Identifying misalignments between the informal construction sector's perceptions and engineering assessments of housing safety in future disasters for capacity development

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ABSTRACT

This study investigates areas where perceptions of those working in Puerto Rico's informal construction sector and engineering assessments of housing safety in future disasters misalign, identifying areas for construction capacity development to reduce hurricane and earthquake risk. We compared survey results from 345 individuals building and advising in the informal construction sector to the recommendations from our prior work assessing wind and seismic performance of informally constructed housing configurations. The study found four misalignments between perceptions and engineering assessments, where survey respondents did not agree with the recommendations. For wood-frame housing, our findings reveal builders and residents may not be prioritizing hurricane straps to strengthen key connections and avoid catastrophic failures because they do not view hurricane straps as efficacious. For reinforced concrete/masonry housing, we found builders and residents are associating heaviness with safety; building confined, rather than infill masonry; and building open-ground-story housing with weak columns, presenting seismic risks. Each of these misalignments was based on local expert insight about unsafe practices that are due to technical construction capacity rather than solely resource constraints. This study contributes to literature on the housing safety perceptions driving informal construction, provides an approach for comparison of local and scientific knowledge, and supports capacity development for disaster risk reduction.

Keywords: Multi-hazard; housing; informal; construction; capacity development; disasters

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1. INTRODUCTION

Globally, disasters are increasing in frequency and severity of impacts (Dinan 2017). These disasters threaten communities in hazard-prone regions, such as the Caribbean, whose residents are in a constant cycle of preparing for and recovering from disasters. In most of the world and many of these hazard-prone regions, houses are constructed primarily through informal processes, wherein residents lead the housing construction process by hiring or recruiting assistance from builders, friends, or family members who have learned about construction primarily through experience (Feliciano et al. 2022; Ferguson and Smets 2010). These informal construction processes are driven by the need for affordable and accessible housing, weak regulatory enforcement of housing construction, homeowner preferences, and builder experiences. Local authorities generally do not enforce code provisions or inspect construction (Clancy et al. 2020). As a result, housing design details and subsequent structural performance vary widely. The local knowledge and resources applied in informal construction processes can produce housing designs that respond to the local hazard environment (Langenbach 2015; Ortega et al. 2015). However, in other cases, these processes may inadvertently create unsafe housing, with builders perceiving housing to be safe when the houses in fact have significant hazard vulnerabilities (Audefroy 2011; Green 2008; Rodgers 2012).

When housing is constructed through these informal processes, the builders' housing safety perceptions ultimately determine their design and construction practices and, thus, the structural safety or hazard resistance of housing. However, despite the important role of these housing safety perceptions in informal construction processes, studies have neither investigated these perceptions nor how they compare to engineering assessments of housing safety. Instead, most of the existing information on informal housing design and construction practices is gathered from post-disaster reconnaissance reports. Particularly, post-earthquake reconnaissance reports have revealed structural vulnerabilities and high collapse incidences of informally constructed reinforced concrete and masonry housing (Lang and Marshall 2011; Marshall et al. 2022; Miranda et al. 2020). These reconnaissance reports provide important insight into structural vulnerabilities, and frequently lead to reports or other technical guidance on safer construction. They do not, however, provide information that compares perceptions of safe practices with technical guidance.

Moreover, this guidance generally omits whether unsafe housing design and construction practices are based on technical construction capacity, i.e., the builders' technical understanding of a particular structural design or construction topic, or primarily on financial or other resource constraints.

Our study focuses on the informal construction sector, comparing housing safety perceptions with engineering assessments of housing safety in hazard events. In doing so, it identifies several focus areas where the perceptions of those constructing housing may not be aligned with engineering assessments of housing safety. We began with a set of recommendations from prior work (Lochhead et al. 2022, Murray 2021) that assessed wind and seismic performance of common informally constructed housing types in a context of interest. Then, for our comparison, we conducted an analysis of a survey of those who frequently build and advise on informal construction practices to identify whether perceptions of safe practices align or misalign with the recommendations, and why they believe unsafe practices are occurring. Findings from prior survey analysis are discussed in Goldwyn et al. (2022), while Supplementary Information S1 and S2 detail additional data analyzed for this study. The contribution of this study is the systematic comparison of these recommendations and housing safety perceptions to address the research question: *How do housing safety perceptions of those working in informal construction align or not align with engineering assessments? Why?* Practically, these results can support interventions to increase housing safety and reduce disaster risk, through, for example, skills trainings or information dissemination. The work focuses on housing and the informal construction sector in Puerto Rico.

2. BACKGROUND

When implementing organizations or agencies are working on disaster risk reduction in hazard-prone contexts, they frequently produce informational materials or host training events in efforts to technically support residents or local builders through capacity building, encouraging "build back better" principles (Clinton 2006; Lyons 2009; Parrack et al. 2014). However, studies have found that these capacity building programs have historically neglected the role of local knowledge (Dekens 2007) and frequently seek to change technical design and construction practices that are rooted in financial constraints (Mannakkara and Wilkinson 2013), rather than the local builder's knowledge of the technical or structural design concepts.

In order to encourage changes to unsafe design and construction practices in the informal construction sector, we posit that it is critical to first understand the technical construction capacity of builders, which includes how perceptions and engineering assessments of housing safety do and do not align. Thus, in this background, we first discuss two key gaps in literature. The first gap relates to our understanding of builders' local knowledge and perceptions of housing safety that motivate their design and construction practices. Second, despite several documented examples of perceptions and technical understanding of safety differing, few studies have looked directly at technical construction capacity in the informal construction sector by comparing perceptions and engineering assessments of housing safety.

2.1 Housing safety perceptions of builders, why these perceptions exist, and how they motivate informal housing construction

Over the past twenty years, there has been increased recognition of the strengths and role of local knowledge as foundational for reducing community disaster risk (Mercer et al. 2009; White et al. 2001). This local knowledge exists within or is acquired by local groups, such as those working in the informal construction sector, through generational knowledge transfer, experiences, and community practices (Mercer et al. 2009). Venable et al. (2021) defines local knowledge of safe construction practices as "what housing people perceive to be safe or vulnerable, their understanding of how to build a house safely, and what housing components people expect to be damaged" (p.2). This knowledge is particularly important to and consequential for the informal construction sector, shaping perceptions of risk and housing safety as well as subsequent design and construction practices (Chmutina and Rose 2018). However, despite the role of local knowledge in reducing disaster risk, the existing power relationships between local and scientific knowledge frequently leads to local knowledge's role being overshadowed or overlooked in research and practice (Mercer et al. 2009), making it an understudied area.

Moreover, globalization has triggered shifts in local knowledge, particularly pertaining to housing risk and safety, including perceptions of design and construction practices and materials. In several cases, studies have noted examples of communities' changing perceptions leading them to adopt less traditional construction practices, perceiving these styles of construction, primarily reinforced concrete and masonry, as inherently "better" than the traditional styles (Audefroy 2011; Kennedy et al. 2008). For instance, experts found the traditional wood-frame building style in Haiti was more earthquake-resistant than the modern style of housing construction with reinforced concrete and block masonry when built informally and without seismic detailing. However, without a major earthquake impacting Hispaniola for around fifty years, builders informally constructing housing turned to a more modern style of reinforced concrete that also readily protected housing from wind and storm surge damage during the Caribbean's annual hurricane season (Audefroy 2011). Researchers also revealed that globalization of housing technologies and designs, particularly masonry, may have decreased safety of informally constructed housing in the 2004 Indian Ocean Earthquake and Tsunami (Kennedy et al. 2008). When researchers compared this informally constructed masonry housing design with the traditional, more earthquake resistant timber housing in Aceh, Indonesia, they found this transition away from traditional housing designs ultimately made housing much less safe (Kennedy et al. 2008).

Local knowledge is also shaped by past hazard experiences. For instance, studies have revealed examples of residents' housing safety perceptions being shaped by individual hazard exposure and prior hazard experience (Venable et al. 2020). In our own work, we found that informal builders developed a nuanced understanding of the ways to construct housing to withstand frequent hazards such as hurricanes (Goldwyn et al. 2021). Goldwyn et al. (2021) also documented changes to risk and housing safety perceptions following the 2019-20 earthquakes in Puerto Rico, a revealing shift towards a greater recognition of seismic risk and a growing interest in consulting with engineers and other professionals in the formal building sector for information on reinforced concrete design

Builders' housing safety perceptions, which are shaped by this local knowledge and the factors that influence it, motivate their design and construction practices. These practices have been described as an informal "value engineering" process, where builders seek to maximize benefits while reducing costs for themselves and residents (Rodgers 2012). In this process, builders make decisions about which design decisions are worth added costs, such as the quantity of reinforcement to include in a concrete column, based on what they perceive to be safe and what they learned on the job. However, in the absence of regulations, this process may lead them to construct housing with vulnerabilities to hazard types that they have not recently experienced, and thus have not learned to design for safety (Rodgers 2012).

Particularly, it can be challenging to design housing that is safe in regions exposed to multiple hazards, where builders must weigh the risk of structures to all hazard types to which they are exposed. For instance, in the Caribbean, builders may develop design and construction practices to build housing resistant to the familiar hurricanes experienced over generations, but not develop the same level of hazard-resistant techniques for less familiar and less frequent hazards, such as earthquakes (Audefroy 2011; Rodgers 2012). Researchers observed this trend in Haiti after the devastating Port-au-Prince earthquake in 2010, revealing construction practices aimed at increasing housing safety for the more commonly experienced hazard, hurricanes, led to increased vulnerability to earthquakes, the less common hazard (Marshall et al. 2011; Mix et al. 2011). In neighboring Puerto Rico, builders and residents also grew to prioritize housing safety for the Caribbean's more familiar hurricane season, leading many, for example, to raise their houses up on weak reinforced concrete columns to avoid flooding; but did not construct these columns with sufficient vertical or transverse reinforcement, thereby increasing seismic risks (Goldwyn et al. 2021).

Overall, while there is evidence of the generational hazard experience and globalization of housing building practices shaping local knowledge, there is a dearth of research related to how these experiences influence the housing safety perceptions that actually motivate informal housing design and construction practices.

2.2 Understanding informal construction sector technical construction capacity

With local knowledge poorly understood (Mercer et al. 2009), the reasons housing is constructed with disaster vulnerabilities are often unaddressed. Some reasons are due to financial or other resource constraints (Hedidor et al. 2016; Jones and Vasvani 2017), which are more difficult to change if resources are unavailable. However, some unsafe practices may be rooted in local knowledge of housing design and construction, or local technical construction capacity.

While limited studies have investigated the knowledge and perceptions driving the informal construction sector, several studies have investigated the technical construction capacity and resource-related barriers preventing builders from building code compliance. This is relevant because building codes in some ways represent the standardized global recommendations for hazard resistance. Studies have found cases of builders that may either be unaware of hazard-resistant building codes or may not have the technical capacity to comply with them (Krimgold 2011; Chmutina and Rose 2018). For instance, Krimgold (2011) documented builders' technical construction capacity limitations, noting that the invisibility of reinforcement detailing that contributes to seismic safety limits knowledge exchange. Thus, in a setting where builders learn through observation and generational experiences, it is more difficult to learn from which specific reinforcement and concrete details did and did not lead to structures withstanding earthquakes. This lack of technical construction capacity may lead builders to construct housing that is not aligned with recommendations to engineering assessments.

We contend that misalignments such as those pertaining to reinforcement detailing and seismic resistance may be able to be addressed through targeted technical construction capacity development efforts that draw from both local and scientific knowledge of housing safety. There is, however, a gap in our understanding of how perceptions of housing safety compare with engineering knowledge and assessments of hazard and risks. A recent study analyzed resident perceptions of safety with wind assessments of donor-built housing (Venable et al. 2021), finding residents' perceptions of expected damage in future hurricanes generally aligned with engineering assessments, especially in terms of damage to particular components. However, residents lacked a systems perspective on how components could interact to cause catastrophic failure. As a result, residents might strengthen roofs causing catastrophic failure of walls. This identification of a misalignment between local and scientific knowledge of structural systems, as well as the understanding that perceptions and engineering assessments of safety were generally aligned at the component level, provides insight into the technical construction capacity of the community and what concepts to address through community capacity building (Venable et al. 2021).

Studying informal settlements in Istanbul, Turkey, Green (2008) found examples of resident perceptions that did not align with professional engineering expertise, again revealing areas to target in building technical construction capacity. Here, the individuals informally constructing housing often did not know that adequate reinforcement detailing and other design features for reinforced concrete housing would increase seismic safety without adding substantial costs (Green 2008). Thus, despite the low cost of changing design and construction practices, residents and builders did not incorporate these hazard resistant practices. Unfortunately, this lack of alignment between builder perceptions and expert evaluation of safety ultimately led this community to build structurally unsafe housing that they viewed as safe, leaving the community vulnerable to the devastating 1999 earthquakes.

Our study addresses this gap by focusing on those unsafe construction practices that are rooted in technical construction capacity, rather than resource limitations such as financial constraints.

3. CONTEXT

We conducted this study in Puerto Rico, a US Caribbean Island where informal housing construction is common, and housing is exposed to both hurricanes and earthquakes. Puerto Rico has recently experienced several devastating disasters: Hurricanes Irma and Maria in 2017, category 5 and 4 storms, respectively, and a series of 2019-20 earthquakes, the largest of which had Magnitude Mw 6.4. Hurricanes Irma and Maria together damaged or destroyed 1.4 million houses (García 2021; Hinojosa and Meléndez 2018), destroyed much of the island's power grid, and led to a substantial increase in mortality (Kishore et al. 2018). The series of over 40 earthquakes and aftershocks from late 2019 to early 2020 damaged or destroyed over 10,000 houses and affected over 40,000 people (FEMA 2020). While hurricanes pass over Puerto Rico regularly, a major earthquake had not struck the island for 100 years.

Prior to Hurricanes Irma and Maria, Puerto Rico's one- and two-family housing stock of approximately 1.1 million structures was estimated at 76% reinforced concrete and masonry, 11% fully wood-frame, and 13% combined concrete and wood (Clancy et al. 2020). It is estimated that most of Puerto Rico's housing is built primarily through informal construction processes with help from family and friends (López-Marrero 2010; Clancy et al. 2020; Hinojosa and Meléndez 2018). This high rate of informal housing construction is due to weak code enforcement, high permitting costs, and frequent absence of property titles due to informally subdivided land, among other reasons (Clancy et al. 2020). Thus, housing in Puerto Rico varies greatly in design and construction details, and subsequently, safety. Typical wood-frame housing includes roof structures with purlins and rafters or trusses supporting corrugated galvanized iron (CGI) roof panels (Cruzado and Pacheco-Crosetti 2018). The reinforced concrete/masonry structures often have reinforced concrete frames, roofs, and floor slabs, and infill block walls. These blocks are industrially manufactured, but quality of blocks, concrete, and mortar are highly variable and often low. Given the higher frequency of hurricanes versus earthquakes and the globalization and status of reinforced concrete housing technologies, housing construction has trended towards heavier reinforced concrete/masonry construction, with many builders and residents doubting the safety of wood-frame housing (Goldwyn et al. 2021), a trend that similarly occurred in neighboring Caribbean islands (Audefroy 2011).

4. METHOD FOR DETERMINING MISALIGNMENTS

To determine (mis)alignments between engineering assessments and safety perceptions, we compare the recommendations for design and construction practices that would most improve the performance of informally constructed housing. We do this by comparing our prior wind and seismic assessments of wood-frame and reinforced concrete/masonry housing on the island (Lochhead et al. 2022; Murray 2021), with housing safety perceptions identified from a survey administered to informal builders and hardware store employees , further analyzing the survey to determine reasons for construction practices, focusing on areas where respondents indicated that technical construction capacity was motivating unsafe construction practices. This analysis enabled us to identify misalignments where survey respondents' perceptions do not align with recommendations for safer housing design and construction and where technical construction capacity development may address unsafe construction practices, as shown in Figure 1.

We begin by discussing the methods of this paper's main contribution: comparing the perceptions found in our survey to the recommendations from engineering assessments. We briefly explain the engineering safety assessment data sets used for this comparison, providing an overview of the wind and seismic housing performance assessment methods and recommendations based upon our prior work (Lochhead et al. 2022; Murray 2021). Then, we discuss the survey used in the comparison to reveal (mis)alignments, and the new analysis conducted to make the comparison based on the survey results. All methods were completed in accordance with the University of Colorado Boulder Institutional Review Board Protocol #19-0337.

4.1 Methods of comparing perceptions and structural assessments of housing safety

We compared the recommendations for design and construction practices with housing safety perceptions from our survey to identify areas where perceptions and engineering assessments of housing safety may not align and which practices are rooted in technical construction capacity, leading builders to engage in unsafe design and construction practices.

To do so, as shown in Figure 2, we began by laying out a list of twelve compiled recommendations from the wind and seismic assessments. We classified recommendations as misaligned with housing safety perceptions when over half of the survey respondents either did not view this recommendation as important to increase housing safety or viewed the unsafe design and construction practices each recommendation seeks to change as safe. We then further analyzed the reason unsafe practices were occurring to determine whether these were rooted in more than just resource constraints, indicating that recommendations may be actionable with technical construction capacity development. We identified misalignments when perceptions were not aligned with structural performance assessments and more respondents attributed relevant practices to technical construction capacity limitations rather than financial constraints.

By focusing first on the recommendations from prior engineering assessments to improve housing performance, then comparing these with the survey results to understand which of these practices misalign with builder's perceptions, and finally focusing on design and construction practices that are attributable to more than financial constraints, we were able to select construction practices that could be integrated into technical capacity development programs. The survey analysis methods and results used for this comparison are detailed alongside the recommendations from engineering assessments in Supplementary Information S2. Because survey data were collected in parallel with the engineering assessments, we did not know the recommendations apriori. As a result, four of the twelve recommendations from the engineering analysis were not addressed in the survey and were omitted from further analysis.

4.2 Recommendations from engineering assessments used to identify misalignments

Our prior work probabilistically assessed the wind and seismic performance of housing typologies to determine design and construction practices that would most improve the expected performance of housing (See Lochhead et al. (2022) and Murray (2021)). To assess the wind and earthquake performance of a wide range of common housing conditions, we identified the typical variations in housing dimensions, walls, windows, roof shape, roof material, elevation, and in structural key components, such as CGI sheet thickness and types of connections components (e.g., between purlins and trusses). These variations were defined through interviews (Goldwyn et al. 2021), photographs from fieldwork over three years, observed inventory at hardware stores across different regions of Puerto Rico (Murray 2021), hurricane and earthquake damage and reconnaissance reports (FEMA 2018; Miranda et al. 2020), and other studies on common informally constructed housing vulnerabilities across North and South America (e.g., Lang and Marshall 2017; Marshall et al. 2011; Villar-Vega et al. 2017). In total, we assessed the performance of over 80 housing configurations, revealing the relative safety of common housing construction practices and design decisions in wind and seismic hazard events.

4.2.1 Wind performance assessments data set

In Lochhead et al. (2022), we adapted and applied a component-level performance-based wind engineering assessment framework, drawing from published literature to quantify component capacities and demands (Venable et al. 2021). We propagated uncertainty through Monte Carlo simulations. We considered the performance of wood-frame and reinforced/concrete masonry housing with wood-frame roof structures in hurricanes' high winds. Previous studies and reconnaissance reports had shown the prominence of these housing types, and the catastrophic damage to wood-frame roofs in Hurricane Maria (FEMA 2018; Wells 2020). Initially, we considered base housing typologies with 16-foot by 24-foot plan dimensions, one or two stories, CGI panels, and wood purlin and truss roof structures. All of these housing typologies had nailed fasteners, with a nailed purlin-to-truss connection, a toe-nailed truss-to-wall connection and 26-gauge CGI roof panels. We also assessed the wind performance of housing with different panel material and gauge (thickness), fastener type and spacing, connections between purlins and truss and between trusses and walls, and truss and purlin spacing.

Then, we quantified the median wind speeds at which failures occurred in the housing configurations and how design and construction variations affected the wind speed when roof failure occurred, using a static, probabilistic component-based method. We considered wind speeds, quantified by the maximum 3-second wind gusts, that spanned across the range of storm categories, ranging from Category 1 to 5 storms with 55 mph (90 kph) to 250 mph (405 kph) wind speeds (NOAA n.d.). Based on this wind speed, we determined wind pressures in accordance with ASCE 7 procedures for low-rise buildings (ASCE/SEI 2016). We defined failure as occurring when the first component or system failure occurred, considering panel loss, purlin failures, and failures at the various types of connections, and tracked the wind speed at which this failure occurred in 50% of Monte Carlo realizations. Uncertainties in demands and capacities on components were considered. The governing failure mode was defined as the failure that occurred at the lowest wind speed. Some failure modes, such as failure at the roof panel-fastener interface, are less catastrophic than others, such as failure at the truss-to-wall connection, which would be more likely to lead to failure of the entire roof-to-wall systems. After analyzing the base housing typologies and determining their governing failure modes, we assessed how changes in design and construction changed performance, or the percent change in the median wind speed at failure. More details about these assessments are provided in Lochhead et al. (2022).

4.2.2 Recommendations from the wind performance assessment

Our component-based analysis of wind performance revealed that the governing failure mode was roof panel loss due to fastener tear-out at the panel-fastener interface, occurring at a median wind speed of 85 mph for the baseline gable roof configuration (Category 1 hurricane). This interface can be improved by reducing fastener spacing, using thicker CGI panels than 26-Gauge, using trapezoidal CGI panels, or using umbrella nails. However, while improvements to the panel-roof connection can increase the wind speed the roof can withstand, they also can potentially create a more catastrophic failure mode, i.e. complete roof loss, by moving the failure to the truss-to-wall connections.

Recommendations were prioritized based on a philosophy of reducing catastrophic failure. Thus, we prioritized strengthening the connection between truss and wall with hurricane straps because failure at this connection would result in the catastrophic loss of the entire roof structure. Then, we recommend strengthening the purlins and truss connections with hurricane straps. Finally, we suggest improving the panel-fastener interface by reducing fastener spacing, installing thicker CGI panels, and/or using umbrella nails with a wider head diameter. Lochhead et al. (2022) recommends installing hurricane straps at each purlin-to-truss and truss-to-wall connection. For the full discussion of housing design and construction recommendations from this study (e.g., constructing with treated wood, etc.), please see Lochhead et al. (2022).

4.2.3 Earthquake performance assessment data set

In Murray (2021), we focused on the seismic structural response of reinforced concrete/masonry housing typologies. These typologies included reinforced concrete/masonry housing with reinforced concrete frames and either confined or infill masonry walls; roofs and floors were flat reinforced concrete slabs. We also evaluated typologies with open-ground-stories, which were raised on reinforced concrete columns (stilts). Each of the housing typologies had 30-foot by 24-foot dimensions, with either one or two stories, with slabs spanning 10-12 ft. We varied reinforcement detailing, material strengths, wall openings, and other construction methods and design characteristics. We also investigated retrofitting techniques discussed in pilot interviews and field observations.

We then assessed the effect of variations in design and construction decisions on overall seismic performance, looking at collapse risk in future seismic events as a measure of safety. The response of each housing typology variation was simulated dynamically with a nonlinear simulation model. We assessed the collapse safety performance using incremental dynamic analysis over a range of ground motion intensities, quantified using an intensity measure of spectral acceleration at the fundamental period. Collapse performance of each typology was summarized through collapse fragility curves, which represent the probability of collapse as a function of ground motion intensity. We also evaluated the relative feasibility of the design and construction practices that improve performance, revealing which practices could be implemented at no or low additional cost that would also increase the collapse capacity to meet the target. More details about these assessments are provided in Murray (2021).

4.2.4 Recommendations from earthquake performance assessment

Our seismic performance assessment of reinforced concrete/masonry housing found that common design and construction practices for heavy reinforced concrete and masonry construction increase seismic vulnerabilities. For many of the cases, the provided columns and walls do not have the strength and deformation capacity to resist seismic demands. Reinforced concrete/masonry housing with infill techniques, heavy roof and floor slabs, and open-ground-stories performed worse than that built through confined masonry or without open ground stories. The housing typologies with confined masonry walls had 90% greater collapse capacity, compared to the typologies with infill walls. Lighter weight buildings (mainly achieved through thinner floor slabs) outperformed heavier houses, recognizing that slabs need to be at least about 6 inches deep to withstand winds loads in hurricanes. The findings also suggest that open-ground-story houses can be effectively retrofitted by either jacketing columns with reinforced concrete or adding infill panels. While the infill panels reduce the utility of open-ground-story housing for reducing flooding risk, well-designed reinforced concrete jackets maintain the open story while reducing collapse risk significantly.

The recommendations aimed to increase collapse capacity to align with targets in U.S. standards for seismic safety. For new housing construction, our findings recommend that builders construct housing through confined, rather than infill, masonry construction and avoid open-ground-story construction. While confined and infill masonry structures look similar to residents, their differences in order of construction, ring beams, and reinforcement detailing affects the structural performance in seismic events. They also suggest the need to reduce the weight of floor and roof slabs, while still providing appropriate concrete cover and sufficient thickness for hurricane winds. For more information on these seismic performance assessments, see Murray (2021).

We also looked at the multi-hazard performance of the recommended modifications, discussing the way both wood-frame and reinforced concrete/masonry housing can be constructed in consideration of both seismic and wind events in Puerto Rico. For both hazard types, housing performance can be improved through the use of stronger connections and materials, well-designed reinforcement detailing, and sufficient lateral bracing (Lochhead et al. 2022). Together, engineering assessments provide design and construction recommendations to compare with housing safety perceptions.

4.3 Survey results of safety perceptions used to identify misalignments

To understand the housing safety perceptions and construction practices of those informally constructing housing in Puerto Rico, we conducted surveys with builders and hardware store employees familiar with housing design and construction practices as described in Goldwyn et al. (2022). We developed this survey based on pilot, semi-structured interviews with contractors, engineers, architects, residents, and others involved with construction processes. Data collection was completed over fifteen months with a team of eight research assistants and enumerators with context-specific knowledge. Over these fifteen months, we visited every distinguishable hardware store across the island identified through online searches and referrals and interviewed builders in these locations. Thus, these surveys are representative of typical Puerto Rican hardware stores and the perceptions of builders constructing housing informally across Puerto Rico.

Overall, 345 builders and hardware store employees took the survey either online, using Qualtrics, or in person. Of the survey respondents, 257 (70%) were hardware store employees and 93 (30%) were employed as builders. In total, 212 (61%) reported some experience constructing housing, with 100% of the builders and 46% of the hardware store employees indicating this experience. Most of the respondents, or 257 (74%), were male and 88 (26%) were female. Most respondents (215, or 62%) reported that they had not received any formal training in housing construction; only 42 (12%) indicated receiving vocational school training in construction, 68 (20%) indicated they received training by an employer, and 20 (6%) indicated receiving training from a governmental, non-governmental, or community-based organization (Goldwyn et al. 2022).

The survey largely covered three topics: perceptions of safety of common design and construction practices (i.e., which practices are and are not safe); perceived reasons for the design and construction practices identified by respondents as unsafe; and potential changes to those design and construction practices perceived to be important to increase housing safety. We asked questions for both wood-frame and reinforced concrete/masonry housing in both hurricanes and earthquakes. To capture additional information on some of the more complex design and construction practices, such as the perceived safety of infill and confined masonry building practices, we added detailed questions. We pulled from a selected subset of questions for this study's analysis, listed in Supplementary Information S1. From this subset of questions, we analyzed the percentages of respondents who did not agree with the wind and seismic performance assessments, shown in Supplementary Information S2. By asking about which common practices respondents perceived as unsafe in future hurricanes and earthquakes, we captured perceptions of key practices that we could then compare with the engineering-based recommendations to identify misalignments. For instance, we asked respondents about whether they believed builders using deteriorating or deteriorated materials, including wood, was unsafe; this response was then compared to our recommendations for builders to replace deteriorating wood members. If 50% of respondents did not agree with the recommendations, we considered perceptions to be misaligned with the recommendations.

We also analyzed what respondents indicated were the reasons for these unsafe practices to understand whether each unsafe practice was rooted in financial constraints, material constraints, and technical construction capacity, recognizing that past studies have shown the important role finances play for decisions about hazard mitigation (Terpstra and Lindell 2013; Tobin 1997). If more respondents indicated technical construction capacity than other constraints, we considered the relevant unsafe practices to be rooted in misalignments between the recommendations and housing safety perceptions By understanding which of these practices are rooted in technical construction capacity, we were able to identify the unsafe design and construction practices that may be more motivated by misalignments between perceptions and engineering assessments of safety rather than limited finances. For example, looking again at the unsafe practice of using deteriorated materials in wood-frame housing, most respondents indicated that this practice was rooted in financial constraints rather than technical construction capacity due to the cost of purchasing and installing new wood regularly, indicating that this practice is not likely to be changed through capacity development.

In addition, we analyzed responses to questions about respondents' perceived importance of each recommended design and construction practice, with the intent of capturing respondents' perceived efficacy of different methods of increasing housing safety. Our interest in perceived efficacy stemmed from studies that have shown this perceived efficacy influences decisions of whether to take action to mitigate hazards (Terpstra and Lindell 2013). For instance, we asked respondents about whether they perceived using thicker roof panels as important for increasing wood-frame housing safety. We also asked more specific questions about the order of reinforced concrete/masonry housing construction and reinforced concrete column design to capture a more robust understanding of respondent perceptions related to those design and construction practices. We analyzed this perceived importance to determine if greater than 50% of respondents' perceptions aligned with the recommendations. If most respondents did not align with recommendations, we considered these perceptions misaligned with the engineering assessments. Together, these survey results reveal respondent housing safety perceptions and provide insight into whether respondents agree with the structural engineering recommendations as well as their perceived reasons for unsafe construction practices.

5. IDENTIFIED MISALIGNMENTS BETWEEN HOUSING SAFETY PERCEPTIONS AND ENGINEERING RECOMMENDATIONS

We compared results from survey data on housing safety perceptions with the recommendations to determine whether these were misaligned (See Table 1).

Table 1. Prioritized recommendations from wind and seismic performance assessments, with results of this comparison with survey data on housing safety perceptions, identifying areas of misalignment

Recommendations	Is there survey data for a comparison?	Are perceptions misaligned with this recommendation?
From wind performance assessments		
Strengthen truss-to-wall and purlin-to-truss connections with hurricane straps	Yes	Yes*[1]
Improve panel-fastener interface with reduced nail spacing or umbrella nails; thicker gauge or trapezoidal CGI	Yes	No
Reduce purlin and truss spacing	Yes	No*
Use hip, rather than gable roofs	No	*Unknown*
Increase roof slope (up to 28°)	No	*Unknown*
Replace deteriorating wood members	Yes	No
From seismic performance assessments		
Construct lighter weight/thinner roof and floor slabs	Yes	Yes*[2]
Use confined, rather than infill, masonry	Yes	Yes*[1,2]
Either avoid or retrofit open-ground-story construction with infill panels or retrofit vulnerable columns with RC jackets	Yes	Yes*[1,2]
Use uncorroded steel reinforcing bars	Yes	No
Avoid partial-height infill configurations	No	*Unknown*
Expand horizontally with concrete/masonry, vertically with wood	No	*Unknown*

[1]Many survey respondents did not view this recommendation as important to increase housing safety
[2]Many survey respondents viewed the common, unsafe design or construction practice this recommendation seeks to change as safe
**More respondents indicated technical construction capacity as the reason for the relevant practices than those who indicated financial constraints*

To illustrate this process, we look to our first listed recommendation from the wind performance assessments: to strengthen the connections between the purlins and trusses and the trusses and walls with hurricane straps. From the survey results, we found that a majority, 55% (n=190), did not indicate it was important to "use hurricane straps," indicating a misalignment. While our survey also revealed that greater than 50% of respondents indicated that the practice of "not using hurricane straps" was unsafe, which is aligned with the recommendation, we still consider this a misalignment as the perceptions pertaining to this recommendation satisfied *one* of these two established criteria. Further, of those respondents who indicated that not using hurricane straps was an unsafe practice, 71% indicated this was rooted in technical construction capacity while only 52% listed financial constraints. Thus, recognizing these misaligned perceptions and that the relevant practices were rooted in technical construction capacity, we discuss hurricane straps as a misalignment. Please see S2 for full results comparing survey responses with recommendations.

Based on this analysis, we identified four focus areas of misalignment indicated by "Yes" in Table 1 (1) strengthening key connections in the roof structure with hurricane straps; (2) building thinner or lighter reinforced concrete roofs; (3) building confined, rather than infill, masonry; and (4) avoiding or retrofitting open-ground-story housing with weak columns.

6. DISCUSSION OF MISALIGNMENTS

In this discussion, we focus on the four recommendations from the engineering assessments identified as areas of misalignment that respondents attributed to technical capacity development. In addition to discussing the survey results, we bring in supporting information from post-disaster reconnaissance reports, literature, pilot interviews (described in Goldwyn et al. 2021), field observations (described in Goldwyn et al. 2021 and Murray 2021), and case knowledge to elaborate on the context and reasons for these misalignments.

6.1 Using hurricane straps in wood-frame roof construction to strengthen key connections

We found that respondents view wood-frame roofs as unsafe, with 89% expecting wood housing to be damaged or destroyed in a future hurricane like Hurricane Maria. However, a minority of survey respondents (45%) indicated that it was important to use hurricane straps to increase wood-frame housing safety for hurricanes.

Reconnaissance reports after Caribbean hurricanes, including Hurricane Maria, have found that common nailed and toe-nailed roof connections at both the purlin-to-truss and truss-to-wall interfaces are not able to resist the shear and uplift forces that are experienced during a high wind event. Thus, these reports have attributed roof structure failures to both connections (Build Change 2016; FEMA 1999, 2018; Kijewski-Correa et al. 2019). Our wind performance assessments further revealed that the practice of using hurricane straps at both purlin-to-truss and truss-to-wall connections, rather than wooden cleat or nailed/toe-nailed connections, improves performance. These assessments assumed a single type of locally available hurricane strap at all the purlin-to-truss and truss-to-wall connections.

During pilot interviews and field observations, we learned that builders often build nailed and toe-nailed connections without hurricane straps in their wood-frame roof construction, despite hurricane straps being readily available across Puerto Rico. Several interviewees explained that hurricane straps have grown more commonly available and used since Hurricane Hugo in 1986 and that their use grew even more popular after Hurricane Maria. In interviews, many builders emphasized the need to employ hurricane straps to build a safe wooden roof, yet explained that many people "*do not know how or where to use them.*" However, several builders also doubted their utility in these interviews, saying they prefer nailed or toe-nailed connections without hurricane straps as it is "*better to stick with wood*," explaining that they view wood-on-wood connections as safer than introducing other materials. In interviews with residents who built their own houses or worked with friends and family to build their houses, it was clear that most did not use hurricane straps.

Respondents more frequently indicated that the decision to use nailed connections instead of hurricane straps was due to technical construction capacity rather than financial constraints. When compared to other construction materials, hurricane straps are rather inexpensive in Puerto Rico; for materials alone, we expect the cost of these recommendations for hurricane straps to be approximately $100 total with 2-foot purlin and 4-foot truss spacing in a house with 16 by 24-foot dimensions and a gable roof (Lochhead et al. 2022).

The survey results reveal that those in the informal construction industry are likely more concerned with strengthening the connection (fasteners) between the roof structure and the roof panels, locally referred to as "zinc," than other roof connections. This is because the respondents were more likely to expect failure at the panel-fastener interface than failure at the connections where a hurricane strap would be used.

Interviewees frequently mentioned the roof panels only when describing why they viewed wood-frame roofs as unsafe, saying statements like, *"The zinc roofs were flying away*" and "*because of my experience with Hurricane Georges as a kid, I learned that houses with zinc roofs are not safe.*" This concern with the panel-fastener interface aligns with our engineering assessment findings, which showed that roof panels are likely to be lost first. Indeed, our survey data suggests that the primary reason why builders may be foregoing hurricane straps is to prioritize strengthening the panel-fastener interface. However, our engineering assessment revealed that when sufficient improvements are made to the panel-fastener interface, through use of umbrella nails, reduced fastener spacing, or thicker metal roof panels, the connections between the trusses and purlins become the governing failure mode with only a modest change in the speed that the roofs can withstand. Failures between the trusses and purlins could occur at wind speeds corresponding to a Category 2 hurricane. While improving the panel-fastener interface does improve performance of that system, the subsequent failure at the purlin-to-truss or truss-to-wall connection is more catastrophic. Failure of the truss-to-wall connection leads to loss of the entire roof structure. Failure of the purlin-to-truss connections may look like panel loss, but is more widespread. Respondents may be attributing the panel failure they have observed in prior hurricanes to the panel-fastener interface alone, rather than to both the panel-fastener and purlin-to-truss connections.

Respondents were also more likely to expect failure at the truss-to-wall than the purlin-to-truss connection, likely because the failure between the truss and wall is both a more visible connection and catastrophic failure than a failure at the purlin-to-truss connection. These perceptions do not align with our engineering assessments, which showed the purlin-to-truss connection would fail before the truss-to-wall connection in the majority of typologies that we examined. As with Venable et al. (2021), this breakdown suggests that the systems perspective may be poorly captured in builder's perceptions. In particular, the confusion around expected component failures in a wood-frame roof structure, specifically the uncertainty about failure of the purlin-to-truss and truss-to-wall connections where hurricane straps are recommended, provide insight into misalignments between perceptions and engineering assessments of wood roof systems.

We found that, despite the importance of hurricane straps to increase safety of the purlin-to-truss and truss-to-wall connections, builders and other individuals constructing housing do not view hurricane straps as important. Instead, builders are prioritizing practices to strengthen the panel-fastener interface which provide limited benefit unless paired with improvements to other connections. Survey responses indicate that this is likely due to technical construction capacity rather than financial or material constraints, indicating that it could be an area of emphasis in training for builders and residents. Thus, our findings show the benefits of constructing housing with hurricane straps at the purlin-to-truss and truss-to-wall connections, as well as the need to focus on these connection types in training to develop technical construction capacity around this focus area.

6.2 Building roof and floor slabs that consider multi-hazard performance

Next, we consider the fact that residents and builders connect heaviness with improved performance of reinforced concrete/masonry housing, producing structures that withstand hurricanes but are more vulnerable in earthquakes. We asked respondents in our survey whether they believed the construction practice of building thin roofs was unsafe for future hurricanes, earthquakes, or both hazards. In hurricanes, 47% of respondents indicated thin roofs could lead to damage, which aligned with our engineering assessments. Our assessments revealed that roof and floor slabs of at least six inches thick are needed to withstand wind loading and should also have sufficient concrete cover over the reinforcing bars. However, over 84% of the respondents indicated that building thin roofs was unsafe in future earthquakes, which is misaligned with our recommendations. Instead, slimmer roof and floor slabs are associated with better seismic performance because their lighter weight reduces inertial forces (Murray et al. 2022). Even though the thinner roofs were safer in earthquakes, 60% of respondents believed that others were building thin roofs because they had insufficient technical construction capacity, and 66% believed it was due to financial constraints, rather than due to them perceiving benefits of lighter construction for earthquakes.

Pilot interviews also showed that many residents perceived thin roofs as a structural vulnerability for both future hurricanes and earthquakes. Interviewees frequently mentioned a widely shared image of a house in Yabucoa that had a thin reinforced concrete roof torn off by Hurricane Maria’s winds. Over generations, builders across the Caribbean have constructed housing with heavy reinforced concrete and masonry materials to withstand annual hurricane seasons (Goldwyn et al. 2021; Marshall et al. 2011). Interviews and field observations revealed that builders have prioritized wind- and storm surge-resistant heavy reinforced concrete and masonry construction, explaining that they prefer heavier building materials, such as reinforced concrete and masonry blocks, because lighter materials would "*blow away like playing cards*" in a hurricane, as one homeowner stated. However, in earthquakes, these heavy structures may not perform well.

Unfortunately, when both the 2010 earthquake occurred in Haiti and the 2019-20 earthquakes occurred in Puerto Rico, this tendency towards heavy reinforced concrete and masonry construction practices contributed to widespread housing damage and destruction (Marshall et al. 2011; Miranda et al. 2020; Mix et al. 2011). Specifically, post-earthquake reconnaissance reports in Puerto Rico revealed that houses with heavy roof and floor slabs sustained damage due to the larger inertial forces acting on walls and columns that were likely designed to primarily resist gravity loads (Miranda et al. 2020). Our engineering assessments quantitatively showed how collapse risk increases with weight (Murray 2021).

Survey respondents largely attribute housing safety to heavier concrete construction practices and more materials. This attribution appears to be based, in part, due to the relative cost and strength of concrete and wood, with lighter weight housing construction historically associated with lower income housing. For instance, in one pilot interview, a retired builder expressed this association between heavy concrete and increased cost, saying, *"instead of investing in strong concrete, they are buying wood and zinc again, because it's cheaper and they can save more money.*" Other interviewees emphasized that wealth and security are tied to heavier reinforced concrete/masonry structures.

Despite shifting housing safety perceptions after the 2019-20 earthquakes, and greater doubt in the safety of reinforced concrete/masonry housing in general, we have identified a misalignment between perceptions and engineering assessments of the safety of thick reinforced concrete roof slabs. To many who are unfamiliar with seismic loading, and particularly those more familiar with wind and storm surge from hurricanes, it can be counterintuitive that a lighter concrete slab could outperform a heavier one. The prevalence of misaligned beliefs that thin roofs cannot be made safe means that there are not established building practices for designing and building this kind of system, a technical construction capacity limitation.

6.3 Building confined, rather than infill, masonry housing

The seismic performance assessment recommendations revealed confined masonry significantly outperformed infill masonry construction. Confined masonry is built by first placing any vertical reinforcement into the foundation, then laying the masonry blocks, and finally adding the reinforced concrete elements. In contrast, infill masonry is built by first casting the columns and then infilling the space between the columns (Brzev et al. 2017; Lang and Marshall 2011; Marshall et al. 2011). With appropriately tied beams and columns, confined masonry systems are stronger and more ductile than infill masonry structures, significantly improving performance in earthquakes (Brzev and Mitra 2007).However, only 44% of respondents' responses aligned with our findings. Further, ring beams are a critical component of the reinforced concrete frame systems in confined masonry construction, but only 52% of survey respondents indicated it was important to include a ring beam. Instead, builders may directly support the slab with masonry walls. Moreover, 75% of respondents indicated builders commonly did not include ring beams in housing design because of technical construction capacity and 52% listed financial constraints. When asked about which order of construction was safer, 56% of the respondents indicated that it was safer to build with infill than confined masonry, that one practice was not safer than the other, or that they didn't know which practice was safer. Thus, most respondents held housing safety perceptions that were not aligned with results from our structural assessments of housing safety, which find that confined masonry techniques increase the relative safety of housing.

Fieldwork observations and pilot interviews indicate the prevalence of infill versus confined masonry on the island. In interviews with builders, perceptions were generally mixed, with some builders explaining that they view confined masonry construction as safer than infill techniques, but that infill construction often occurs because it is easier and less time-consuming process, with one builder saying *"putting the blocks first is a little harder than making the column... it is more convenient for the builder, not for the* *client or consumer who requests the construction."* While there may be some small increase in labor costs with this form of construction, the significant factor seems to be the lack of technical knowledge of the relative seismic performance of confined and infill masonry and familiarity with the superiority of the better practice, which leads to builders constructing infill masonry in most cases. Changes to building practice to achieve confined masonry would likely include changes to order of construction as well detailing in the reinforced concrete frame to tie the system together.

Overall, the survey results related to infill and confined masonry housing construction show that some, but not all, builders in Puerto Rico are likely constructing infill masonry housing and sometimes without ring beams and these practices are likely rooted in a technical capacity related to constructing safer confined masonry structures and perceived utility of these structures.

6.4 Avoiding or retrofitting open-ground-story housing with weak columns

Open-ground-story housing has an open first story raised on columns that are locally referred to as "zancos" or stilts. This housing is common across Puerto Rico, often built to avoid flooding damage (López-Marrero 2010) and to provide additional area for parking or other outdoor, covered storage. In earthquakes, however, open-ground-story housing with weak columns is unsafe. As one hardware store employee shared in a pilot interview following the 2019-20 earthquakes, *"Before the earthquake, you knew you had to build tall stilts to avoid the seawater, but now that's also dangerous because if you don't take the right measures, they can crush down easily."*

Our seismic performance assessments confirmed findings from a reconnaissance report after the 2019-20 earthquakes, showing that the most significant vulnerability in reinforced concrete/masonry houses is weak columns in an open-ground-story (Miranda et al. 2020). The assessments showed that significant, well-built reinforced concrete jackets were needed to improve seismic safety. These jackets approximately doubled the collapse capacity of open-ground-story housing configurations. The engineering assessments also found that, while other aspects of column designs could be improved, the first story columns in open-ground-story houses were by far the most critical (Murray 2021).

In contrast, almost half (45%) of the respondents did not perceive reinforced concrete jacketing as an important method of increasing safety of open-ground-story housing. While over half of the respondents agreed with the retrofit recommendations from the engineering assessment, we selected this focus area because many residents and builders had expressed concern and fatalism about open-ground-story houses in interviews. Residents and builders began to doubt the safety of open-ground-story houses built on weak columns after the 2019-20 earthquakes, expressing uncertainty regarding the safety of open-ground-story housing, reinforced concrete construction in general, and the ways to retrofit this housing to increase safety. For instance, in a pilot interview for this study after the 2019-20 earthquakes, one individual said they felt safe in their house "*because it is on solid ground, not stilts.*" Retrofit of these stilts is not yet common practice.

In the survey, it appeared that respondents expressed more expected damage to columns in general than to the vulnerable first-story columns specifically. For instance, when asked about the damage they expected to reinforced concrete/masonry housing in future earthquakes, 55% of respondents expected column collapse in general, while 38% expected damage to the columns supporting the open-ground-story housing specifically, or stilts. When asked about the reasons why respondents believed others construct weak columns, 69% listed technical construction capacity and 63% listed financial constraints. We also asked respondents to elaborate on all the specific practices they believed are leading to these weak columns, of which most indicated they believe builders are using insufficient vertical reinforcement (68%), insufficient transverse reinforcement (56%), and poor concrete mix (54%). While ranges in concrete quality also influenced seismic performance, these variations did not have as large of an impact as the reinforcement detailing (Murray 2021).

Our findings suggest the need for engineering guidance on how to build stronger columns to support open-ground-story housing, including details of vertical and transverse reinforcements as well as concrete mix design that can be adopted across the island. It is necessary to ensure columns provide adequate strength and deformation capacity, with adequate cross-sectional area, and longitudinal and transverse reinforcing bars for expected earthquake loads. Increased engineering guidance on how to build these stronger columns could contribute to standardizing safer column design and construction practices of the informal construction sector, increasing technical construction capacity. Similarly, considering the retrofit options, retrofitting vulnerable columns with the recommended reinforced concrete jackets requires engineering design consultation.

Overall, there is likely a large amount of uncertainty regarding the safety of open-ground-story housing and the ways to retrofit this housing or improve this practice for new construction. For this housing, the seismic performance assessment recommendations suggest two retrofit options: infill panels, which make the house no longer an open-ground-story structure, reducing the benefits for flooding, and reinforced concrete jackets, which requires specialized engineering design consultation before the practice becomes standardized and a larger part of informal sector technical construction capacity.

7. LIMITATIONS

This study provides new insight into how engineering assessments and perceptions of housing safety compare, which are misaligned, and if these misalignments are rooted in limitations of technical construction capacity or financial constraints. However, as with all studies, there are some limitations. Due to the nature of informally constructed housing, actual housing designs vary greatly in design and construction. Thus, our engineering assessments are based on a series of informed assumptions from reconnaissance reports, pilot interviews, and field observations. Lochhead et al. (2022) and Murray (2021) detail the wind and seismic performance assessments, respectively, including all assumptions made and methods used. The wind analysis focuses on housing superstructure while the seismic performance assessments are based on USGS Site Class B and a fixed foundation (Murray 2021). In addition, there are many studies of technologies that can improve seismic performance of masonry/reinforced concrete buildings (e.g. Tarque et al. 2019). Future studies could investigate other housing foundations and soil configurations, considering vulnerabilities potentially presented by siting and soil conditions and potential misalignments associated with those.

Further, comparisons between these engineering assessments and housing safety perceptions are based on a survey of builders and hardware store employees across Puerto Rico. These surveys were designed to be understood easily by individuals with a range of design and construction experience and to be short enough that we could get many participants. Thus, respondents were not given the same level of detail as was included in the engineering assessments. Moreover, due to the timing between engineering assessments and the survey, questions were not included on some recommendations, which future studies can expand upon. Importantly, our approach to identifying these misalignments was supported by case knowledge from the authors as well as pilot interview and study data. We also based our identification of misalignments on what perceptions of "most," or around 45% or higher of the survey respondents. We selected this proportion of respondents in order to generally discuss common perceptions of those working and advising in Puerto Rico's informal construction sector. We recommend that future studies aim to strengthen these prioritized areas of misalignment collaboratively with community-based organizations in Puerto Rico.

8. CONCLUSION

In Puerto Rico, informally constructed housing is common and exposed to both hurricanes and earthquakes. This context is ideal to study how those working in the informal construction sector perceive the safety of different design and construction practices to different hazards, and how these housing safety perceptions may not align with engineering assessments of housing safety. We compared housing safety perceptions with specific recommendations of how to increase wood-frame and reinforced concrete/masonry housing safety in future hurricanes and earthquakes to identify misalignments. We analyzed survey data to evaluate whether more respondents indicated the relevant practices for each recommendation were rooted in technical construction capacity, rather than solely financial constraints, to identify focus areas for technical capacity development within the informal construction sector. Based on the results from our survey of those advising and building in the informal construction sector, we identified four misalignments where unsafe housing design and construction is rooted in technical construction capacity.

First, our results reveal that builders and residents may not be thinking about wood-frame structures from a systems perspective. Thus, builders and residents are prioritizing methods of securing their roof panels rather than strengthening the connections between structural members within the roof structure. This lack of a systems perspective is leading to housing that is vulnerable to more catastrophic failures of the entire roof structure in wind events, rather than less catastrophic panel tear off alone. Our results thus suggest that capacity development focuses on the efficacy and appropriate implementation of hurricane straps and systems understanding of wood-frame structures.

Due to prior hazard experiences with frequent hurricanes and less frequent earthquakes, builders have grown to prioritize methods of strengthening housing in hurricanes, often associating the ‘heaviness’ of reinforced concrete/masonry housing with its strength. However, the recent earthquakes led to increased uncertainty around housing safety, with many doubting the local knowledge of informal builders when it came to earthquake safety (Goldwyn et al. 2021). As earthquake safe design detailing is less visible than safety to other hazards (Krimgold 2011), we suggest technical construction capacity development should emphasize the ways earthquakes affect buildings with lateral forces, causing damage to heavy housing, infill walls, and open-ground-story housing raised on weak columns. By working within existing structures of grassroots and community-based organizations in Puerto Rico, technical construction capacity development should work to build upon the foundation of local knowledge to show how confined masonry and retrofitted columns can reduce these vulnerabilities.

This study contributes to literature on the housing safety perceptions of those making design decisions and engaging in construction practices informally in multi-hazard environments such as the Caribbean. Moreover, this study provides an approach for comparison of local and scientific knowledge, or perceptions and engineering assessments, and identifying misalignments to focus on for capacity development. Practically, this study’s results will support groups in their efforts to intervene in ongoing housing construction practices with skills training and information dissemination approaches to increase housing safety and reduce disaster risk.

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10. DATA AVAILABILITY

Data that support the findings of this study are available from the corresponding author upon reasonable request.

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