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Seismic safety of informally constructed reinforced concrete houses in Puerto Rico

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Abstract

More than 1.6 billion people worldwide live in informally constructed houses, many of which are reinforced with concrete. Patterns of past earthquake damage suggest that these homes have significant seismic vulnerabilities, endangering their occupants. The characteristics of these houses vary widely with local building practices. In addition, these vulnerabilities are potentially exacerbated by incremental construction practices and building practices that address wind/flood risk in multi-hazard environments. Yet, despite the ubiquity of this type of construction, there have not been efforts to systematically assess the seismic risks to support risk-reducing design and construction strategies. In this study, we developed a method to assess the seismic collapse capacity of informally constructed housing that accounts for local building practices and materials, quantifying the effect of building characteristics on collapse risk. We exercise the method to assess seismic performance of housing in the US. Caribbean Island of Puerto Rico, which has high seismic hazard and experiences frequent hurricanes. This analysis showed that heavy construction, often due to the addition of a second story, and the presence of an open ground story leads to a high collapse risk. Severely corroded steel bars could also worsen performance. Although houses with infill performed better than those with an open ground story, confined masonry construction techniques produced a major reduction in collapse risk when compared to infilled or open-frame construction. Infill construction with partial height walls performed very poorly. Well-built reinforced concrete column jackets and the addition of infill in open first-story bays can reduce the greater risks of open-ground-story houses. These findings, which are quantified in the results portion of this article, are intended to support the development of design and construction recommendations for safer housing.

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Introduction

Worldwide, more than 1.6 billion people live in informally constructed houses (Murray, 2015), which comprise 50–90% of residential construction in low- and middle-income countries (Ferguson and Smets, 2010). Although the nature and degree of informality of informal construction vary widely, here we use the term to refer to housing construction that is self-managed, with construction carried out by residents or builders who may not have formal construction training, and often without permitting, explicit adherence to building codes, or formalized land tenure (Department of Housing, 2018; Samper, 2014; Talbot et al., 2020). In many parts of the world, informally constructed houses are commonly reinforced with concrete (RC), because the materials are widely available (Earthquake Engineering Research Institute (EERI) and International Association for Earthquake Engineering (IAEE), 2021) and because of the association of this material with status and the perception that these materials are safer (Goldwyn et al., 2021; Venable et al., 2020).

Informally built RC houses may be vulnerable to severe damage or collapse in an earthquake. Indeed, reconnaissance in the aftermath of recent earthquakes has revealed a high incidence of collapse in houses that were built informally in—among other locations—Turkey (Arslan and Korkmaz, 2007), Nepal (Brando et al., 2017; Chen et al., 2017), Haiti (Eberhard et al., 2010; Lang and Marshall, 2011; Marshall et al., 2011), and Puerto Rico (Miranda et al., 2020). Taken together, previous literature has shown damage and collapse to be of particular concern in RC houses with weak materials, inadequate numbers of longitudinal or transverse reinforcing bars in columns, or building designs that lead to excessive deformations in under-designed members, such as soft stories or partial height infill walls that induce a short column with high shear demands (Arslan and Korkmaz, 2007; Barbosa et al., 2017; Chen et al., 2017; Gautam et al., 2016; Guevara and García, 2005; Lang and Marshall, 2011). Masonry infill walls, though often considered nonstructural elements, may improve or worsen structural seismic performance depending on their relative strength and design details (e.g. Eberhard et al., 2010). Confined masonry panels can provide good earthquake resistance, but vary in material and construction quality (Brzev et al., 2010; Tarque and Pancca-Calsin, 2022). In addition, informal construction often takes place in stages, or incrementally, to accommodate a family's changing needs and access to materials or funding (Ferguson and Smets, 2010; Greene and Rojas, 2008; Lallemant et al., 2017; Tipple, 2000). These incremental building practices may negatively affect seismic performance because of the heavier weight and seismic demands in expanded homes (Brando et al., 2017; Lallemant et al., 2017), as well as the effect of rebar corrosion on structural strength and deformation capacity (McKee et al., 2020; Yu et al., 2021). Despite these potential vulnerabilities affecting earthquake outcomes for communities around the globe (Calderon and Silva, 2019; Yepes-Estrada et al., 2017), detailed seismic performance assessments of informally constructed RC houses have been extremely limited (Blondet et al., 2004; Holliday and Kang, 2015; Lallemant et al., 2017; Villar-Vega et al., 2017), and efforts to assess the seismic performance are hampered by the wide variation in

(a) (b)

Figure 1. Damage to RC houses in Guánica, Puerto Rico in recent earthquakes showing (a) loss of the first open story, and (b) diagonal (shear) cracking in walls and columns. [Photos: Polly B. Murray].

design details and construction practices, which can vary significantly by builder and according to the local building practices (Goldwyn et al., 2021; Rodgers, 2012).

In the interest of improving housing safety in these conditions to support community recovery and resilience (Burton et al., 2017), we developed a method to assess informally constructed houses that accounts for local building practices. This method first involves fieldwork, including interviews with builders and residents, and observations of past earthquake damage in the relevant context, to identify common housing characteristics. These characteristics are used to define a set of "archetype" informally constructed RC houses representative of those found in the location of interest and capturing the key potential seismic vulnerabilities. The method then involves assessing the seismic collapse capacity of the archetype houses through nonlinear dynamic simulations as a measure of seismic safety. The impacts of modifications that could be made in new or existing houses and their impact on collapse capacity are similarly assessed, focusing on investigating locally feasible, accessible, and practical recommendations (Kijewski-Correa et al., 2012).

We apply this method to conduct a seismic risk assessment of informally constructed houses in the Caribbean island of Puerto Rico. An estimated 55% of Puerto Rican houses have been built informally (Department of Housing, 2018). In Puerto Rico, hurricanes are frequent and have caused extensive housing damage (Federal Emergency Management Agency (FEMA), 2018) and, as a result, have strongly influenced local building practice (Goldwyn et al., 2021). A series of earthquakes in 2019 and 2020 has recently intensified interest in earthquake safety (Goldwyn et al., 2021; Mazzei et al., 2020). The largest events of this series—magnitude (Mw) 5.8 and 6.4 earthquakes—occurred on January 6 and 7, 2020, with the most intense shaking around PGA = 0.50 g (United States Geological Survey (USGS), 2020a). Reports noted the collapse of at least 80 structures and damage to more than 10,000 houses, with 8,000 people displaced and more than 40,000 applying for disaster assistance (Miranda et al., 2020; Pérez Méndez, 2020; Robles, 2020). Figure 1 illustrates some of the housing damage. Due at least in part to the absence of formal documentation of ownership and construction, assistance after both Hurricane Maria and the earthquakes from the Federal Emergency Management Agency (FEMA) was much more limited in Puerto Rico than in the mainland US in terms of funding and staffing (García, 2021; Willison et al., 2019). The archetype houses we develop for this context vary in terms of material strength and detailing, component sizes, presence and configuration of masonry walls, and roof system/weight. We also examine the effects of window and door openings, including partial height infill walls, and the effects of incremental construction practices. Each of these configurations is simulated through nonlinear dynamic analysis to assess the seismic collapse capacity, quantifying the risks associated with each set of design or construction features. Finally, we consider several mitigation strategies, including design modifications (*e.g.* confined, rather than infilled, construction) and retrofit strategies (*e.g.* RC jacketing and infill panels), to assess the benefits for seismic safety and to provide recommendations for residents.

This article describes fieldwork conducted to characterize the wide variability of design and construction characteristics of this type of housing, obtained through interviews with builders and residents, as well as observations of earthquake damage in the relevant context. We then define the nonlinear dynamic seismic performance assessment methods and interrogate results to quantify the impact of design and construction variation on seismic collapse risk. Though informally constructed houses are common in regions throughout the world, there has been limited study of their seismic performance. This study provides a framework for assessing informal construction and applies that framework to housing in Puerto Rico. The results of this framework can be used to guide homeowners and builders toward seismically safer houses.

Informally constructed housing in Puerto Rico

Housing characteristics

We first developed a set of interview questions and fieldwork observation protocols that could be used to identify common construction practices associated with informally constructed housing. This fieldwork aimed to identify commonly available materials, associated strengths (including concrete mixes, reinforcing bars, and masonry blocks), and building design characteristics that could be used to define archetype buildings and element configurations. This process involved interviews with residents and local builders, visits to hardware stores, and observations of construction characteristics and damage from the recent earthquakes. For example, interview questions included: *What is the process for mixing and pouring concrete? What provisions are included in construction to allow for incremental expansion later?* A complete list of questions can be found in the Supplemental Information. We also conducted post-earthquake reconnaissance in Ponce and Guánica in February 2020 and reviewed reports by StEER (Miranda et al., 2020), FEMA (2020a) and the Earthquake Engineering Research Institute (EERI, 2020).

In total, our team conducted 55 interviews, surveyed 50 damaged and undamaged houses, exemplified in Figures 1 and 2, and visited eight hardware stores, where we also conducted interviews. Much of the informally constructed housing is RC, which is our focus here. These houses are commonly one or two stories and consist of RC framing elements, floor slabs, and masonry walls/partitions. Masonry is almost always constructed from concrete blocks. Roofs can be a RC slab or a wooden roof structure with metal panels. Some of these houses have an open ground story (Figure 2a). It is not uncommon for the first story to be made of reinforced concrete and the second to be constructed of wood (*e.g.*Figure 3b).

Our conversations and observations revealed a number of potential seismic vulnerabilities of RC houses. In general, materials used for informal construction in Puerto Rico are weaker than those conventionally used in engineered construction. These include the potential for weak concrete due to, for example, high water-cement ratios, poor mixing or

(a) (b)

Figure 2. Typical RC houses in (a) Guánica and (b) Humacao, Puerto Rico [1 in = 2.5 cm; 1 ft = 0.3 m]. [Photos: Polly B. Murray].

(a) (b)

Figure 3. (a) House with exposed reinforcing bars to facilitate future house expansion and (b) home with RC first story and wood frame second story (Yabucoa, Puerto Rico). [Photos: Polly B. Murray].

a lack of vibration, and large or smooth aggregate. Both longitudinal and transverse reinforcement are minimally provided and lack seismic reinforcement detailing in beams, columns, slabs and other RC elements (*e.g.* instead having large lateral tie spacing and few longitudinal bars). The masonry walls are either added as infill, after the construction of the frame, or in more of a confined masonry modality, in which walls are built first (Brzev et al., 2017). When built as confined masonry, the wall panel and frame act as a single unit that can effectively resist lateral loads. Nevertheless, we did not observe much evidence of the connections between columns and walls needed to achieve confined construction. We also observed that many of the materials available on the island were of low or uneven quality (*e.g.* reinforcing bars are often rusted from storage outside). We conducted drop tests of concrete masonry blocks from the island's major supplier, and these experienced brittle failure during our team's drop tests (Build Change, 2013). Mortar is of inconsistent quality and sometimes provided sparingly.

In Puerto Rico, as elsewhere, the process of building incrementally, expanding as funds allow, is widespread. This practice is driven in part by a lack of formal home financing options (Greene and Rojas, 2008; Talbot et al., 2020). In this process, reinforcing bars are often left exposed above the roof slab to facilitate connections to upper stories, as shown in Figure 3. Our interviewees reported time between expansions on the order of months and years that increased total space by 50%.

Puerto Rican home construction is also strongly influenced by hurricane risk, which has contributed to the desire for RC construction, to which residents have observed less wind damage, and preference for an open ground story to reduce vulnerability to flooding. One hardware store employee told us that a "majority of people want a concrete house." However, this situation may be changing, as, in the aftermath of the recent earthquakes, the number of interviewees who reported a preference for RC construction dropped from 83% to 36% (Goldwyn et al., 2021). Several interviewees indicated an interest in improving the seismic resistance of RC housing (Goldwyn et al., 2021).

Archetype houses

From these interviews and observations, we generated Table 1, which defines characteristics of and variation in RC housing, which we used to define informally constructed RC house archetypes to represent the building inventory. As illustrated by Figure 1a, houses with open ground stories were particularly susceptible to damage and collapse in the earthquakes (Miranda et al., 2020), and comprised a portion of the archetype buildings in this study. We also studied one- and two-story houses with masonry walls, as damage to wall panels was also common in the earthquakes (see Figure 1b). We analyzed houses with infilled and confined masonry walls, as both methods of construction were frequently cited as correct by local builders with whom we met (Goldwyn et al., 2021), although it is not clear how many builders incorporate all of the key features of confined masonry (Brzev and Mitra, 2007).

Figure 4 shows the floor plan and elevation views for the archetype houses. Story heights are 10 ft (3 m) and bay widths are 10 ft in the NS direction and 12 ft (3.6 m) in the EW direction. We assumed a slab foundation, which is common in Puerto Rico, though we also observed concrete footings and concrete masonry block foundations. With one exception, the houses are assumed to have a reinforced concrete floor and roof slabs. We considered houses with 4, 8, and 12 in (10, 20, and 30 cm) slabs, and a house with a wood second story (and a wood roof). Table 2 summarizes the key parameters of the open-ground-story archetypes, as well as measures of seismic performance that are discussed in the section detailing nonlinear simulation. Variations of these archetypes have columns that differ in terms of concrete strength, longitudinal bar detailing, transverse tie spacing, thickness of floor/roof slabs, and the presence of longitudinal PVC gutters embedded in columns. In all cases, we assumed infilled walls in the second story.

Figure 5 shows the adopted column cross-section of 8 × 14 in (20 × 36 cm), which is oriented in the weak-axis direction in the frame line considered (Figure 4). Sizes and placement of archetype steel reinforcement, including no. 4 and 5 for longitudinal bars and no. 3 for transverse ties, reflect typical practice. While builders reported a typical tie spacing of around 6 in (15 cm), we observed a much larger spacing in some of the collapsed houses in Guánica (see Figure 5a). In some houses, a PVC gutter is embedded in the column to reduce roof water accumulation and the associated aesthetics of exterior gutters. These gutters may reduce axial capacity (Kassim and Ahmad, 2018) and stiffness (Murugesan and Narayanan, 2018).

Table 3 summarizes RC house archetypes with concrete masonry walls, which have variations in material strength, construction method, opening type, and slab thickness. Block

Table 1. Archetype housing characteristics and their justification. [1 in = 2.5 cm; 1 ksi = 6.9 MPa.]

	Parameter	Value or Range	Rationale
Building properties	Story height	10 ft	Field observations
	Bay width	10, 12 ft	Field observations
	Slab thickness	4, 8 or 12 in	Field observations
	Foundation	Slab on grade	Field observations
	Wall configuration	0, 1, or 2 filled bays	Field observations
	Window, door sizes	3 × 3 ft, 7 × 3 ft	Field observations
	Soil conditions	Site class B	USGS
Component properties	Column/beam size	8 × 8 or 8 × 14 in	Interviews; field observations
	Column/beam longitudinal bars	4 or 6 bars, no. 4 or no. 5	Interviews; field observations, particularly the availability and popularity of pre-formed transverse ties measuring 6 × 12 in
	Column/beam transverse ties	No. 3 bars at 6 or 14 in	Interviews; field observations
	Corrosion	0% to 20%[a] in column rebar	Field observations of incremental construction and rebar stored outside; prior studies (McKee et al., 2020; Yu et al., 2021)
	PVC pipe	3 in diameter gutter in all exterior columns	Field observations
	Concrete masonry block size	8 × 16 × 6 in	Interviews, field observations
	Masonry wall construction	Infilled or confined	Interviews
Materials	Concrete strength[b]	1.5 to 3 ksi	Interviews, particularly calculations from mix designs described
	Masonry unit strength	0.4 to 1.5 ksi	Interviews; drop tests
	Steel strength[b]	40 ksi	Hardware stores
Loads	Dead loads[b]	100 – 200 psf	Calculated from RC slabs, masonry walls[c]
	Live loads[b]	10 psf (floor), 5 psf (roof)	25% of design loads (American Society of Civil Engineers (ASCE)/Structural Engineering Institute (SEI), 2017)
Retrofit	Open ground story houses	RC jacketing; added infill	Interviews; prior studies (Chaulagain et al., 2015; Martínez Cruzado et al., 2013)

USGS: United States Geological Survey; RC: reinforced concrete; ASCE/SEI: American Society of Civil Engineers/ Structural Engineering Institute.
[a]Cross-sectional area of reinforcing bars lost by corrosion.
[b]Expected strengths and loads.
[c]We assumed smaller blocks measuring 4 × 8 × 16 in (10 × 20 × 40 cm) in internal walls.

strength is reported as 2200 psi (15 MPa) (Home Depot, 2020). However, we assessed block quality through drop tests (Build Change, 2013), which indicated that may be an overestimate. From interviews, we judged that mortar is typically type N or S, which corresponds to masonry unit strengths of $f'_m = 750$ and 1500 psi (5 and 10 MPa), respectively (ASTM International, 2019). These RC frames in these houses have 8 × 8 in (20 × 20 cm) columns, which are typical of houses with walls. We considered walls with openings, illustrated in Figure 4. We did not consider the heaviest (12 in) slab case because the weight of these buildings is driven by the masonry walls.

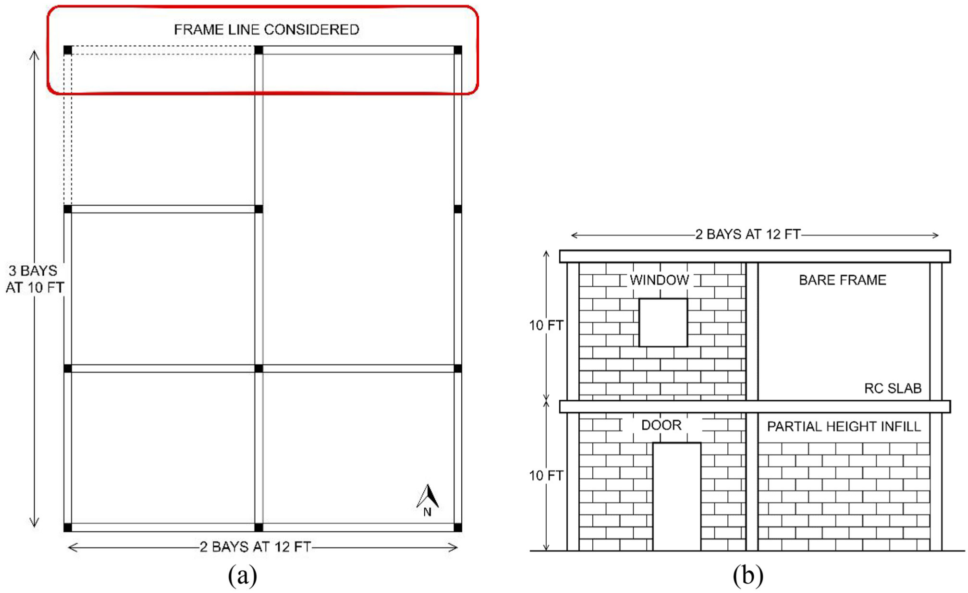

Figure 4. Floor plan and elevation views for archetype houses. The infill/opening configuration and the number of stories are two of the characteristics varied. [1 ft = 0.3 m].

Incremental construction. We considered the effects of incremental construction practices in two ways, listed in Table 4. First, we compared the performance of one-story buildings with masonry walls or a second story that is lightweight (wood) with that of a second story that has RC and masonry construction. Second, we explored the effect of the common construction practice in which, typically, around 24 in (61 cm) of reinforcing bars are left extending above columns to facilitate future construction of an additional story (Figure 3a). These bars, when not protected from exposure by coating, can corrode. The level of corrosion varies with time and proximity to the coast (McKee et al., 2020; Ou et al., 2016; Yu et al., 2021); we incorporated an anticipated upper bound of bar area loss due to corrosion, 20%, to capture a scenario where a bar may be exposed for more than a decade and is close to the coast, as is the case in much of Puerto Rico, and a lower bound in which no corrosion has occurred.

Retrofit. We heard substantial community interest in building modifications that could improve seismic performance, particularly for open-ground-story buildings. We have investigated the potential benefits of two retrofit options (Table 2) that are accessible to Puerto Ricans: RC jacketing and infill walls. Retrofit with jackets includes the addition of concrete steel reinforcement to vulnerable columns and maintains the open story. Researchers (*e.g.*Chaulagain et al., 2015; Sahoo and Rai, 2013) have previously shown that column jacketing can improve seismic performance for similar RC buildings to those investigated here. Timsina et al. (2021) demonstrated the value of adding infill walls. Infill and other retrofits, like shear walls (Martínez Cruzado et al., 2013) and steel braces, have also been found to improve performance, but these may be impractical in many contexts as they limit access to floor area and materials are not widely available (Antonopoulos and Anagnostopoulos, 2012; Chaulagain et al., 2015; Timsina et al., 2021).

Table 2. Archetype RC open-ground-story houses and outcomes of seismic performance assessment. [1 in = 2.5 cm; 1 ksi = 6.9 MPa.]

ID	Archetype Characteristics						Performance Assessment Metrics[a]			
	Column height, h (in)	Column width, b (in)	Conc. strength, f'_c (ksi)	Number of long. bars	Transverse tie spacing, s (in)	Slab thickness, t (in)	Period, T (s)	Strength (V/W)	Def. capacity (% drift)	Med. collapse Sa(T = 0.8s) (g)
OGS1	8	14	3	6	6	4	0.6	0.14	4.7	0.65
OGS2					14		0.6	0.14	3.0	0.54
OGS3					6	8	0.7	0.11	4.4	0.65
OGS4					14		0.7	0.11	3.3	0.55
OGS5					6	12	0.8	0.10	4.0	0.64
OGS6					14		0.8	0.10	3.2	0.55
OGS7			1.5		6	4	0.6	0.13	4.6	0.62
OGS8					14		0.6	0.13	2.5	0.51
OGS9					6	8	0.7	0.10	3.9	0.56
OGS10					14		0.7	0.10	3.0	0.47
OGS11					6	12	0.8	0.08	3.5	0.58
OGS12					14		0.8	0.08	2.6	0.48
OGS13			3	4	6	4	0.6	0.11	4.3	0.57
OGS14						14	0.6	0.11	3.3	0.49
OGS15					6	8	0.7	0.09	3.8	0.58
OGS16					14		0.7	0.09	3.1	0.49
OGS17					6	12	0.8	0.08	3.4	0.58
OGS18					14		0.8	0.08	3.0	0.51
OGS19			1.5		6	4	0.6	0.11	4.1	0.53
OGS20					14		0.6	0.11	2.2	0.45
OGS21					6	8	0.7	0.08	3.5	0.51
OGS22					14		0.7	0.08	2.8	0.43
OGS23					6	12	0.8	0.07	3.1	0.50
OGS24					14		0.8	0.07	2.5	0.43
OGS25-P[b]	8	14	3	4	6	8	0.7	0.09	3.6	0.59

(continued)

Table 2. Continued

ID	Archetype Characteristics						Performance Assessment Metrics[a]			
	Column height, h (in)	Column width, b (in)	Conc. strength, f'_c (ksi)	Number of long. bars	Transverse tie spacing, s (in)	Slab thickness, t (in)	Period, T (s)	Strength (V/W)	Def. capacity (% drift)	Med. collapse Sa(T = 0.8s) (g)
OGS26-R[c]	12	18	3	12	3	8	0.3	0.14	4.6	0.59
OGS27-PR[c]	12	18	3	12	3	8	0.3	0.13	4.4	0.58
OGS28-C[d]	8	14	3	6	6	8	0.7	0.11	4.4	0.47
OGS29-R[e]	16	22	3	18	3	8	0.2	0.17	6.5	0.94
W12[f]	8	8	1.5	4	6	4	0.1	0.7	NC[g]	0.80

[a]Metrics defined in text.
[b]PVC gutter.
[c]Retrofit with small RC jacket.
[d]Corroded reinforcing steel assumed in all columns.
[e]Retrofit with large RC jacket.
[f]House with masonry infill walls in first story.
[g]NC: Pushover analysis did not converge.

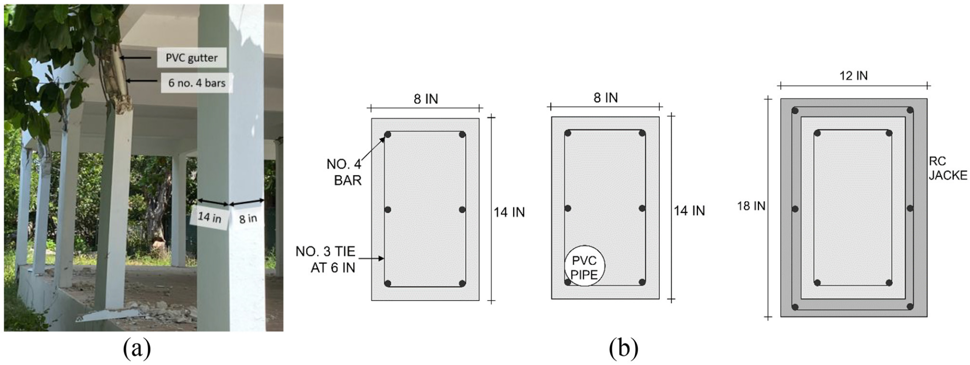

Figure 5. (a) Columns damaged during the January 7, 2020 earthquake (Guánica, Puerto Rico) and (b) baseline column configuration for the open-ground-story buildings, and two variations. [1 in = 2.5 cm].

As shown in Table 2, we consider two RC jacket retrofits in this study that are representative of a range in potential construction quality. This includes 2 in (5 cm) and 4 in (10 cm) jackets with 6 and 10 no. 5 longitudinal bars, respectively. Transverse ties in both cases are no. 3 bars at 3 in. In each case, the retrofit is applied to all columns in the open-ground story. We assume the jacket is well connected to the existing column through dowels and a roughened surface such that the length of the column acts as an equivalent monolithic element (Bousias et al., 2007). We also explored infilling the open-ground-story houses, as this can significantly increase the strength and stiffness of open ground stories.

Seismic performance assessment methods

Nonlinear simulation models

To assess seismic safety, we developed nonlinear simulation models to capture the response of the archetype informally constructed house up to the point of collapse. For this purpose, we developed a 2D model of each archetype in *OpenSees* (McKenna et al., 2010), representing the building orientation and frame line that is expected to control the structural response (*i.e.* the weaker direction), as shown in Figure 4. As the houses in this study are regular in plan, torsion is not a concern, and 2D models offer enhanced computational efficiency over their 3D counterparts. Figure 6 shows a schematic of the model for the archetype houses, in which lumped plasticity hinges are employed to represent the nonlinear behavior of columns and diagonal struts to represent the behavior of infill or confined masonry panels.

In all building models, we applied 3% Rayleigh damping to the initial (cracked) first and third modes, determined using eigenvalue analysis. Gravity loads are based on expected estimated weights of walls, roofs, and floor slabs, and beams and columns for dead loads, along with 25% of design live loads for residential buildings (ASCE/SEI, 2017). These loads were applied as masses to generate inertial seismic forces and as distributed loads. We represented the slab foundation with a fixed base, focusing our assessment on structural response. In this analysis, we considered P-Δ effects through the *PDelta* geometric transformation (Mazzoni et al., 2007).

Key properties of all building models are provided in Tables 2 and 3. The building period is determined using eigenvalue analysis. Strength and deformation capacity are

Table 3. Archetype RC house with masonry walls and outcomes of seismic assessment. [1 in = 2.5 cm; 1 ksi = 6.9 MPa.]

ID	Archetype Characteristics						Performance Assessment Metrics[a]			
	Wall construc-tion[b]	Conc. strength, f'_c (ksi)	Masonry strength, f'_m (ksi)	Num. stories	Slab thickness, s (in)	First story, bays[c]	Period, T (s)	Strength (V/W)	Def. capacity (% drift)	Med. collapse Sa(T = 0.1s) (g)
W1	I	1.5	0.75	1	8	S—S	0.05	1.0	0.58	2.0
W2				2	4	S—B	0.11	0.4	0.67	0.7
W3						W—B	0.11	0.4	0.63	0.6
W4						D—B	0.13	0.3	0.63	0.6
W5					8	S—S	0.1	0.7	NC[d]	0.9
W6	C			1			0.05	1.9	0.58	3.5
W7				2			0.09	1.2	0.67	1.4
W8	I	3	1.5	1			0.04	1.6	0.50	2.8
W9				2			0.08	0.8	0.63	1.1
W10	C			1			0.04	2.2	0.42	4.4
W11				2			0.08	0.8	0.46	1.5
W12	I	1.5	0.75		4		0.10	1.2	0.63	1.0
W13				1	8	PHI—PHI	0.12	1.1	0.57	0.6
W14		3	1.5				0.12	0.6	NC	0.6
W15		1.5	0.75	2			0.10	0.6	0.57	0.6
W16		3	1.5				0.09	0.7	NC	0.6
W17		1.5	0.75		4	W—W	0.10	0.6	0.61	1.0
W18						D—D	0.10	0.1	0.61	0.9
W19-C[e,f]					8	S—S	1.0	0.1	6.67	1.5
W20[f]							1.0	0.7	7.50	1.0
W21			0.4				0.13	0.7	NC	0.8

[a]Metrics defined in text.
[b]I: Infilled, C: Confined.
[c]S: Solid, W: Window, D: Door, PHI: Partial height infill, B: Bare frame (see Figure 4);—indicates configuration in each bay of the analyzed frame.
[d]NC: Pushover analysis did not converge.
[e]Corroded reinforcing bars assumed at base of second story.
[f]No infill in second story.

Table 4. Archetype houses used to assess effects of incremental construction

ID	Description	Med. Collapse Sa(T = 0.1s) (g)
W1	One-story, 8 in roof slab OR Two-story, 4 in slab with wood second story	2.0 g
W2	Two-story, 4 in floor and roof slabs and infill walls	0.7 g
W5	Two-story, 8 in floor and roof slabs and infill walls	0.9 g
W19	Two-story, RC frame second story (no infill) with corrosion	1.0 g
W20	Two-story, RC frame second story (no infill) without corrosion	0.8 g

RC: reinforced concrete.

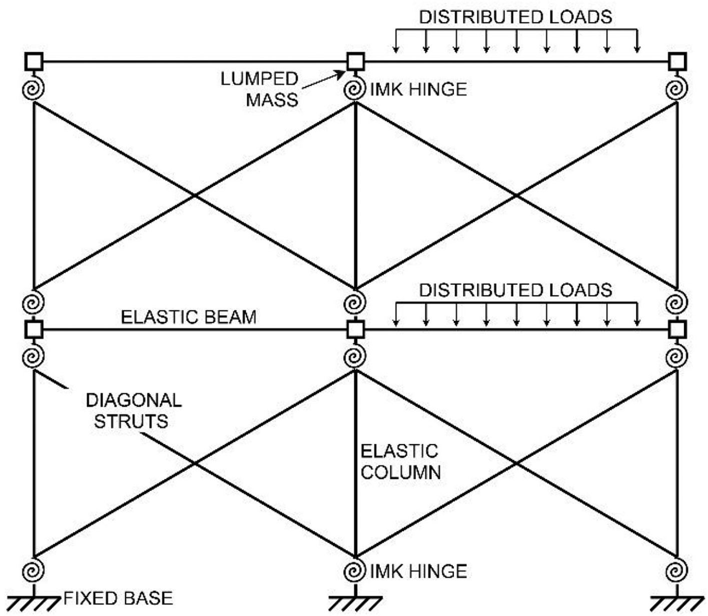

Figure 6. Schematic diagram of nonlinear simulation model; diagonal struts are eliminated in bare bays.

determined from static pushover analysis conducted with a displacement-controlled analysis and an applied inverted triangular lateral load. Building strength is presented as the maximum lateral base shear from pushover normalized by building weight (V/W). Deformation capacity is quantified as the level of story drift when 20% of strength has been lost in a pushover (FEMA, 2009).

RC columns. Due to their design details, the bare columns in this study are flexure-critical, with ratios of flexural to shear strength of 0.2 to 0.5. Columns are accordingly modeled using a lumped plasticity approach with rotational springs defined using the Peak-Oriented Ibarra, Medina, Krawinkler (IMK) material (Ibarra et al., 2005). The IMK model parameters for each column are based on equations calibrated by Haselton et al. (2016) in relation to a large database of column tests, which consider each column's reinforcement, axial load ratio, and transverse tie spacing, and account for bar slip. Elastic beam-column elements, defined by cracked sections, connect the rotational springs. Well-

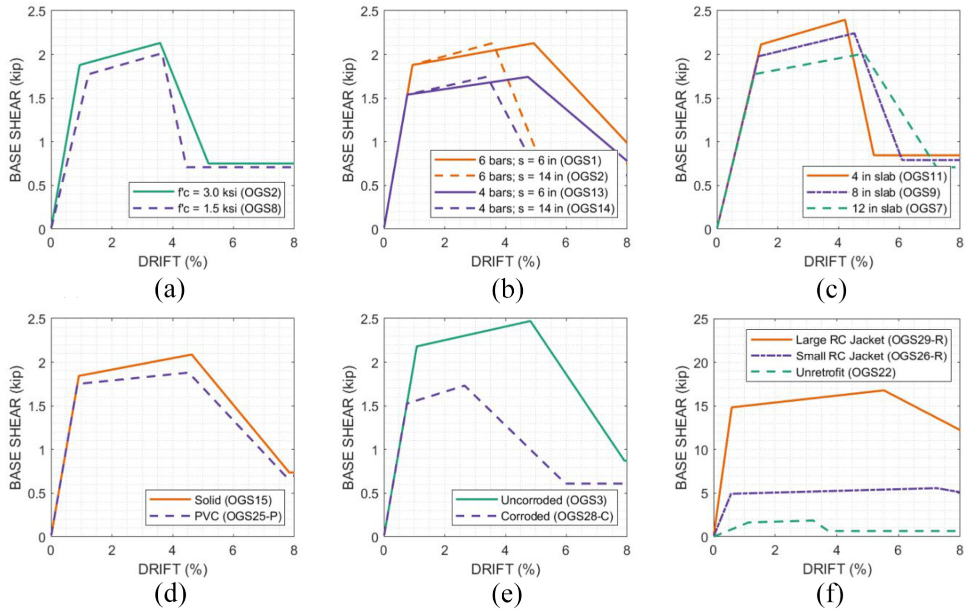

Figure 7. Backbone response of selected column configurations. [1 kip = 4.45 kN]. (a) concrete strength, (b) rebar detailing, (c) slab thickness, (d) cross section, (e) rebar corrosion and (f) retrofit.

connected RC jackets respond as an equivalent monolithic section (Bousias et al., 2007), so the models for the RC jacket cases are modeled as larger columns, with properties calibrated in the same manner and based on the entire composite section.

We also modified the analytical model for the columns to account for reinforcing bar corrosion for several years of exposure in a coastal environment. The literature reviewed indicated a reduction (~30%) in the yield and ultimate strength of bars (*e.g.*Di Carlo et al., 2017; Meda et al., 2014; Zhang et al., 2012), and a reduction in column strength and deformation capacity of 50% (Meda et al., 2014; Ou et al., 2016). We modified the backbone defining the nonlinear response of IMK material for the corroded columns based on (Meda et al., 2014). Based on field observations that showed the length of exposed rebar typically exceeds minimum splice length requirements per ACI 318 (American Concrete Institute (ACI), 2014), we did not consider vulnerabilities associated with short lap splices or corrosion of these splices.

We also modeled the seismic performance of RC columns with PVC gutters, which we represented as longitudinal holes, determining the flexural strength, stiffness, and deformation capacity of an RC column with a longitudinal hole using a distributed plasticity fiber analytical model. Details of the fiber models are provided in Murray (2021). We then calibrated a lumped plasticity (IMK) model such that its backbone matched that of the fiber model and used the lumped plasticity model to determine the effect of PVC gutters on collapse capacity. We do not consider the loss in performance if a gutter exits the column at the hinge region.

Figure 7 shows the effect of design variation on the modeled column backbones, illustrating the changes in strength, stiffness, and deformation capacity associated with each configuration. Longitudinal reinforcement, both the number of bars and the level of corrosion, has the most significant effect on the flexure capacity of columns. Deformation capacity is most influenced by corrosion and the spacing of transverse ties in the columns and the gravity (axial) load level (quantified as slab thickness). The RC jacket retrofit significantly increases strength, stiffness, and deformation capacity. PVC gutters slightly reduce the strength of columns, but this effect is small compared to other column details.

Masonry walls. Several methods exist for numerical modeling of the in-plane behavior of infill and confined walls in RC frames with varying levels of detail (*e.g.* micro-modeling and finite element (FE) modeling) with computational efficiency (*e.g.* diagonal strut models) (Bose et al., 2019; Burton and Deierlein, 2014; Huang et al., 2020; Mohammad Noh et al., 2017; Sattar and Liel, 2016). Here, we adopt a strut modeling approach, in which diagonal struts are used to represent the masonry panel. To define the strut properties for infilled RC frames, we followed the methodology proposed by Bose et al. (2019). Martín Tempestti and Stavridis (2017) subsequently developed force-deformation relations for use in the Bose et al. (2019) methodology, calibrated to experimental data. This model was developed from experimental tests, including those of infilled RC frames with concrete blocks like those of interest here, with multiple failure modes. It accounts for the effects of vertical (gravity) loading, concrete and masonry strength, and openings. Bose et al. (2016) used this approach to assess a multi-story infilled RC frame building that was damaged in the 2015 Nepal Earthquake, showing its efficacy in predicting damage in an informally constructed building. Out-of-plane failure of the concrete block walls is unlikely due to their relatively low height to thickness ratio and comparably large out-of-plane stiffness (Agnihotri et al., 2013).

Following the Bose et al. (2019) approach, we first identify the anticipated force-deformation analytical backbone of each infilled bay (*i.e.* aggregate of columns, beam, and infill panel) using empirical equations developed by Martín Tempestti and Stavridis (2017), with example results shown in Figure 8 for a selected infill configuration. This backbone was obtained as follows: Following Martín Tempestti and Stavridis (2017), the RC frame is classified as “ductile” or “nonductile” by the ratio of shear demands corresponding to flexure strength and shear strength in the bare column. The infill panel is classified as strong or weak based on its stiffness relative to the column. We found the configurations considered in this study are all “ductile” frames, meaning they are flexure critical despite their relatively non-ductile detailing, except for cases with partial height infill (discussed more below). Depending on the masonry unit strength, the infill was classified as either strong or weak. These systems are expected to fail through crushing or sliding in the masonry panel (weak infill) or flexural hinging in columns (stronger infill) (Martín Tempestti and Stavridis, 2017).

In the *OpenSees* model, the wall is represented by a diagonal strut, defined by truss elements calibrated with a pinched hysteretic response and activated only in compression (Mazzoni et al., 2007), following recommendations from Mohammad Noh et al. (2017). The strut material is *Pinching4* (Mazzoni et al., 2007), with input parameters determined following the empirical equations developed by Huang et al. (2020) based on a database of experimental results. We then adjusted the parameters of the strut so that the pushover response of the bay matches the analytical backbone defined by Martín Tempestti and Stavridis (2017). Figure 8 compares the analytical backbone and the corresponding *OpenSees* model for one confined and one infilled wall case. These backbones, shown in Figure 8, capture the expected response of two walls typical of Puerto Rican construction,

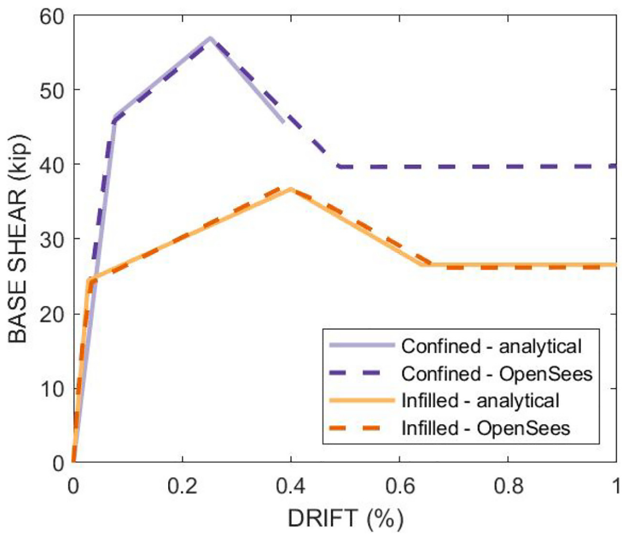

Figure 8. Illustration of analytical backbone and static pushover response of one bay calibrated for infilled and confined construction. These backbones are for masonry panels in archetypes W9 and W11 (see Table 3). [1 kip = 4.45 kN; 1 ksi = 6.9 MPa.].

based on equations derived from large experimental databases and numerical models used for nonlinear analysis.

We assessed the performance of archetypes with openings in masonry panels, including windows, doors, and partial height infill. The analytical backbone equations from Martín Tempestti and Stavridis (2017) account for openings by reducing the expected strength and stiffness proportionally to the area of the opening. In panels where the opening is within 2 feet (61 cm) of the column, the length of the column is modified to match the height of the opening, following Stavridis (2009). In this study, this condition only applies in the partial height infill case, illustrated in Figure 4. In this partial height infill configuration, the column is shear critical due to short column effects. We determined the shear strength of the short column using the formulation in ASCE/SEI 41-17 (2017) and modified the column force-displacement (backbone) response to degrade sharply when shear force demands exceed capacity, as has been observed by researchers who assessed the behavior of shear critical RC columns (e.g. Elwood, 2004; Pan and Li, 2013; Yu et al., 2016). We modeled the behavior of the partial height infill panel with struts connecting the base of the frame to the bottom of the opening.

For the confined masonry systems, we again calibrated diagonal struts to represent the behavior of the walls. The force-deformation backbones for the confined masonry wall systems are calibrated using equations developed by Riahi et al. (2009). These equations were based on a database of 102 confined masonry wall tests. These equations define response up to the ultimate drift capacity, defined as the level of drift at which 20% of lateral strength is lost. We assumed this to be the residual capacity of the wall system. For systems with similar details (*e.g.* column detailing, masonry and mortar strength, gravity loads), a bay of confined masonry construction is stronger than an infilled frame, as illustrated by Figure 8.

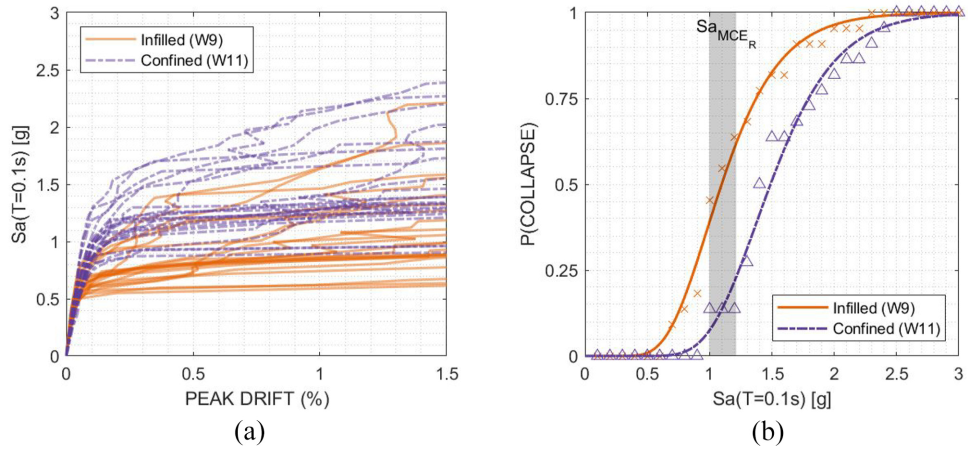

Figure 9. (a) IDA results for single-story RC houses with infilled and confined masonry construction, and (b) corresponding fragility curves (both empirical and fitted distributions).

Seismic collapse assessment

The collapse safety performance of each archetype building in Tables 2 and 3 is assessed using incremental dynamic analysis (IDA) (Vamvatsikos and Cornell, 2002), as illustrated in Figure 9. IDA involves the use of multiple ground motions, each scaled in increasing intensity until collapse occurs, and can be used to quantify the effects of record-to-record variability in the response. We quantified ground motion intensity as the spectral acceleration (Sa) at the structural period of interest. For open-ground-story houses, we adopt an intensity measure of Sa(T = 0.8s), and for houses with masonry walls, Sa(T = 0.1s). These periods are typical of each subset of archetypes. Collapse occurs, for houses with infilled or confined walls, if story drifts exceed 1.5% (Cardone and Perrone, 2015), and, for open-ground-story houses, if story drifts exceed 5% (Liel et al., 2010). Because the IDA curves, illustrated in Figure 9a, have flatlined by the time these values are reached, the collapse assessment is not sensitive to the precise drift threshold used. We used the FEMA P-695 (FEMA, 2009) far-field record set in IDA because the ground motion records contain variation in duration and frequency content appropriate given Puerto Rico's seismic hazard (Mueller et al., 2010) and because these motions have been widely used to assess collapse capacity (e.g. Christovasilis et al., 2009; Haselton et al., 2011). This set contains record pairs from 22 ground motions; we applied each horizontal motion record, 44 in total, to each 2D frame of the archetype building. The use of the same set of ground motions to represent the range of intensities in IDA can be criticized due to its inability to appropriately represent the spectral shape of the ground motions at a range of intensities. However, because these buildings are all fairly nonductile, spectral shape does not have a large influence on collapse results (Haselton et al., 2011).

We derive collapse fragility curves from the ground motion intensity at which the collapse threshold is reached for each ground motion, with values fitted to a lognormal cumulative distribution to quantify the probability of collapse as a function of ground motion intensity. The median collapse capacity is defined as the ground motion associated with a 50% collapse probability; standard deviations of these values range from 0.1 to 0.7. Figure 9 shows the collapse fragilities for two of the archetypes and the IDA from which they were

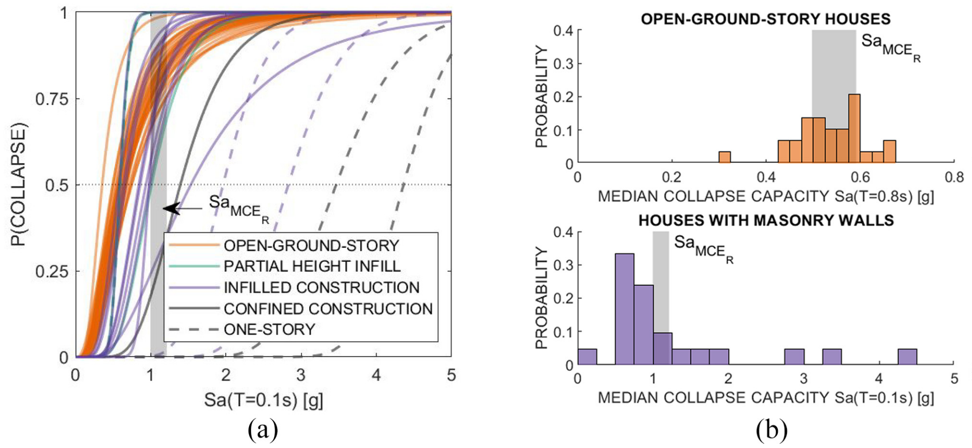

Figure 10. (a) Collapse fragilities for all archetype houses and (b) distribution of median collapse capacities for RC open-ground-story houses and houses with masonry walls.

derived, considering record-to-record variability only. For context, we show the Sa range for the risk-targeted maximum considered earthquake (MCE_R) values that are the basis for seismic design on the island from ASCE 7-16, assuming site class B (ASCE/SEI, 2017).

Seismic performance of informally constructed houses

The seismic performance assessment results are provided in Figure 10, and reported in Tables 2 and 3 for all the buildings. The key metric of interest here is the collapse fragility and the median collapse capacity, defined as Sa(T = 0.8s) or Sa(T = 0.1s), depending on the type of building. Generally, RC houses with masonry walls perform better in earthquakes than those with open ground stories due to the strength and stiffness provided by the concrete block walls, as explored in more detail below. In the United States, building codes target a less than 10% probability of collapse under an MCE_R-level ground motion (ASCE/SEI, 2017). As illustrated by Figure 10b, most archetype houses in this study do not meet that criterion. In particular, open-ground-story houses and those with partial height infill are most vulnerable to collapse; the median collapse capacity of these houses is below the intensity of an MCE_R-level ground motion. However, one-story houses with walls, particularly those built as confined masonry panels, perform relatively well, with a sufficiently low probability (< 10%) of collapse at MCE_R levels. The following results illustrate the effects of individual building characteristics (*e.g.* material strength, construction type, detailing) on overall collapse capacity and their implications for improving seismic resilience.

Collapse risk of open-ground-story RC houses

The collapse risk for all open-ground-story houses considered in this study in Table 2 during an MCE_R-level ground motion is high, with $P(collapse|MCE_R) > 0.75$. These houses fail in a soft-story mechanism in the first story, with flexural hinging at top and bottom of columns. The probability of collapse increases with seismic weight, which varied in this archetype set with roof and floor slab thickness, with the worse performance of heavier

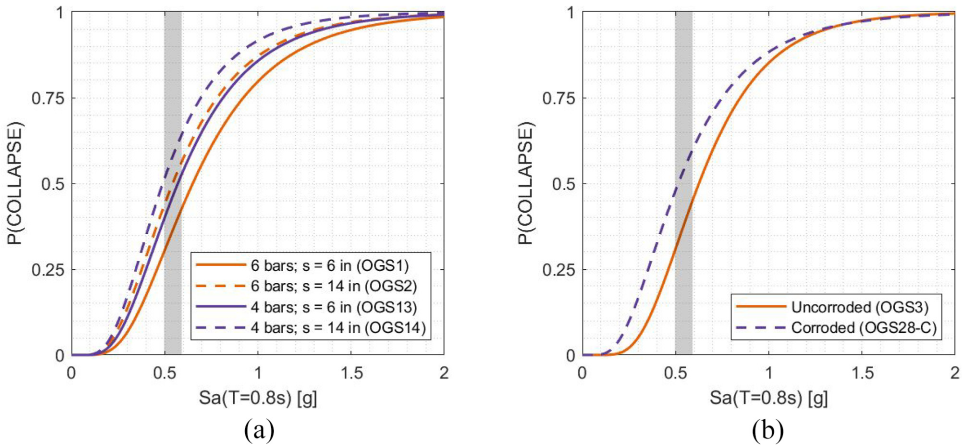

Figure 11. Collapse fragilities of open-ground-story houses with variation in (a) number of column longitudinal bars and transverse tie spacing, showing improvement in collapse capacity with more reinforcing bars and better detailing, and (b) columns with and without corroded reinforcing steel, illustrating the increased collapsed vulnerability introduced by corrosion.

construction (up to 6% lower collapse capacity), but this difference is less significant than those discussed in the following sections. The results are broadly consistent with the most dramatic damage in the recent earthquakes, which was observed in this type of construction. For many of the open-ground-story archetype houses, the probability of collapse under the most severe shaking levels experienced in the recent earthquakes of Sa(T = 0.3s) $\approx$ 0.5 g (USGS, 2020a) from this assessment is approximately 50%.

Effect of column design and condition. We assessed the effect of column steel reinforcement on the seismic performance of these houses, with the results shown in Figure 11a. Columns perform better with 6 longitudinal bars (reinforcement ratio, $\rho = 0.011$) when compared to columns with 4 longitudinal bars ($\rho = 0.007$), improving the median collapse capacity by 14%. Similarly, the median collapse capacity is increased by 20% by closer spacing of transverse ties ($\rho_{sh} = 0.003$ vs $\rho_{sh} = 0.001$). Transverse tie spacing increases deformation capacity. We only included tie spacings typical of informal construction in Puerto Rico, which do not provide any confinement effect to the concrete core (Moehle, 2014). Concrete strength has a smaller influence on collapse capacity, with only a 5%–15% change in median collapse capacity, than steel reinforcement detailing.

Figure 11b shows the effect of reinforcing steel corrosion in all columns. When critical columns, such as those in an open-ground-story, are affected by corrosion, this reduction in strength and deformation capacity manifests as a higher collapse risk during an earthquake (reduction in median collapse capacity of 38%). Our assessment does not find a significant effect of PVC gutters embedded in columns when compared to houses with solid columns, despite the modest changes in strength and stiffness associated with the PVC and hole. The worst-performing archetype, OGS24, had columns with only 4 longitudinal bars and 14 in (35 cm) transverse tie spacing. Its collapse capacity is 26% lower than an archetype with 6 longitudinal and 6 in (15 cm) tie spacing (OGS11).

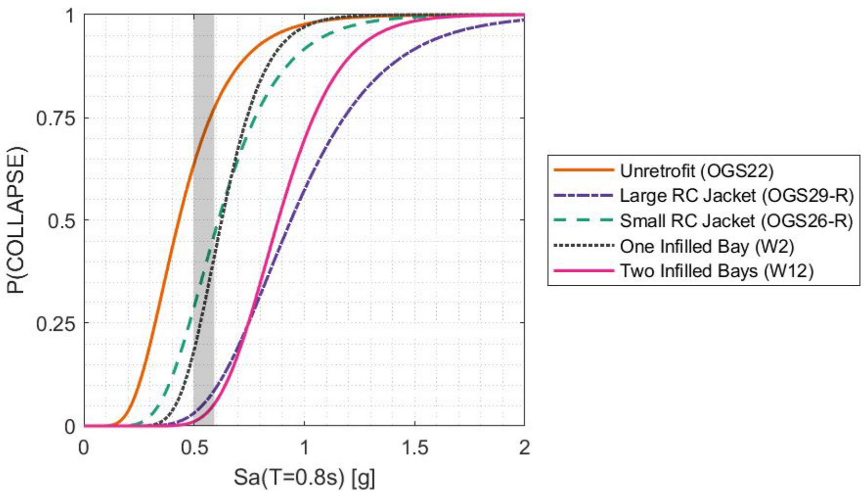

Figure 12. Collapse fragilities of open-ground-story house retrofit with full or partial RC jackets, one, and two bays of infill, showing the benefits of jackets and added infill at first story.

Effect of retrofit strategies. The retrofit strategies considered increase the strength and stiffness of the vulnerable open-ground-story houses and, when infill is added to previously bare frames, change the failure mechanism. Figure 12 shows the reduction in collapse risk of adding a small or large RC jacket, approximately 43% or 115% increase in the median collapse capacity, respectively, although these houses will still fail in the first story. These retrofits doubled the strength and deformation capacity of the open-ground-story columns through the addition of concrete and steel longitudinal and transverse reinforcement (see Figure 7f). Retrofitting bare bays of an open-ground-story building with infill increases the collapse capacity by 100%, but reduces access to the open story, and may not be preferable to homeowners in flood-prone regions. Well-designed RC jackets or infill may reduce collapse risk to the less than 10% probability at the MCE_R (ASCE/SEI, 2017).

Collapse risk of RC houses with walls

The collapse risk of the informally constructed RC houses with masonry walls varies widely, as shown in Figure 10b. The full set of performance assessment metrics is provided in Table 3. In the recent earthquakes, these houses exhibited damage in the form of in-plane shear cracking in masonry panels, which is consistent with the strong-infill-ductile frames assessed in this study (Martín Tempestti and Stavridis, 2017).

Effect of infilled versus confined construction methods. Figure 13a illustrates the collapse fragilities for one- and two-story houses with infilled and confined masonry walls, to explore the effect of the construction method. In all cases, confined construction increases collapse capacity by at least 90% relative to infilled construction. This benefit is achieved by the gravity load distribution through the masonry and the confined masonry panel's behavior as a shear wall (Brzev et al., 2010), which increases lateral strength.

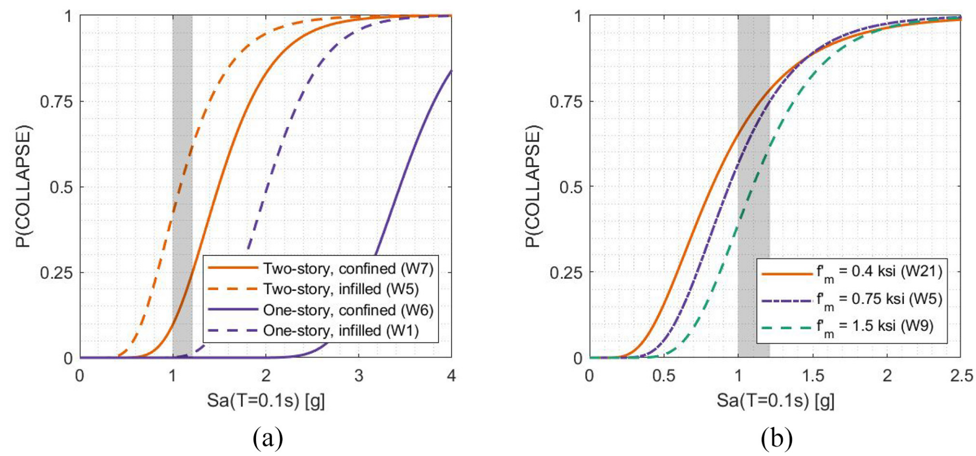

Figure 13. Collapse fragilities for one- and two-story houses with (a) infilled and confined masonry walls, and (b) and infilled construction with varying masonry properties, showing that construction method has a greater influence on collapse risk than material properties.

Effect of material strengths. We assessed archetypes with a range of concrete and masonry unit strengths to represent the available materials on the island, as reported in Figure 13b. Stronger materials increase the overall strength of wall panels and can increase collapse capacity by up to 25%. Of these materials, masonry unit strength is the most important. Though material properties affect seismic performance, they do not improve outcomes as significantly as employing confined construction instead of infilled.

Effect of openings. Figure 14a shows the collapse fragilities of two-story houses with window or door openings, with a solid infill panel, and with a partial height infill panel that induces a short column (see Figure 4b). The reduced strength and stiffness of the houses with window and door openings (on the order of 15% and 10% in terms of pushover strength, see Table 3) leads to a modest reduction in collapse capacity (around 10%). The archetype with door openings performs worse than the one with windows, as the openings are larger. However, the house with partial height infill in the first story is far more vulnerable to collapse in an earthquake. This configuration is susceptible to brittle shear failure of the short columns and has suffered extensive damage in recent earthquakes, including in Puerto Rico (Duran et al., 2020).

Effect of weight, incremental construction, and a second story. The effect of adding a second story has a very significant increase in collapse risk (reducing median collapse capacity by 50%), as shown in Figure 14. The heavy and moderate weight cases correspond to a weight of the second story of 200 psf (9.6 kPa) and 100 psf (4.8 kPa) compared to a wood frame second story of 10 psf (0.5 kPa). The additional seismic weight is largely a result of slab thickness. In two-story cases, failure occurs in the first story, and the increased weight generates larger lateral demands that are not compensated for by the local building practices (*e.g.* column and wall properties are typically the same in one- and two-story houses). The addition of a wood frame second story, which does not increase building weight significantly, does not affect collapse risk, but this practice may dwindle in popularity due to major hurricane damage to wood roofs and wood frame second stories. Reconnaissance photos after

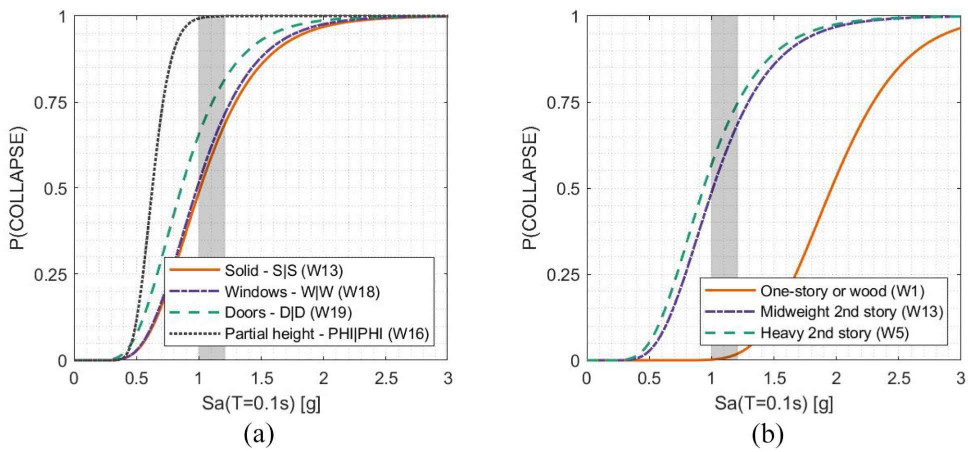

Figure 14. Collapse fragilities for (a) two-story RC houses with infilled walls with openings, showing greatest collapse vulnerability of the partial height infill configuration; and (b) for one- and two-story houses, illustrating the significant increase in collapse risk with the addition of a RC second story.

the earthquakes in Puerto Rico also showed that masonry walls in the first stories of two-story houses tended to see more damage than one-story houses with masonry walls. We aimed to determine the risk associated with corrosion of bars at the location in the connection between the original house and the second-story expansion. This does not seem to have a significant effect on overall collapse risk, as these columns only support the roof slab, and lateral demands are relatively small as a result.

Limitations

There are some limitations to this study. First, materials used in informal construction can be highly variable and depend on manufacturing (*e.g.* concrete masonry blocks), available raw materials (*e.g.* source of sand or rounded river aggregate), storage (*e.g.* exposure and corrosion of steel), and craftsmanship (*e.g.* concrete mixing). We accounted for many of these variations through parametric assessment of archetypes, but the uncertainty of this assessment could be reduced through future work involving material testing of typical materials. Other building variations common in Puerto Rico could be considered, including different foundations and soil conditions and those with wood roofs. Hillside buildings and vulnerable foundation configurations have both been shown to exacerbate collapse risk (Martínez Cruzado et al., 2013; Patil and Raghunandan, 2021). We observed limited cover in RC slabs and columns, and in some cases, pre-earthquake deterioration and spalling of these elements, which has not been fully considered. There are many possible retrofit strategies, including diagonal braces or RC walls (Martínez Cruzado et al., 2013; Tarque et al., 2019), as we aimed to focus on strategies that are most feasible in this context.

Methodologically, this study also used 2D models of a single frame line likely to control the behavior of the building without considering torsion or out-of-plane response. Our models also assume a fixed foundation, but soil-structure interaction can increase displacement demands in stiff structures (*i.e.* those with masonry walls) and may increase displacements during ground shaking (FEMA, 2020b). It would also be desirable to use a set of hazard consistent ground motions for the assessment. However, the required hazard deaggregation is not currently available for Puerto Rico (USGS, 2020b).

Summary and recommendations

This study develops and demonstrates a method for evaluating the seismic safety performance of informally constructed RC houses, with results for housing in Puerto Rico. We began by characterizing a set of archetype buildings through interviews with local builders and hardware store owners, and through reconnaissance following the recent earthquakes. We then modeled these archetype houses, employing nonlinear dynamic analyses to determine the collapse fragility associated with building characteristics, including material strength, reinforcing bar detailing, gravity loads, and masonry wall construction.

This study shows that, generally, lighter houses performed better than their heavier counterparts. While both the RC columns and confined masonry walls see a modest increase in strength with higher gravity loads, the increase in seismic mass outweighed this benefit, such that the two-story houses have a 50% lower median collapse capacity than one-story houses. The results also show that open-ground-story RC houses are more vulnerable than those with masonry walls (with about 60% lower median collapse capacity). Confined masonry performed better than infilled (an improvement of 90% in terms of median collapse capacity). Among the open ground story houses, the most important building characteristics are column detailing, including transverse and longitudinal reinforcing, and reinforcing bar corrosion. Houses built incrementally upward have an increased seismic risk because of the demands generated by additional seismic weight. Partial height infills the most vulnerable configuration of the RC houses with walls.

We assessed two retrofit options for open-ground-story houses. RC jacketing and infill walls, and found that both improved seismic performances. The most effective solution included in this work is the addition of infill walls in all open bays. RC jacketing can improve median collapse capacity by 115% if the jacket is well-designed and well-connected to the existing column by roughening the surface and the use of dowels. Future work could investigate additional retrofit methods.

We used these results to produce a set of recommended strategies in Table 5 for improving the collapse safety of housing. These recommendations have been developed based on material availability and local building practice, and are rated based on the quantified reduction of collapse risk, the feasibility of implementation (in terms of departure from current practice), and estimated cost. These recommendations suggest the need for future work to develop guidelines and training for the informal building sector for retrofit or strengthening of open-ground-story homes; for construction in confined masonry rather than infill; and for safe expansion methods. It would also be valuable to demonstrate the importance of high-quality materials, including uncorroded reinforcing bars, and seismic detailing of structural elements. For Puerto Rico and residents around the world living in seismic prone regions and informally constructed housing these recommendations can improve the seismic outcomes, and increase community resilience.

Table 5. Recommendations to improve seismic safety of informally constructed housing in Puerto Rico

Recommendation	Barriers to implementation	Departure from current practice	Cost[a]	Impact[b]
New construction				
Lighter weight construction where possible, including thinner slabs	Roof slabs must be deep enough (> 6 in) to withstand high winds.	Heavy construction is perceived as safer during hurricanes.	$	L
Use confined construction when building with masonry	Confined masonry may require additional training regarding construction and connections.	Some builders believe infilled construction is better.	$	H
Avoid open-ground-story construction, or ensure columns are designed for large lateral loads	Access to engineered design may be limited; RC design recommendations must be developed.	This mode of construction minimizes damage from flooding.	$	H
Use uncorroded steel reinforcing bars, with adequate longitudinal and closely spaced transverse ties	Corroded steel may be the only available option.	Many builders do not believe additional/better reinforcement is needed.	$	M
Avoid partial-height infill configurations or detail columns to prevent shear failure.	Access to engineered design may be limited; RC design recommendations could be developed.	Partial-height infill is common in houses for ventilation.	$	M
Existing construction				
Retrofit vulnerable columns using strong RC jackets that are well-connected to the rest of the structure.	Design and implementation of RC jacket requires engineering consultation and training; RC design recommendations must be developed.	Retrofit is not widely considered to be efficacious. (Goldwyn et al., 2021)	$	M
Retrofit open-ground-story houses by adding infill panels	Infill panels reduce access to open story and can create shear critical columns.	See above	$	H
Expand horizontally, rather than vertically	Dependent on availability and cost of additional land.	Vertical expansion is standard practice.	$$	H
Build vertical expansions using wood	Requires consideration of hurricanes[c]	Practice is relatively common	$	H

RC: reinforced concrete.
[a]Cost is estimated based on materials and labor needed for implementation. $: no or low cost, $: moderate cost, $$: significant cost.
[b]Impact on collapse risk is based on the change in the probability of collapse in an MCE_R level event. L indicates a change in collapse capacity is < 10%, M indicates a change in collapse capacity between 10% and 50%, and H indicates a change is > 50%.
[c]See Lochhead et al. (2022) for assessment of informally constructed houses in Puerto Rico during hurricanes.

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Supplemental material

Supplemental material for this article is available online.

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