan for Seismic Safety (CAPSS) Project, Redwood City, California.

ATC, 2010a, *Here Today—Here Tomorrow: The Road to Earthquake Resilience in San Francisco, Potential Earthquake Impacts*, ATC 52-1 report, prepared for San Francisco Department of Building Inspection under the Community Action Plan for Seismic Safety (CAPSS) Project, Redwood City, California.

ATC, 2010b, *Here Today—Here Tomorrow: The Road to Earthquake Resilience in San Francisco, Potential Earthquake Impacts*, *Technical Documentation,* ATC 52-1A report, prepared for San Francisco Department of Building Inspection under the Community Action Plan for Seismic Safety (CAPSS) Project, Redwood City, California.

Bailey, 2015, Scott, Personal communication, August. *Mr. Bailey is with Willson Bailey Construction, Inc., Richmond.*

Burbank, 2008, *Repair of Earthquake Damaged Chimneys,* City of Burbank Community Development Department, Building Division.

CSSC, 2005, *Homeowner's Guide to Seismic Safety,* SSC No. 05-01, California Seismic Safety Commission, Sacramento, California.

EERI, 2010, *The M_W 6.5 Offshore Northern California Earthquake of January 9, 2010*, Special Earthquake Report, Earthquake Engineering Research Institute, Oakland, California.

EERI, 2014, *M 6.0 South Napa Earthquake of August 24, 2014*, Special Earthquake Report, Earthquake Engineering Research Institute, Oakland, California.

Eidinger, J., Yashinsky, M., and Schiff, A., 2000, *Napa M5.2 Earthquake of September 3, 2000: Evaluation of Lifeline Performance*, Earthquake Engineering Research Institute, Oakland, California. Available at: https://www.eeri.org/lfe/pdf/usa_**napa_lifeline**.pdf, last accessed September 21, 2015.

ESIP, 2014, *Mandatory Soft Story Retrofit Program: Preliminary Return*s Earthquake Safety Implementation Program, San Francisco, California. Available at http://sfgsa.org/Modules/ShowDocument.aspx?documentID=12790. Last accessed September 18, 2015. Last accessed September 18, 2015.

EQE, 1992, *The Landers and Big Bear Earthquakes of June 28, 1992*, EQE International.

FEMA, 2006, *Techniques for the Seismic Rehabilitation of Existing Buildings*, FEMA 547, prepared by Rutherford & Chekene Consulting Engineers under contract with National Institute of Standards and Technology with funding provided by the Federal Emergency Management Agency, Washington, D.C.

FEMA, 2012a, *Reducing the Risks of Nonstructural Earthquake damage – A Practical Guide*, FEMA E-74CD, prepared by the Applied Technology Council for the Federal Emergency Management Agency, Washington, D.C.

FEMA, 2012b, *Seismic Performance Assessment of Buildings*, FEMA P-58CD, prepared by the Applied Technology Council for the Federal Emergency Management Agency, Washington, D.C.

FEMA, 2012c, *Fragility of Masonry Chimneys*, Background Document FEMA P-58/BD-3.9.7 by Osteraas, J. and Krawinkler, H., prepared by the Applied Technology Council for the Federal Emergency Management Agency, Washington, D.C.

FEMA, 2015, *Repair of Earthquake-Damaged Masonry Fireplace Chimneys*, South Napa Earthquake Recovery Advisory FEMA DR-4193-RA1, prepared by the Applied Technology Council for the Federal Emergency Management Agency, Washington, D.C.

Graf, W., 2008, *Woodframe Buildings*, Supplemental Study for the ShakeOut Scenario, United States Geological Survey, Menloy Park, California.

Himmelwright, A.L.A., 1906, *The San Francisco Earthquake and Fire: A Brief History of the Disaster,* the Roebling Construction Company, New York, New York.

ICC, 2012, *International Building Code,* International Code Council, Whittier, California.

ICC, 2013, *California Building Code*, International Code Council, Whittier, California.

ICC, 2015, *International Building Code,* International Code Council, Whittier, California.

Krawinkler, H., Osteraas, J., McDonald, B., and Hunt, J.P., 2012, "Development of damage fragility functions for URM chimneys and parapets," in *Proceedings of the 15th World Conference on Earthquake Engineering*, Lisbon.

Lawson et al., 1908, *The California Earthquake of April 18, 1906: Report of the State Earthquake Investigation Commission*, the Carnegie Institution of Washington, reprinted 1969.

Look, D., Wong, T., and Augustus, S.A., 1997, *The Seismic Retrofit of Historic Buildings: Keeping Preservation in the Forefront*, Preservation Brief 41, National Park Service, U.S. Department of the Interior, Washington, D.C.

Los Angeles, 2014, *Reconstruction and Replacement of Earthquake Damaged Masonry Chimneys*, P/BC 2014-070, City of Los Angeles Department of Building and Safety.

McGuire, P., 2015. Personal communication, including photos of the chimney and a copy of a construction cost estimate and proposal from a San Francisco Bay Area masonry and chimney contractor, May.

McKee, K., 2015, Personal communication, February 13. *Mr. McKee is with Okell's Fireplace, San Francisco.*

Napa-A, *Bracing Details for Damaged Interior Masonry Chimmneys [sic] and Flues,* City of Napa Community Development Department, undated.

Napa-B, *Retro-fitting [sic] Masonry Fireplace with Factory-Built Flue*, City of Napa Community Development Department, undated.

Napa-C, *Retro Fitting [sic] Masonry Fireplace with Factory Built Metal Chimney*, City of Napa Community Development Department, undated.

NTHP, 2014. *Older, Smaller, Better: Measuring How the Character of Buildings and Blocks Influences Urban Vitality*, National Trust for Historic Preservation, Washington, D.C. *Cited map is available at* http://www.preservationnation.org/information-center/sustainable-communities/green-lab/oldersmallerbetter/. Last accessed September 18, 2015.

Samblanet, P., 1992, *Troubled Chimneys,* Publication #M920454, the Aberdeen Group.

San Francisco, 2015, *Building Code 2013 Edition*, the City and County of San Francisco. Available at: http://www.amlegal.com/nxt/gateway.dll/California/sfbuilding/buildingcode2013edition?f=templates$fn=default.htm$3.0$vid=amlegal:sanfrancisco_ca$anc=JD_Building. Last accessed September 17, 2015

San Francisco Planning Department, 2014. *San Francisco Housing Inventory 2013*. San Francisco Planning Department. Available at: http://www.sf-planning.org/ftp/files/publications_reports/Housing_Inventory_2013.pdf. Last accessed September 18, 2015.

San Luis Obispo, 2004, *Reconstruction and Replacement of Earthquake Damaged Masonry Chimneys*, Information Bulletin 1-2004, City of San Luis Obispo Community Development Department, Building & Safety Division.

Seattle, 2004, *Alteration and Repair of Unreinforced Masonry Chimneys*, Director's Rule 5-2004, City of Seattle Department of Planning and Development.

Sewell, J.S., 1907, "The effects of the earthquake and fire on buildings, engineering structures, and structural materials," *The San Francisco Earthquake and Fire of April 18, 1906*, Bulletin No. 324, Department of the Interior, United States Geological Survey, Government Printing Office, Washington, D.C.

Tobriner. S., 2006, *Bracing For Disaster: Earthquake Resistant Architecture and Engineering in San Francisco, 1838-1933,* Heyday Books, Berkeley, California.

Wikipedia, 2015, *Painted Ladies.* Available at: http://en.wikipedia.org/wiki/Painted_ladies. Last accessed March 31, 2015.

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