CHIMNEY AND MOBILE HOME PERFORMANCE IN RECENT U.S. EARTHQUAKES

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Abstract

This paper documents the seismic performance of chimneys associated with permanent residential dwellings, and mobile homes in the cities of Anchorage, Alaska and Ridgecrest, California during, respectively, the 2018 Anchorage and the 2019 Searles Valley earthquakes. The authors performed on-site reconnaissance including interviews with local officials and contractors familiar with the earthquake damage and recovery efforts.

2018 Anchorage (M7.1) Alaska earthquake. The Municipality of Anchorage has the largest population (300,000) of any urban area in Alaska. There were greater than 100,000 housing units including more than 5,000 mobile homes in the Municipality at the time of the earthquake. Given the large magnitude of the earthquake and its proximity to Anchorage, it could be expected to find much damage to chimneys and to mobile homes. However, relatively few chimneys suffered damage, and no toppling of mobile homes was reported. The lack of damage can be attributed to relatively modest shaking intensities in addition to aspects of the housing inventory. Two-thirds of the housing units were built after 1970 resulting with relatively small numbers of vulnerable older plain masonry chimneys as opposed to the large numbers of newer more rugged metal and reinforced masonry types. Mobile homes had tie-down systems anchoring them to the ground; however, their effectiveness in preventing toppling during earthquakes is an open question for reasons discussed.

2019 Searles Valley (M6.4 and M7.1) California earthquakes. Ridgecrest was the largest city close to the epicenters. It has a population of 29,400 sheltered in 13,000 housing units including 900 mobile homes. Chimneys generally performed well. The housing inventory is relatively young (75% built after 1970), and the chimneys are mostly rugged metal and reinforced masonry types. Observed damage to masonry chimneys was largely attributed to poor construction practices and lack of adherence to building code provisions. The authors surveyed over 600 mobile homes in 12 mobile home parks. About 8% (50 units) of the surveyed homes significantly shifted or collapsed to the ground. Damage was mostly to older mobile homes having deficient steel pier support connections, and no tie-down anchoring systems.

Findings based on the reconnaissance indicate that chimneys and mobile homes conforming to modern regulations generally performed well under the shaking intensities from the earthquakes; however the performance under higher intensity shaking is an open question. At the *shaking intensities from the earthquakes*:

- Few (if any) chimneys appeared to have suffered damage—if properly constructed to current building codes.
- Few (if any) mobile homes shifted significantly or fell to the ground—if installed under current regulatory requirements.

Keywords: chimneys; mobile homes; fragility; 2018 Anchorage earthquake; 2019 Searles Valley earthquake

1. Introduction

Chimneys located on residential dwellings and mobile homes are ubiquitous in cities across the United States. This paper presents a reconnaissance report on their performance during the 2018 Anchorage, Alaska and the 2019 Searles Valley, California earthquakes. The authors performed on-site surveys including interviews with local officials and contractors familiar with the earthquake damage and recovery efforts.

1.1 Background

Conventional wisdom holds that chimneys and mobile homes are highly susceptible to damage from earthquakes, based in part on their historical performance in California. The following is a brief summary of the California experience.

1.1.1 Chimneys

The International Building Code [1] first produced in 2000 combined the three model codes used previously, and is now used nation-wide. It requires masonry chimneys in seismic zones to be reinforced masonry and anchored to the home at floor and roof levels. Existing chimneys might not meet current code requirements depending on customary practices, code requirements and level of code enforcement at time of their construction. Figure 1a illustates the hazard posed by a falling chimney. It shows a crushed parked automobile resulting from the collapse of the upper portion of a plain (unreinforced) masonry chimney. Figure 1b shows the internal features of failed reinforced masonry chimney having deficient construction. The 1994 Northridge earthquake (M6.7) in California affecting Los Angeles revealed poor construction practices and lack of adherence to building code provisions resulted in considerable damage to chimneys [2]. This event led to better code enforcement and promoted use of chimneys having metal flues enclosed by rugged wood enclosures. However, there remains many vulnerable existing masonry chimneys having deficient construction and/or consisting of plain masonry.

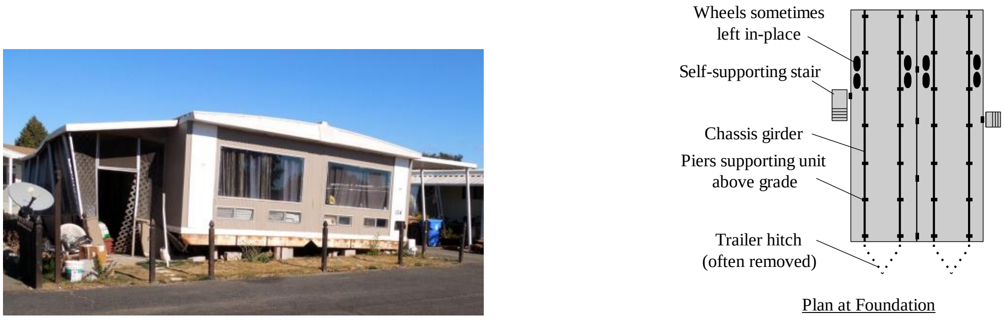
(a) (b)

Fig. 1 – Example of collapsed chimneys from the 2014 South Napa California earthquake [3]. (a) Collapse of upper portion of chimney. (b) Features of failed reinforced masonry chimney. Hollow cavity at A and clay tile flue at B. Bent rebar at C that pulled out apparently due to insufficient bond strength.

1.1.2 Mobile Homes

Mobile homes are a class of housing manufactured in factories, transported to sites as complete units, and installed. Such homes built after 1976 are legally referred to as *manufactured* homes, and those built before 1976 retain the common name of *mobile home* as is used here. Numerous mobile homes are typically located together in communities referred to as mobile home parks. Current regulations require all new mobile home installations to have at the minimum, so-called tie-downs consisting of metal straps connecting the chassis girders to ground anchors to provide an explicit lateral force resisting system. However, many older mobile homes in California lack tie-downs due to a peculiarity in statutes dating from the 1960s. Figure

2 shows a double-wide mobile home consisting of two units that fell off the supports. In this case, the mobile home was situated on piers consisting of stacked concrete masonry units, and lacked tie-downs.



(a) (b)

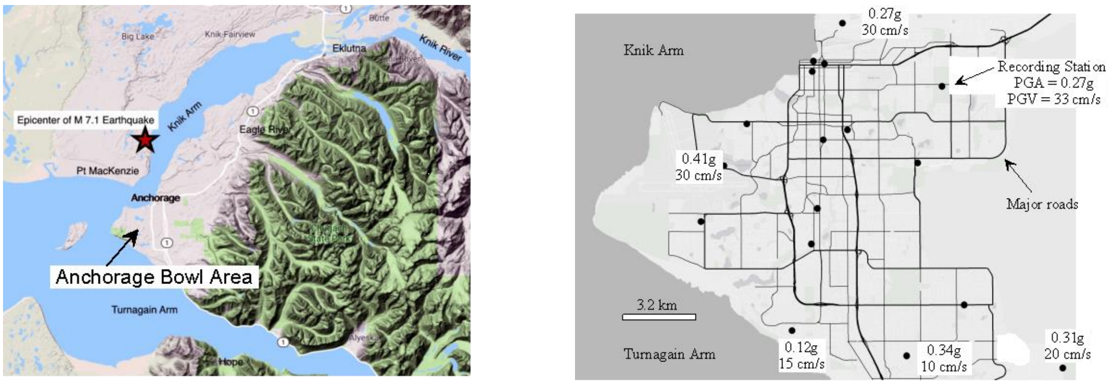
Fig. 2 – Example of double-wide mobile home after the 2014 South Napa California earthquake [4]. (a) Mobile home toppled off its supports and fell to the left. (b) Support system underneath home having piers consisting of stacked concrete masonry units and lacking tie-downs.

2. The 2018 Anchorage Alaska Earthquake

The 30 November 2018 earthquake (M7.1) struck 14 km north-northwest of Anchorage, Alaska. The Municipality of Anchorage has the largest population (292,000 in 2010) of any urban area in Alaska. There were greater than 100,000 housing units including about 5,000 mobile homes in the Municipality at the time of the earthquake. Given the large magnitude of the earthquake and its close proximity to Anchorage, it could be expected to find much damage to chimneys associated with permanent residential dwellings, and to mobile homes. The authors performed on-site reconnaissance in June 2019 including interviews with building officials and contractors familiar with the earthquake damage and recovery efforts. It was found that relatively few chimneys suffered structural damage, and no toppling of mobile homes was reported.

2.1 Anchorage Shaking Intensity

Earthquake ground motions were recorded by numerous instruments across the Anchorage Bowl area (Figure 3). USGS Shakemaps indicate median estimates of peak ground accelerations (PGA) and peak ground velocities (PGV) across much of Anchorage as approximately 0.32g and 28 cm/s, respectively. Although the epicenter of the magnitude 7.1 earthquake was only about 14 km from Anchorage, the relatively modest shaking intensities can be attributed in part to the normal fault source mechanism having a depth of 47 km. Shakemap also assigned Modified Mercalli Intensities from VI to VII across Anchorage indicating light to moderate damage potential.



(a) (b)

Fig. 3 – Anchorage maps. (a) Anchorage region. (b) Anchorage Bowl area showing distribution of seventeen recording instruments (indicated by black dots).

2.2 Anchorage Chimneys

Anchorage has a relatively young housing inventory with about two-thirds built after 1970 (greater than 75,000 units). There is a trend of chimneys types depending on when the home was built. Most new chimneys are metal types often enclosed by wood-framed enclosures (Figure 4a). The enclosures consist of conventional stud framing sheathed with wood structural panels, and are lightweight and very rugged. The Anchorage earthquake had no reported structural failures for this type of chimney. California also seems to have had few, if any, reported of failures in numerous California earthquakes. Indeed, this type of chimney has been prescribed as replacement for masonry chimneys by jurisdictions in California.

Chimneys on older homes typically consist of concrete block masonry with clay tile flues (Figure 4b). Homes masonry chimneys constructed after 1970 should have steel reinforcement and strapping to the home as required by the building code. However, there are some homes undoubtedly having vulnerable masonry chimneys (i.e., old plain masonry or deficient construction that evaded code).

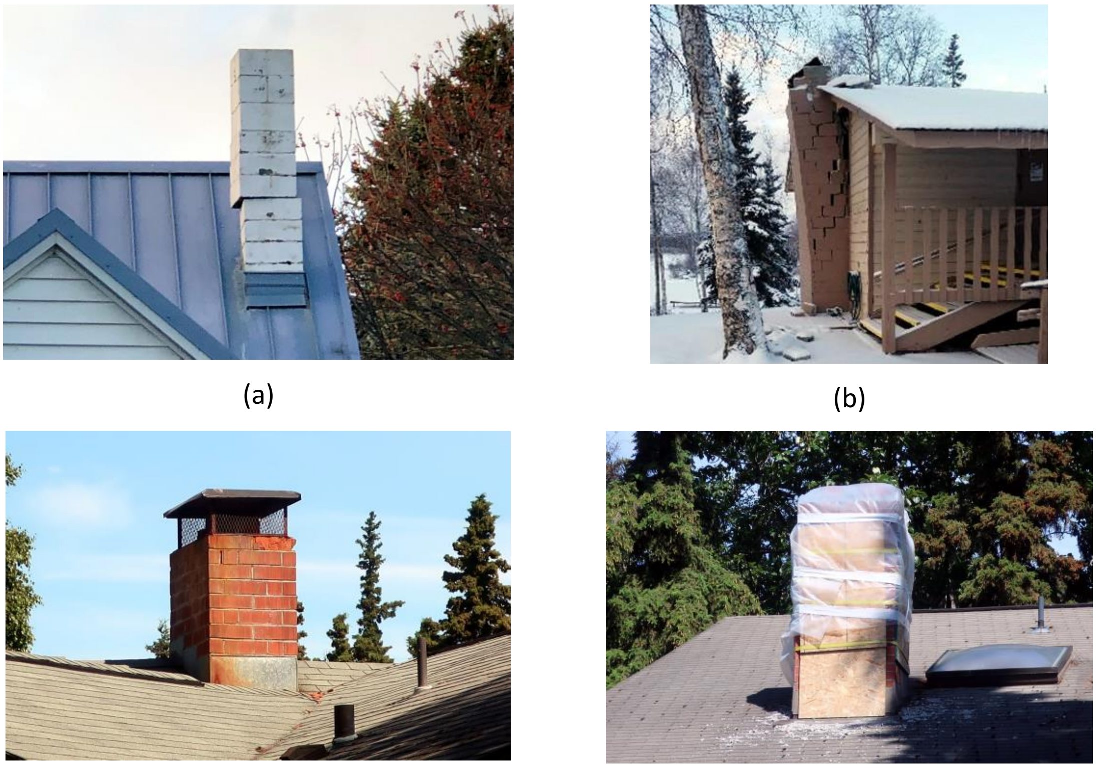
(a)

(b)

Fig. 4 – Anchorage chimneys. (a) Metal chimney flue enclosed by wood-framed enclosure (1980s tract homes shown). These are found on newer homes. (b) Concrete block masonry chimney (home built in 1951). These are much fewer and found on older homes.

The authors performed on-site reconnaissance in June 2019 including discussions with Anchorage officials and contractors familiar with Anchorage earthquake damage and recovery efforts. Damage to very few masonry chimneys was apparent (Figure 5). This was confirmed by review of the Anchorage building department damage survey database.

Masonry chimney fragility depends on several factors including: shaking intensity, height above roof, section dimensions, masonry tensile strength in the case of plain masonry, whether it has steel reinforcement, and quality of construction or lack thereof. Figure 6 shows fragility curves for what may be considered as somewhat typical situations. It relates PGA to likelihood of extensive chimney damage defined as incipient collapse for plain masonry, and 2% peak drift in reinforced masonry. The shaded areas indicate ranges based on numerical simulations in reference [3]. Chimneys having wider sections and shorter heights are more rugged. Also shown is the fragility curve [5] for chimney toppling used in the Federal Emergency Management Agency report, FEMA P-58. It is for plain masonry and does not distinguish between different section dimensions and heights above roof.



(a) (b) (c) (d)

Fig. 5 – Examples of masonry chimney damage by the 2018 Anchorage earthquake. (a) Incipient collapse of the portion above CMU mortar joint (Jessica Feenstra). (b) collapse of upper portion of CMU chimney (Janise Rodgers). (c) Short chimney having minor brick spalling from earthquake. Brick flakes visible in roof valley. (d) Chimney damaged by earthquake and covered by particle boards and plastic wrap. Owner indicated masonry was reinforced with rebar. Chimney apparently not considered a falling hazard since repairs yet to be enacted. Photos (a) and (b) taken shortly after quake; and (c) and (d) taken in June 2019.

Since PGAs in Anchorage were about 0.32g, the fragility curves indicate that most reinforced chimneys had a negligible chance of extensive damage (Figure 6), consistent with observations. Older plain masonry chimneys of expected quality tensile strengths, which were in fewer numbers, might have been vulnerable by having 10 to 30% chance of extensive damage, where exposed to 0.32g PGA. Indeed, the few damaged chimneys observed seem to fit this situation. Weak masonry chimneys could be from inferior construction and these would have high likelihoods of damage. However, apparently these were rare because of the few incidents of reported damage, which reflects that the inventory of such chimneys was extremely small in Anchorage.

The overall good performance of chimneys in Anchorage can be attributed to the following factors. A large proportion of housing stock was built after 1970 when the chimney types were generally rugged (i.e., lightweight metal types, and masonry chimneys having reinforcement and strapping to the home). There were relatively few vulnerable plain masonry chimneys. The shaking intensities were relatively low due in part to the deep source depth. Accordingly, the PGAs were relatively modest and at such intensities, only a small subset of plain masonry chimneys was susceptible to damage.

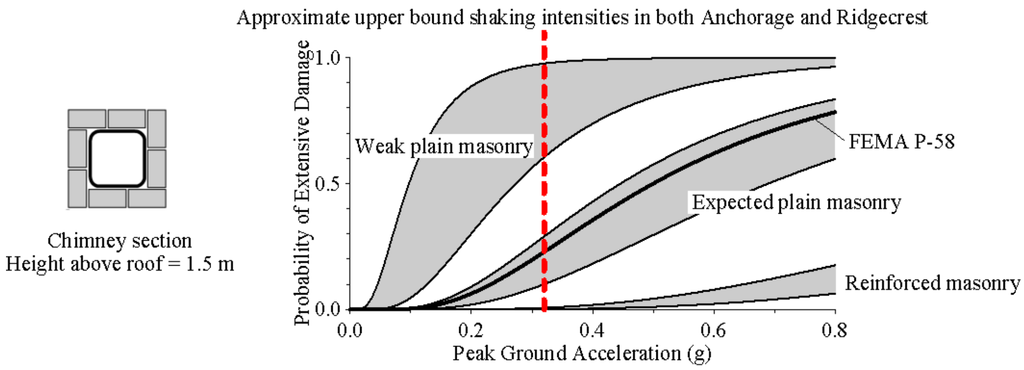


Fig. 6 – Chimney fragility curves for cracking at roof elevation causing extensive damage. Expected and weak plain masonry taken as having masonry tensile strengths, respectively, of 60 psi (0.41 N/mm2) and 10 psi (0.069 N/mm^2) tensile strength. Reinforced masonry taken as having code-conforming four vertical rebar fully grouted into chimney. FEMA P-58 fragility curve with uncertainty parameter beta (β) of 0.6 intended to reflect uncertainties in ground motions and component capacities [5].

2.3 Anchorage Mobile Homes

The majority of Anchorage mobile homes were installed in the 1970s (about 5,000 units). Figure 7a shows a typical home observed. The typical support system consists of stacked concrete masonry unit piers located under the chassis girders, and metal strap tie-downs connecting the chassis girder to anchors embedded in the ground (Figure 7b).

(a) (b)

Fig. 7 – Typical Anchorage mobile home. (a) Exterior view. (b) View of support systems consisting of Stacked concrete masonry units (at left) and tie-down system consisting of a steel strap placed around chassis girder and connected to soil anchor by steel cable (at center). Inclined wood 2x4 struts brace the lower portion of home perimeter skirt (at right).

Figure 8 shows fragility curves for mobile homes based on South Napa California earthquake experience [4]. The curves are for unanchored homes supported only on piers (no tie-downs). It relates PGV to the likelihood of the home toppling due to tipping of concrete masonry piers. The function suggests that the PGVs in Anchorage of about 28 cm/s were such that mobile homes were very unlikely to topple *even if they were unanchored* (less than 10% chance). The good performance of mobile homes in Anchorage can be attributed largely to the shaking intensities being relatively low.

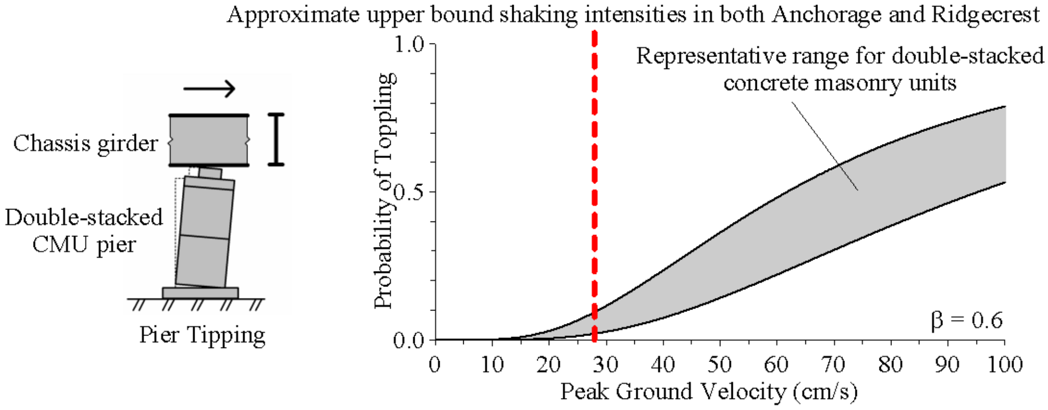


Fig. 8 – Fragility curves for mobile home toppling via tipping of piers. Curves are for *unanchored* mobile homes (no tie-downs) supported on stacked concrete masonry units (CMUs).

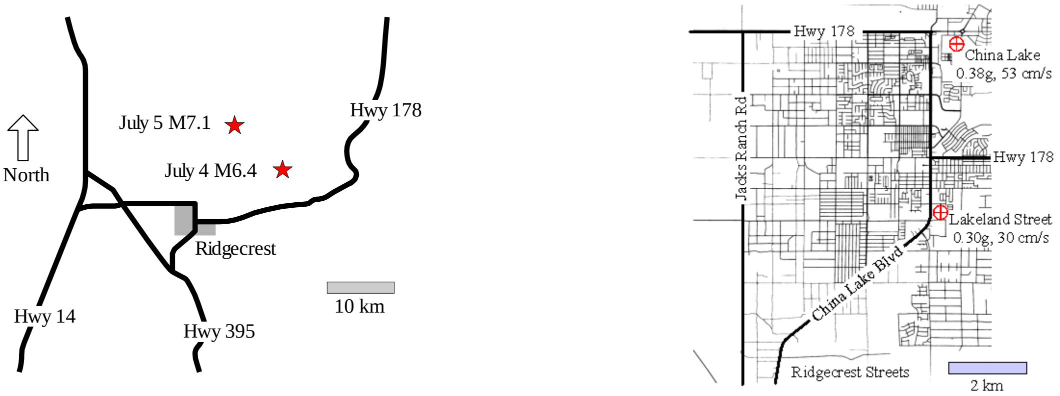
It should be noted that tie-down systems in the 1970s dealt with wind forces that are greatest in the home transverse direction because of the large longitudinal vertical area. Accordingly, tie-downs were required only in the transverse direction. Lateral support in the longitudinal direction was provided by friction between the mobile home, piers and foundation. Moreover, slack provided in the tie-down system to accommodate seasonal freeze-thaw movements could inhibit the effectiveness of the tie-downs to mitigate damaging lateral movements of the home. Hence, it is an open question how effective the observed tie-downs (Figure 7b) might be in mitigating toppling under higher intensity shaking.

3. The 2019 Searles Valley Earthquakes

Two strong earthquakes occurred on consecutive days near the city of Ridgecrest, California (population 29,400). The 4 July 2019 earthquake (M6.4) struck 18 km (11.2 miles) east-northeast of Ridgecrest, and the 5 July event (M7.1) occurred 19 km northeast of Ridgecrest (Figure 9a). There were about 13,000 housing units including 900 mobile homes in Ridgecrest at the time of the earthquakes. Given the large magnitude of the earthquakes and their close proximity to Ridgecrest, it could be expected to find much damage to chimneys and mobile homes. The authors performed on-site reconnaissance in July 2019 including interviews with mobile home officials and contractors familiar the earthquake damage and recovery efforts. It was found that very few chimneys were damaged in Ridgecrest and some mobile homes significantly shifted on their supports or fell to the ground. The small community of Trona (< 2,000 population) was also affected by the earthquakes, but was not covered in the survey.

3.1 Ridgecrest Shaking Intensity

Earthquake ground motions were recorded at two sites at Ridgecrest. One station was located roughly in the middle of Ridgecrest and the other just east on the China Lake Naval Station (Figure 9b). USGS Shakemap processing has ways of assessing shaking intensity and estimated median PGAs and PGVs across much of Ridgecrest as approximately 0.3g and 30 cm/s, respectively. Although the epicenters of the earthquakes were near Ridgecrest and their hypocenters were relatively shallow (about 9 km), the shaking intensities in Ridgecrest were relatively modest. The USGS Shakemap assigned Modified Mercalli Intensities slightly greater than VII for Ridgecrest indicating moderate damage potential. Shaking intensity maps indicate that the M7.1 event had much of its strong shaking oriented along the fault to the northwest and away from Ridgecrest.



(a) (b)

Fig. 9 – Searles Valley earthquakes. (a) Locations of earthquake epicenters. (b) Street map showing locations and values of recorded peak ground accelerations and velocities. China Lake values are maximum values from either the July 4 and 5 events whereas the Lakeland Street values are from the July 5 event.

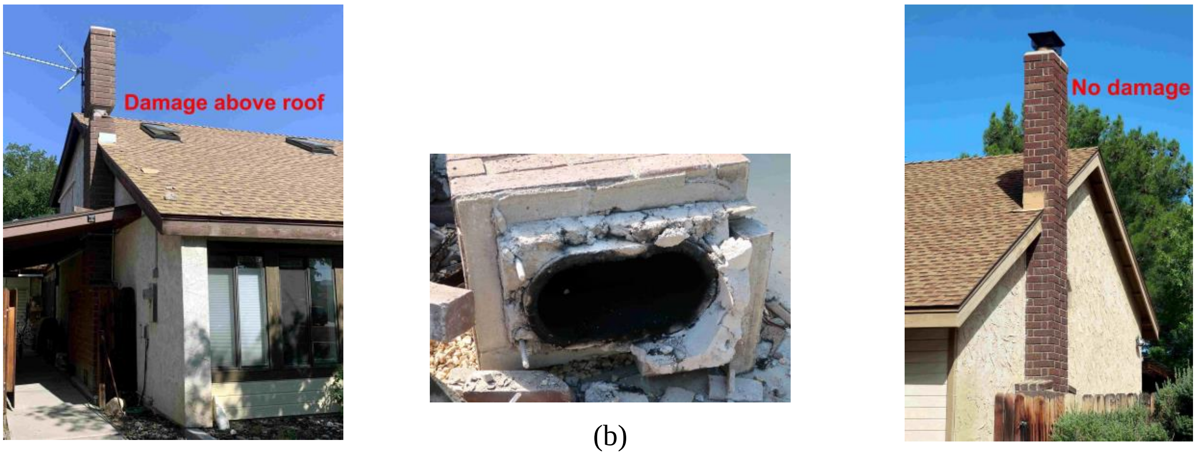
3.2 Ridgecrest Chimneys

Like Anchorage, Ridgecrest has a relatively young housing stock with about three-quarters built after 1970 (about 9,800 housing units out of 13,000 total units). Figure 10 shows typical chimneys.

(a) (b) (c)

Fig. 10 – Typical Ridgecrest chimneys. (a) Metal chimney flue enclosed by rugged wood-framed enclosure. Home built in circa 1990. (b) Masonry chimney on home built in 1985. (c) Masonry chimney on home built in 1972.

No damage was observed to metal chimneys like the type in Figure 10a, and relatively few masonry chimneys were found to be damaged. A key factor contributing to damage appears to be deficient construction as illustrated by the following examples. Figure 11a shows a damaged chimney in a neighborhood having numerous tract homes built circa 1982. The chimney had the building code-required four vertical rebar, but the grout had voids thereby poor bonding to the bricks allowing them to fall away (Figure 11b). The neighboring homes were ostensibly the same (Figure 11c), yet suffered no damage suggesting that faulty construction played a role in the damaged chimney. Figure 12 shows more Ridgecrest damaged masonry chimneys exhibiting deficient construction. The grout had voids and no rebar was observed at places where the bricks fell away. Figure 13 shows a different type of damage where a masonry chimney pulled away from the home likely from deficient anchoring (strapping) of the chimney to the house floors and roof.

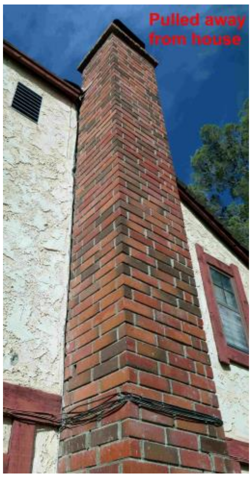


(a) (b) (c)

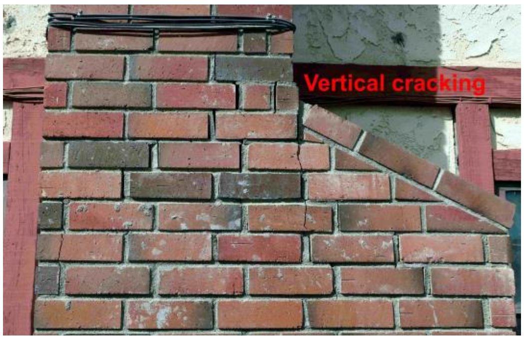
Fig. 11 – Damage to reinforced masonry chimney on Ridgecrest tract home. (a) Chimney damage at roof elevation. (b) Photo taken after chimney demolition showing poor grouting at location where bricks fell away. (c) Similar neighboring home having no chimney damage.

(a) (b) (c)

Fig. 12 – Examples of deficient masonry construction observed in damaged Ridgecrest chimneys.



(a)



(b)

Fig. 13 – Example of Ridgecrest masonry chimney that pulled away from home likely from deficient anchoring to home at floor and roof levels.

Estimated median PGAs in Ridgecrest were about 0.3g and the fragility curves in Figure 6 indicate reinforced chimneys had a negligible chance of extensive damage provided they were of good quality construction meeting building code requirements. The relatively few number of damaged masonry chimneys observed had apparent construction deficiencies.

3.3 Ridgecrest Mobile Homes

The authors performed street-by-street surveys of the 12 mobile home parks including all the major parks in Ridgecrest. About 600 mobile homes were surveyed. There were about a total of 900 mobile homes in Ridgecrest according to census data so the 300 mobile homes not surveyed were mainly scattered on private property lots that did not allow for close inspection.

About 50 mobile homes were observed to have significantly shifted on their supports or fell to the ground representing about 8% of the mobile homes surveyed. One mobile home park noteably had about 30% of its mobile homes damage while the other parks had less than 15% damaged. The was a trend of damage in the older parks with the most heavily damaged one dating to 1964. Examples of damaged mobile homes are shown in Figure 12. Notice how the mobile homes shifted off their supports and fell like rigid blocks. The mobile home unit itself had relatively modest damage and could be re-installed and occupied in each of these cases.

(a)

(b)

(c)

Fig. 14 – Examples of damaged mobile homes in Ridgecrest.

Figure 15 shows support types observed underneath mobile homes. Steel piers were very common, and in this case, the mobile home had fallen and crushed the pier (Figure 15a). The mobile home chassis girder initially sat on the L-shaped bracket shown at the top of the pier. It lacked a positive (bolted or welded) connection to the chassis girder so the mobile home slid off the pier at relatively small displacements. Most of the observed damaged mobile homes used this type of steel pier and also lacked tie-downs. However, several mobile homes having tie-downs were also damaged, and Figure 15b shows a tie-down after collapse of a mobile home. The mobile home slipped off the steel piers at small displacements before the straps became taut thereby making them ineffective in providing lateral restraint. Figure 15c shows the support system under a mobile home installed circa 1987 that suffered no damage. Lateral restraint was provided by a steel stanchion system bolted to the chassis girder and connected to the ground with embedded steel rods. The steel piers were also bolted to the chassis girder thereby preventing its sliding off. These systems are very rugged and no damage was observed to homes having them.


(a)


(b)


(c)

Fig. 15 – Mobile home support systems. (a) Steel pier crushed by falling of mobile home. The chassis girder lies on the ground (at rear). (b) Tie-down system under a collapsed home. Steel strap connected to a ground anchor (at center) and wraps around the mobile home chassis girder now lying on ground (to the right). The girder slipped off the steel piers like those shown in (a). (c) Modern support system under a mobile home installed circa 1987. A steel stanchions system is shown at right and steel piers in background. Notice the bolted connections at the chassis girder.

It should be noted that the steel piers were mostly used in Ridgecrest (Figure 10a), whereas stacked concrete masonry piers were common in Anchorage (Figure 7b). The failure mode in Ridgecrest was different than the possible failure mode in Anchorage due to the different pier types. In Ridgecrest, some mobile homes slid off steel piers at small displacements. Although no Anchorage mobile homes were reported to have significantly shifted or fallen, the likely failure mode is that of concrete masonry unit pier tipping as opposed to sliding. Hence, the fragility curve in Figure 8 does not apply to Ridgecrest mobile homes.

4. Discussion

The shaking intensities were relatively modest in Anchorage and Ridgecrest considering the magnitudes of the strong 2018 and 2019 earthquakes being greater than 7.0. Chimneys generally performed well in both cities. The housing stock in Anchorage and Ridgecrest is considered young by having most homes constructed after 1970 with mostly rugged chimneys consisting of metal flues enclosed by wood-framing, and masonry having steel reinforcement and strapping to the home. There were relatively few vulnerable plain (unreinforced) masonry chimneys, and these would be found on older homes, perhaps those built pre-1950 when codes lacked reinforcement and strapping requirements. Deficient construction appears to be an important factor in the relatively few damaged masonry chimneys observed in Ridgecrest.

Anchorage mobile homes performed well since none were reported to have significantly shifted or fell to the ground. They had tie-downs to resist lateral forces, but they were required only in the mobile home transverse direction. It is an open question how effective the observed installations might be in mitigating damage under stronger shaking, especially in the longitudinal direction that is essentially unanchored. Hence, the observed good performance is likely due in large part to the relatively low intensity of shaking.

Approximately 8% of the mobile homes surveyed in Ridgecrest significantly shifted on their supports or fell to the ground. It appears that the damaged mobile homes were supported on steel piers having no positive connection to the chassis girder (e.g., bolted brackets). This shortcoming undoubtedly contributed to the damage since it was observed that many mobile homes slid off their piers at apparently small displacements. Mobile homes installed in California after 1994 are required to have positive connections so the deficiency exits in older installations. This contrasts with Anchorage mobile homes typically supported by stacked concrete masonry units having wide dimensions greatly reducing the potential of mobile homes sliding off their piers.

5. Conclusions

General findings based on the reconnaissance follow.

1. Chimneys and mobile homes conforming to modern regulations collectively performed well under the level of shaking intensity from the earthquakes that was approximately 0.3g PGA and 30 cm/s PGV. The performance under higher intensity shaking is an open question.
2. At the reported shaking intensities, few (if any) chimneys appeared to have suffered damage—if properly constructed to current building codes. The observed damage to masonry chimneys were those having deficient construction including poor grouting and missing rebar. Older chimneys consisting of plain masonry also might be vulnerable at lower shaking intensities.
3. At the reported shaking intensities, few (if any) mobile homes significantly shifted or fell to the ground—provided they were installed under current regulatory requirements. The observed damage to mobile homes was to older installations having steel piers lacking positive connections to the girders.

6. Acknowledgements

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