The Impact of Nonstructural Damage on Building Function

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Abstract. To reduce the impacts of disasters on communities, recent initiatives have focused on improving the performance of the building stock by designing for limited damage and downtime. Through these initiatives, researchers and engineers have highlighted the key role that nonstructural damage plays in building performance, especially in terms of maintaining or regaining the post-earthquake functionality of a building. While new performance-based frameworks have emerged that allow the functional recovery of a building to be probabilistically estimated based on the vulnerability of the various structural and nonstructural components within the building, it is unclear which types of nonstructural components or configurations have the largest impact on building function and the types of nonstructural system that need further research to better define vulnerability and reduce uncertainty in the assessment.

To quantify the impact of nonstructural damage on building function, we perform a sensitivity analysis on nonstructural component vulnerability using the latest performance-based frameworks. More specifically, this study investigates how variation in fragility capacity and uncertainty impacts estimates of post-earthquake building function. The sensitivity study is performed on a set of simplified structural response models covering shear-type (frames) and flexure-type (cantilever walls) response behavior and considering uncertainties in ground motion, structural response, and component performance.

This study provides key insights into the design and assessment of nonstructural components, targeting functional recovery, and helps focus the next efforts in nonstructural research. Results from the study are compared with documented empirical data on nonstructural performance in previous earthquakes and recommendations are made for future studies to improve our understanding of nonstructural performance in the areas that are most critical for recovery.

Keywords: Functional Recovery, Nonstructural Loss Analysis, Performance-Based Earthquake Engineering.

1. Introduction

The performance of nonstructural components within a building plays a crucial role in maintaining building function and mitigating downtime after earthquakes. As engineers and policymakers consider new design standards for functional recovery, the use of new performance-based methods to probabilistically quantify the functional recovery of a building, explicitly considering the performance of the building's nonstructural components, instead of just structural performance, is becoming more prevalent. However, the component fragility and consequence data that these methods rely on are sparse compared to the actual variation in nonstructural components and often not based on extensive empirical or experimental observations.

Therefore, to reduce uncertainty in recovery-based modeling, future studies should further investigate nonstructural seismic vulnerability and consequences and improve upon the readily available data. But where should we start? Which nonstructural components and systems have the largest potential impact on building function? Which nonstructural fragilities have the largest uncertainties or are based on limited data sources?

To answer these questions and to identify critical nonstructural components for future investigation, this study reviews the literature to identify the most vulnerable systems and gaps in data and performs a sensitivity study, using state-of-the-art recovery modeling methods to identify nonstructural systems and components that have the highest impact on expected post-earthquake building function. We identify the most critical components for future study as the overlap between components with the highest analytical impact on building function, those that have frequently impacted building function in previous earthquakes, and component fragility models based on the most limited data sources.

2. Nonstructural Damage in Previous Earthquakes

While post-earthquake reconnaissance and disaster failure investigations have traditionally focused on structural damage to buildings and infrastructure, recent studies have documented important nonstructural damage in earthquakes over the last few decades. From a review of these studies, we highlight commonalities among the types of nonstructural damage that impacted building function in past events. A summary of the most prevalent sources of nonstructural damage is provided in Table 1.

In review of recent earthquakes, we observe the two most common sources of nonstructural damage to be dislodging of suspended ceilings, creating a falling hazard, and water damage from burst pipes or fire sprinklers. Other common sources include elevator damage and broken windows and glazing. In this review, we specifically omitted damage to tenant contents, damage to unreinforced masonry components such as chimneys and parapets, and loss of use due to failure of an external utility or lifeline; all of these sources of damage have been shown to be prevalent in previous earthquakes and can have a major impact on building function but are outside the scope of this study.

The 1994 Northridge Earthquake in southern California caused widespread damage to nonstructural components across a large metropolitan area; there were many examples of buildings with only minor structural damage that had to be evacuated or left unoccupied due to severe nonstructural damage [EERI, 1995]. After the Northridge Earthquake, 9 % of the hospitals in Los Angeles County evacuated patients, citing nonstructural damage as a primary reason [Schultz et al., 2003]; common types of damage leading to evacuation were water damage from burst pipes, fire sprinklers, and rooftop water tanks. Other types of nonstructural damage affecting hospital function were failure of backup power systems, damage to partitions and suspended ceilings, proper ventilation, failed fire suppression systems, and damaged elevators [Yavari et al., 2010]. Among other building types, common sources of nonstructural damage impacting building function included broken windows, dislodged suspended ceilings, and perhaps most prevalent, pipe breakage and water damage, including fire sprinkler, chilled water (HVAC), and domestic water piping. Additionally, elevator damage was quite common, with 688 documented occurrences of elevators counterweight damage (EERI, 1995).

Table 1. A summary of common sources of nonstructural damage affecting building function from recent earthquakes

Earthquake	Prevalent Nonstructural Damage	Reference(s)
Northridge (CA), 1994	**Pipes (domestic, fire, and chilled) and fire sprinkler heads**, liquid storage tanks, windows, HVAC/ventilation systems, backup electrical systems, suspended ceiling, partition walls, **elevator counterweights**.	EERI, 1995 Schultz et al., 2003 Yavari et al., 2010
Nisqually (WA), 2001	**Suspended ceilings**, interior and exterior wall cracking, windows, water-line damage causing flooding.	Filiatrault et al., 2001
Maule (Chili), 2010	**Suspended ceilings, fire suppression systems, elevators,** cable trays, poorly anchored equipment.	Miranda et al., 2012 Mitrani-Reiser et al., 2012
Christchurch, (NZ), 2011	**Suspended ceilings and lightings, stairs**, elevators, rooftop equipment, partitions and fire separations, windows.	Jacques et al., 2014 CERC, 2012 Kam et al., 2014
Tohoku, (Jpn), 2011	**Suspended ceilings.**	Motosaka & Mitsuji, 2012
Napa (CA), 2014	**Storefront glazing, façades, small diameter fire sprinkler pipes, sprinkler heads**, pendant lighting, rooftop equipment.	FEMA, 2015
Kaikoura (NZ), 2016	**Suspended ceilings,** other suspended services such as lights and conduit, HVAC equipment, **glazing**.	Baird & Ferner, 2017

In the 2001 Nisqually Earthquake in Washington state, Filiatrault et al. [2001] reported that a large portion of the damage from the earthquake was due to nonstructural damage, even for buildings with well-behaved structural systems. In particular, suspended ceilings were one of the most common types of damage observed. Glass window failure shut down the SEA-TAC airport for 4 hours, and several cases of pipe damage, both mechanical and domestic, caused flooding in some buildings. Additionally, there were many reports of cracking of interior and exterior walls, but typically not significant enough to affect building function.

The 2010 Maule Earthquake in Chili caused widespread nonstructural damage disrupting the post-earthquake occupancy and functionality of many buildings, even in buildings with limited structural damage. Damage to suspended ceilings was commonly observed; most notably, in the Santiago International Airport and the San Carlos Hospital, causing major disruptions to building function [Miranda et al., 2012]. Other frequent occurrences of nonstructural damage included fire sprinkler systems–water leakage was observed in 50 % of the inspected fire suppression systems–and elevators–more than 50 % of the inspected elevators were damaged by the earthquake. Additionally, other sources of nonstructural damage included damage of cable trays (often from interactions with other systems) and poorly anchored equipment. Building facades were noted to have performed quite well due to a rigorous design process; backup power systems also performed well. Mitrani-Reiser et al. [2012] noted that in seven hospitals with relatively undamaged structural systems, the presences of significant nonstructural damage limited hospital function. In particular, damaged elevators impeded patient transport, collapsed ceilings hindered the use of certain areas and patient rooms, and minor flooding shut down surgical rooms and other services.

From the 2011 Christchurch Earthquake in New Zealand, Jacques et al. [2014] reported that much of the hospital function interruptions came from nonstructural damage; sources of loss of function included broken windows, partition wall damage (which affected function during repairs), floor coverings, and in particular, dislodged suspended ceilings and light fixtures. Other notable damage included damage to rooftop equipment causing flooding, stair damage that needed to be temporarily repaired to remain operational, and non-functional elevators. Beyond hospital facilities, damage to fire separation, ceilings, and lighting was widely observed [CERC, 2012]. Fire suppression systems were noted to have performed generally well. Of particular concern., was the collapse and severe damage of staircases in many multi-story buildings [Kam et al., 2014].

While most modern buildings in the 2014 Napa Earthquake in northern California sustained little or no structural damage, many buildings had significant nonstructural damage, resulting in some building closures for over 6 months [FEMA, 2015]. Perhaps the costliest nonstructural type of damage that occurred during the earthquake was from the rupture of fire sprinklers and the flooding that followed; these ruptures were often due to failure of small diameter piping and interactions of sprinkler heads or pipe fittings with adjacent suspended components and ceilings. Other major sources of nonstructural damage included exterior cladding, broken storefront glazing, rooftop equipment, and pendant lighting.

In the 2016 Kaikoura Earthquake in New Zealand, Baird and Ferner [2017] observed that nonstructural damage was significantly more widespread compared with structural damage. Notable damage included suspended services–such as lighting, HVAC equipment and ducts, pipework, and electrical conduit–and ceilings damage, especially where components interacted. Other widely reported damage included glazing and interior partitions, however, partition damage was mostly comprised of minor cracking, typically not significant enough to cause major disruptions in function.

3. The FEMA P-58 Nonstructural Fragility and Consequence Database

Recent performance-based assessment methods have emerged to allow the probabilistic quantification of building function and recovery given damage to structural and nonstructural components [Cook et al., 2022; Molina-Hutt et al., 2022; Terzic & Villanueva, 2021]. Following the FEMA P-58 assessment framework [FEMA, 2012] and the Porter et al. [2001] assembly-based vulnerability procedure, these methods quantify the performance of nonstructural components, in terms of their damage fragility, using data collected in the FEMA P-58 fragility database [FEMA, 2018]. This database collects fragility functions for over 700 structural and nonstructural components to help facilitate performance-based assessments. However, the source of the data forming the basis for each component fragility model varies significantly; some models come from experimental testing, some from earthquake experience data (i.e., post-earthquake field observations), some are derived from prescribed code requirements, and others are based on expert opinion. Along with the lognormal dispersion assigned to the damage states of each fragility, the source of data implies the degree of confidence that assessors should have when using these fragilities, i.e., fragility models derived from experimentation should elicit higher confidence than models derived from sparse earthquake experience data or expert opinion.

To identify the data needs among the nonstructural components within the FEMA P-58 fragility database, Table 2 lists the types of nonstructural components provided in the database according to their fragility source models. In Table 2, even when similarly labeled, the data forming the base of fragility are not necessarily equal, e.g., the experimental data for glazing and interior partition fragilities are based on a larger set of experimental tests than the stair and suspended ceiling fragilities, as indicated by the Number of Observations column.

From a review of the fragility database provided in Table 2, we observe that while many of the architectural components are derived from experimental data, many MEP (mechanical, electrical, and plumbing) components are based on limited data sources, especially distributed MEP components, whose basis of fragility is formed entirely from expert opinion. Other studies have developed fragility models based on finite element models, for example, for historic masonry infill frames with terra-cotta cladding [Dutta et al., 2009], or more recently for suspended ceilings systems [Gopagani et al., 2022]; however, these are not formally part of the FEMA P-58 database and are, therefore, not included in Table 2.

Table 2. Summary of nonstructural fragility models available in the FEMA P-58 database.

Component Type	Fragility Id Group(s)	System	Basis of Fragility	Number of Observations	Average Dispersion (β)
Cladding (precast)	B201	Exterior	Code-defined**	N/A	N/A
Glazing	B202	Exterior	Experimental	44	0.36
Tile Roofing	B301	Exterior	Experimental	24	0.35
Interior Partitions	C101	Interior	Experimental	74	0.39
Suspended Ceilings and Recessed Lighting	C303	Interior	Experimental	13	0.28
Pendant lighting	C3034	Interior	Experimental	18	0.4
Stairs	C201	Stairs and Egress	Experimental	9	0.55
Elevators	D101	Elevators	Earthquake experience	206*	0.375
Domestic and Sanitary Piping	D202, D203	Plumbing	Expert opinion	N/A	0.4
Distributed HVAC	D205, D206, D304	HVAC	Expert opinion	N/A	0.41
HVAC Equipment	D303, D304.1, D305, D306	HVAC	Earthquake experience	1305*	0.45
Fire Suppression	D401	Fire Suppression	Expert opinion	N/A	0.4
Transformers	D5011	Electrical	Earthquake experience	245*	0.5
Distribution Panels	D5012	Electrical	Earthquake experience	199*	0.425
Low Voltage Switchgear	D5012	Electrical	Earthquake experience	196*	0.4
Motor Control Center	D5012	Electrical	Earthquake experience	283*	0.425
Backup Power Equipment	D5092	Electrical	Earthquake experience	631*	0.4

**Most of the earthquake experience datapoints forming the basis for the fragility curves are from observations on non-damage in non-instrumented shaking conditions.*

***The median capacity and uncertainty for precast cladding units are derived by the user according to prescriptive code requirements and recommendations from FEMA P-58.*

4. Sensitivity Analysis: Methods

To identify the nonstructural component and fragility models with the greatest potential impact on building function, we perform a sensitivity analysis using the performance-based functional recovery method outlined in Cook et al. [2022]. This functional recovery method leverages the component fragility models and damage simulation within the FEMA P-58 framework to simulate loss of building function through a series of a fault trees, which relate component damage to system performance; component damage and building function is simulated probabilistically using a Monte Carlo simulation. To estimate loss of building function for a given shaking intensity, the method requires users to estimate the structural response to the expected ground shaking and develop a FEMA P-58-type performance model, representative of the building's vulnerable structural and nonstructural components.

For this study, we quantify the impact of variation in nonstructural component capacity and uncertainty on a set of 20 simplified performance models. Models are developed for buildings ranging from 2-10 stories, of office and multi-unit residential occupancies, and assuming two distinct response behaviors: cantilever-type and frame-type response. The functional recovery performance of each model is defined in terms of building robustness [Molina-Hutt et al., 2022], where robustness is the probability that a building maintains its basic intended function [NIST, 2021], post-event, e.g., a robustness of 0.9 is equivalent to a 90 % probability that the building will still be functional following the earthquake. We quantify the robustness of each model across eight shaking intensities, ranging from elastic response to highly nonlinear response.

The structural response of each model is estimated using the simplified response procedure outlined in the FEMA P-58 method [FEMA, 2012]. The method requires simplified inputs such as fundamental period, base shear strength, shaking intensity, mode shape, and peak ground acceleration (PGA). For each model, we assume the fundamental period of the building (T1), in seconds, is equal n/10, where n represents the number of stories. All models are assumed to have a base shear strength (Vy) of 0.2 g and are assessed for eight shaking intensities ranging from shaking equal to the base shear strength, to shaking equal to eight times the base shear strength. The shaking intensity metric is quantified as the strength ratio (S), where S equals Sa (T1) over Vy; Sa (T1) is the spectral acceleration at the fundamental period, in g's. The mode shape for each model is calculated using the approximate formula developed by Miranda [1999], assuming flexure response for the cantilever-type models and pure shear response for the frame-type models; we populate the structural components and select the nonlinear correction assuming the cantilever-response models are reinforced concrete shear walls, and the frame-type response models are reinforced concrete frames. To estimate peak floor accelerations, the PGA is calculated from Sa (T1) using the uniform hazard spectra from a site in Los Angeles California (latitude = 34.05 deg, longitude = -118.25 deg), assuming a Site Class C. The nonstructural components in each building model are populated using the FEMA P-58 normative quantities sheet [FEMA, 2018], assuming modern construction practices and anchorage requirements. Chapter 13 of ASCE 7-16 [ASCE, 2016] is used to calculate the anchorage of select nonstructural components where required by the fragility models.

To quantify the impact of variation in nonstructural component fragility on building function, we assess two sensitivity cases: (1) where we vary the median capacity of each fragility and hold constant the distributional model (e.g., lognormal) and dispersion (i.e., beta) as defined by FEMA P-58, and (2) we vary the dispersion of each fragility but leave the distributional model and the median capacity unchanged. The goal of investigating the two cases separately is to uniquely understand the impact of two separate actions: (1) modifying the failure point of a nonstructural component and (2) reducing uncertainty in nonstructural component performance. For both cases, we assess a status quo (i.e., per FEMA P-58), an upper-, and a lower-bound condition; upper- and lower-bound conditions are defined by +/- 50 % modifications to the component's median capacity or lognormal dispersion, depending on the case. Based on judgment, we select 50 % to represent a reasonable range of variation of the status quo fragility data.

To assess the sensitivity of building function to nonstructural component variation for each case, we quantify the building's robustness assuming only one major system is damageable at a time and that all components within that system are adjusted together to create the upper- and lower bound conditions; this assumption allows us to isolate any dependencies between systems and components that might hide certain impacts of fragility variation. We then repeat this process for nine major buildings systems (eight system in Table 2 and one structural system) to help identify which systems and component most impact building function.

5. Sensitivity Analysis: Results

In this study, we quantify the impact of nonstructural fragility variation on building function in terms of the building robustness, given the simulated distribution of damage. We do not quantify the time to recover building function, which is influenced by factors such as impeding times, long lead times, and repair schedule; instead, building robustness is more directly related to the fragility of the nonstructural components. The tornado plots in Figure 1a and 1b show the sensitivity of building robustness to the upper- and lower-bound modifications to the system fragility capacity and fragility uncertainty, respectively, averaged across all models for a single shaking intensity at a strength ratio equal to three (representing the point of highest overall variation in robustness). The outcomes show that variation in the fragilities of the HVAC system, electrical system, stairs, exterior, and the fire suppression system all had a major impact on building robustness. Variation in structural, plumbing, and interior fragilities had consistently less of an impact.

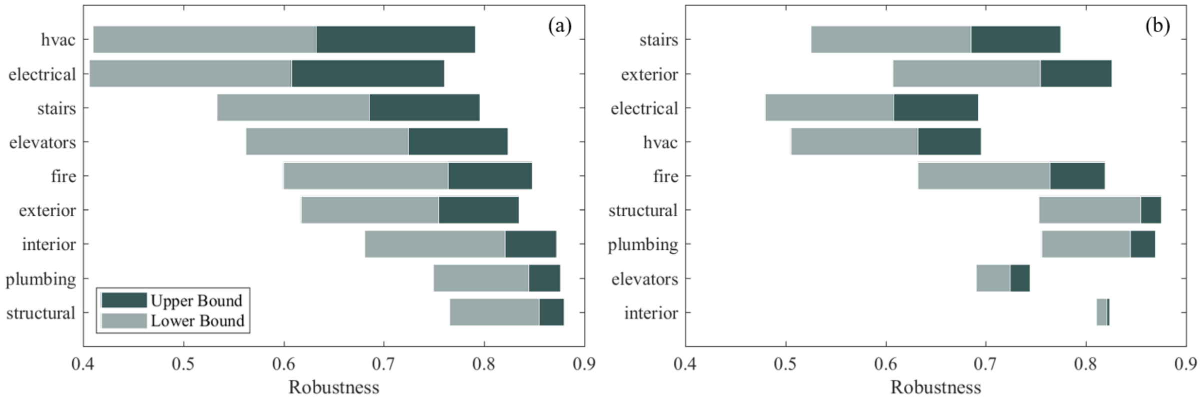

Figure 1. Tornado plots showing the impact of variation of (a) median fragility capacity (case 1) and (b) fragility uncertainty on building robustness (case 2), averaged across all models, for S = 3.

5.1 TREND WITH SHAKING INTENSITY

Figure 1 above shows the average impact of variation in component fragility models on building robustness for a single shaking intensity. However, as shaking intensity changes, so too does the relative impact of various systems on robustness. Figure 2 shows the total change in building robustness (upper bound - lower bound) as shaking intensity ranges from a strength ratio of one (essentially elastic) to a strength ratio of eight (highly nonlinear). At low shaking intensity, variation in component median capacity has only a relatively minor impact on robustness. However, as shaking amplifies, the sensitivity of robustness to the fragility model increases; the sensitivity reaches its peak around a strength ratio of three. After this, the impact begins to saturate as damage becomes so severe that even increasing the component's median capacity by 50 % is unlikely to provide many benefits. Additionally, as shaking intensity increases, the relative impact of variability in structural component capacity significantly increases compared to nonstructural damage; as structural components reach more severe damage states, the likelihood of unsafe and unstable structural conditions dramatically increases. The standard deviation in the total change in building robustness tends to range from about 0.09 at a strength ratio of three to about 0.02 at a strength ratio of eight.

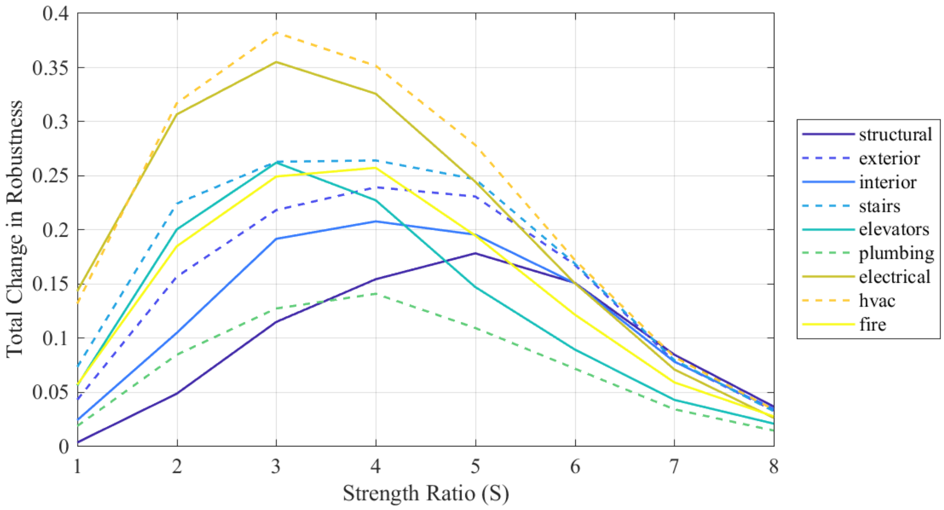

Figure 2. Total change in building robustness (upper bound – lower bound) due to variation in fragility medians (case 1) for each system, averaged across all models.

5.2 FRAME VS CANTILEVER RESPONSE

Breaking down the results among the models assessed in this study, Figure 3 shows the impact of variation in fragility median capacity on the building robustness for both the frame-type and cantilever-type response models. Both response types are similarly sensitive to variation in the fragility models of the HVAC and electrical systems. However, overall, the cantilever-type response models are less robust at the baseline and less sensitive to variation in fragility median capacities compared to the frame-type models. This difference is likely due to the amplification of accelerations and drifts throughout the building in the cantilever-type response models, compared to the tendency for a concentration of deformation demands on a single story in the frame-type response models. As a reminder, for these models, the frame-type and cantilever-type response models share the same period and base shear strength, the only difference is their response profile and structural component fragilities.

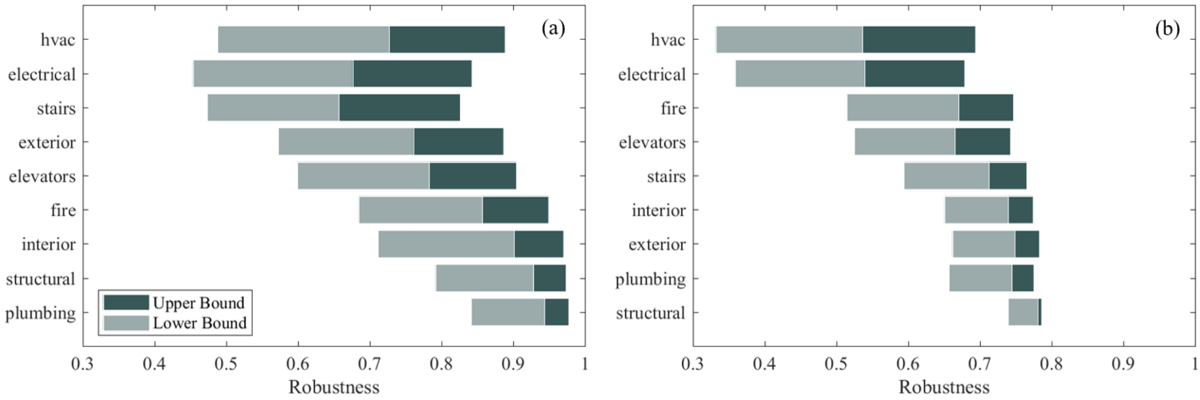

Figure 3. Tornado plots showing the impact of variation of median fragility capacity on building robustness (case 1), averaged across (a) all frame-type models and (b) all cantilever-type models, for S = 3.

5.3 OFFICE VS RESIDENTIAL OCCUPANCY

The overall influence of variation in the nonstructural fragility model on building robustness is very similar between the office and residential occupancies assessed in this study, as shown in Figure 4. The biggest difference between the models is the sensitivity of office occupancies to variations in interior component fragility models, compared to residential occupancies. This difference is directly stemming from a modeling assumption in the performance-based recovery method; the method assumes that to establish tenant function in a residential building, there is a higher tolerance for interior damage, compared to office buildings (i.e., people are more likely to continue to use their homes for their basic intended function than an office building, given the same level of interior damage).

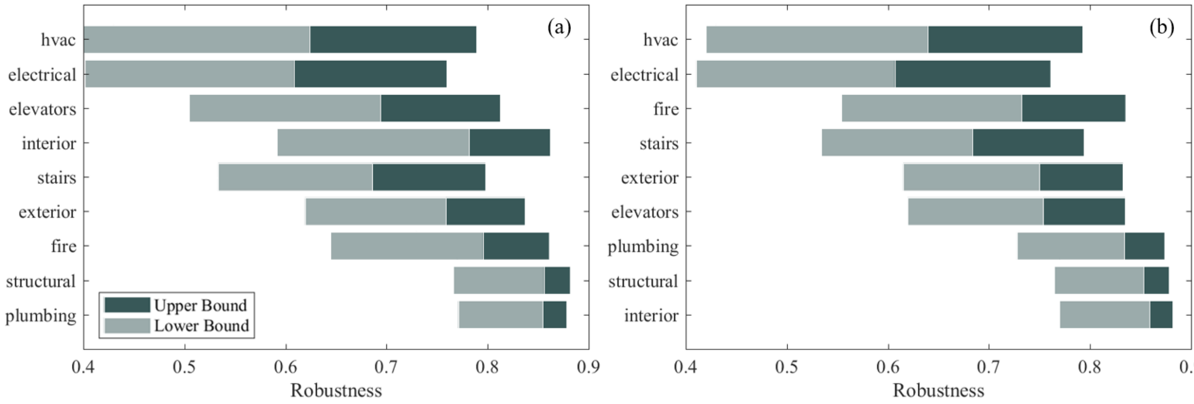

Figure 4. Tornado plots showing the impact of variation of median fragility capacity on building robustness (case 1), averaged across (a) all office occupancy models and (b) all residential occupancy models, for S = 3.

5.4 BUILDING HEIGHT

Many of the results above are presented at a strength ratio of three, representing the shaking intensity with the highest average impact on building function. However, the point of peak impact changes with the height of the building; taller buildings are more likely to lose function at lower shaking intensities compared with shorter buildings due to the increased size of the building and subsequent building systems, i.e., in a probabilistic sense, the bigger the building, the larger the systems (more components), the more possible points of failure. Figure 5a and 5b show the impact of variation in fragility median capacity for 4-story and 10-story models, respectively. Even at a lower shaking intensity (S = 2) the baseline 10-story models are generally less robust compared to the 4-story models at higher shaking intensity (S = 4). In particular, the taller buildings are more sensitive to variation in stair capacity compared to the shorter buildings.

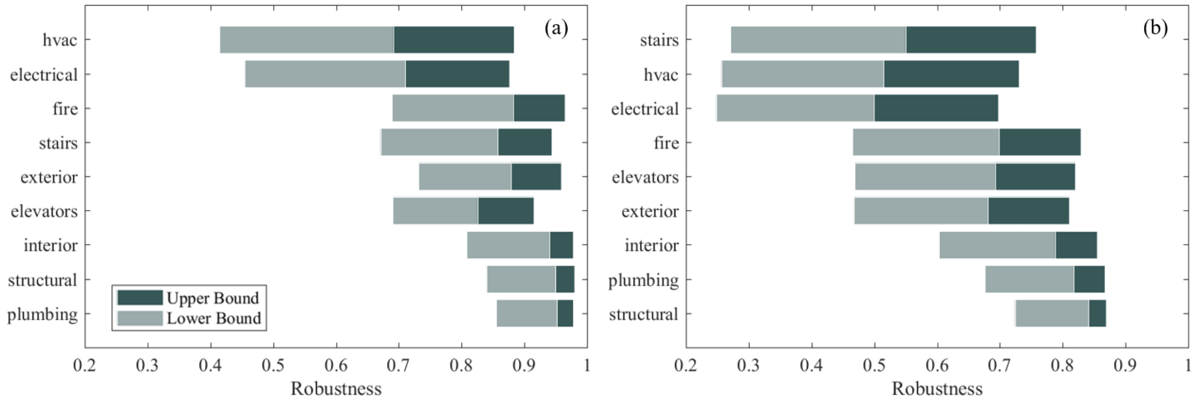

Figure 5. Tornado plots showing the impact of variation of median fragility capacity on building robustness (case 1), averaged across (a) all 4-story models at S = 4 and (b) all 10-story models at S = 2.

6. Summary and Future Work

To identify key research gaps in nonstructural seismic performance quantification, we investigated the impact of nonstructural components and fragility models on building function. In particular, we reviewed evidence of common nonstructural impacts on building function from previous earthquakes, summarized the source models and data quality forming the basis of the nonstructural fragility models in the FEMA P-58 fragility database, and performed a sensitivity analysis quantifying the impact of variation in fragility model capacity and uncertainty on building robustness using a state-of-the-art probabilistic recovery modeling framework.

From our review of earthquake damage, we observe the dislodging of suspended ceilings and broken pipes or fire sprinklers to be common sources of damage impacting building function in past earthquakes, alongside elevator damage and broken windows and glazing. From the review of the FEMA P-58 database, we found most MEP fragility models to be based on limited data, particularly for distributed components such as HVAC ducts, pipes, and fire suppression systems. Finally, results from the sensitivity analysis indicate that variability in the fragility models (median capacity and uncertainty) for HVAC and electrical components have the largest impact on building function, followed by stairs, exterior cladding and glazing, fire suppression systems, and elevators.

Taking all of these observations into consideration, we recommend that future studies focus efforts to improve the seismic performance quantification of piping components—particularly for mechanical and fire suppression systems—as these types of components were shown to have the highest impact across all sources investigated in this study. Additionally, we recommend that future studies look to improve seismic fragility models for stairs, elevators, and MEP equipment. Future studies can improve upon the fragility models in the FEMA P-58 database through a literature review of recent experimental programs that are unaccounted for in the fragility database, perform analytical failure analysis using advanced finite element models, or through an experimental testing program.

While the literature review and sensitivity analysis performed in this study was not exhaustive, this study identifies key gaps and next steps in improving quantitative analysis and prediction of nonstructural behavior and building function. While many building components common to U.S. construction were considered in this study, other nonstructural components, not explicitly considered herein, may indeed be critical for building function and susceptible to seismic excitation, and therefore, important for consideration in future studies.

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