Natural Hazards (2022) 112:1165–1189
https://doi.org/10.1007/s11069-022-05222-0

ORIGINAL PAPER

Assessment of hurricane wind performance and potential design modifications for informally constructed housing in Puerto Rico

Meredith Lochhead[1] · Briar Goldwyn[2] · Casie Venable[3] · Abbie B. Liel[2] · Amy Javernick-Will[2]

Received: 12 June 2021 / Accepted: 17 January 2022 / Published online: 13 February 2022

Abstract

This study assesses the wind performance of various housing typologies representing informal construction practices in Puerto Rico to suggest modifications to enhance housing resilience in hurricanes. Based on fieldwork and interviews, the study defined four base housing typologies and possible variations in design and construction details. Each house was assessed using performance-based static wind analysis of potentially critical components. The results show that the initial governing failure mode in all base house typologies considered is roof panel loss due to tear-through at the fasteners, with subsequent governing failures being panel loss due to failures at the purlin-to-truss connections and failures of the truss-to-wall connections. In-plane wall failures and masonry uplift failures were both found to occur at much higher wind speeds than roof failures. To improve the hurricane performance, several feasible modifications are suggested, including installing hurricane straps at both the truss-to-wall and the purlin-to-truss connections, as well as improving the panel-fastener interface. In the construction of new roofs, this study found that using reduced spacing between roof members, hip roofs instead of gable roofs, and higher roof slopes leads to improved performance. These recommendations can make houses built through informal construction processes safer and more resilient to hurricanes as a form of climate adaptation.

Keywords Housing · Wind engineering · Hurricane risk · Climate adaptation

Abbie B. Liel
abbie.liel@colorado.edu

[1] Department of Civil and Environmental Engineering and Earth Sciences, University of Notre Dame, Notre Dame, IN, USA

[2] Department of Civil, Environmental and Architectural Engineering, University of Colorado, Boulder, CO, USA

[3] Arup, San Francisco, CA, USA

1 Introduction

Globally, tropical hurricanes (also known as cyclones or typhoons) cause nearly half of all direct economic losses from hazard events (CRED and UNISDR 2018). These losses are typically driven by wind and storm surge damage. In the future, the effects of climate change, including sea level rise and warming temperatures, will likely increase the intensity and frequency of hurricanes (Knutson et al. 2013). These hurricanes are expected to particularly affect regions like the Caribbean, where hurricanes have accounted for nearly 95% of all damage to the built environment from hazards in the last sixty years (Burgess et al. 2018; Vosper et al. 2020). Moreover, the World Economic Forum identifies the failure of climate change mitigation and adaptation as its top risk for the built environment in terms of potential future impact (Edmond 2020).

Hazards such as hurricanes disproportionately affect resource-limited communities, which bear 68% of disaster fatalities, despite experiencing only 43% of disasters (CRED and UNISDR 2018; Rentschler 2013). Resource-limited communities are often located in higher-risk or flood-prone areas with poor early-warning systems (Zorn 2018). In addition, they have a greater proportion of the population living in potentially vulnerable or informally constructed housing (Zorn 2018). Here, informally constructed housing is housing constructed without explicitly adhering to building codes or other regulations, and likely without the guidance of formally trained engineers or architects. This practice is ubiquitous in regions with weak regulatory enforcement of construction processes (Talbot et al. 2020; Rodgers 2012). Around the world, informal construction is often the only form of affordable housing (Lallemant et al. 2017), and, after disasters, rebuilding follows the same pattern because over 80% of households worldwide recover without external assistance (Hendriks et al. 2018, Parrack et al. 2014).

For this informally constructed housing, the available resources, risk perceptions, and construction knowledge of individual households and builders determine what is built or modified (Goldwyn et al. 2021), producing a wide range of construction and design decisions. Local builders often engage in an informal practice of "value engineering," whereby builders use their experience to decrease cost (Rodgers 2012). This practice, which mirrors formal construction value engineering processes, includes the substitution of fewer materials (e.g., reinforcement or nails) or the adoption of quicker methods, without the intent to sacrifice structural performance. However, when informal builders navigate tradeoffs between cost and performance to make these value engineering propositions, the resulting design choices may increase structural vulnerability to hazards such as hurricanes (Rodgers 2012). Understanding how common informal construction and these informal value engineering processes are, many governments and organizations have developed training programs aimed at reaching informal builders and households to illustrate methods of reducing disaster risk. These programs involve, for example, illustrated handouts and other training materials showing "good" and "bad" construction practices (e.g., different truss structures, roof shapes, and members spacing) (e.g., Enterprise Community Partners 2019). These communication strategies are typically responsive to the structural vulnerabilities identified in post-disaster reconnaissance, such as weak connections between roof trusses and walls in hurricanes (FEMA 2018a).

In this paper, we assess the relative hurricane performance of informally constructed housing with a variety of locally relevant materials and design choices and explore potential modifications to improve this performance. We focus on the Caribbean island of Puerto Rico because it is a region with significant informal housing construction that is exposed to frequent hurricanes. To assess the performance of the broad variation in informally constructed housing in Puerto Rico, we develop a set of baseline housing typologies and common component and system variations that capture the variety of material and design choices made on the island. Hurricane, or high wind, performance is assessed through a component-based static procedure of roof and wall systems, based on established wind pressure models. We then assess the effect of various designs or materials on performance. The results of this study show how design choices affect performance in high wind events and compare strategies for mitigating structural vulnerabilities through material and design modifications. These results are intended to improve the performance of informally constructed housing in wind events by providing an understanding of cost-effective options to increase housing safety within the context of local materials and construction choices.

2 Context

This study focuses on Puerto Rico, a U.S. territory located in the Caribbean that has repeatedly incurred damage from hurricanes and other hazards. There have been many documented hurricanes with paths crossing over or near to Puerto Rico in the last two centuries, with over 24 Category 1 or greater hurricanes impacting the country throughout the 1900s (Puerto Rico Hurricane Center 2005a; Puerto Rico Hurricane Center 2005b). Already in this century, 12 hurricanes have impacted Puerto Rico, in addition to many tropical storms (NOAA 2021a). The frequency at which this island is impacted by hurricane-force winds makes hazard damage to residential construction a concern.

Most recently, Hurricanes Irma and Maria devastated Puerto Rico in late 2017. These Category 5 and 4 storms, respectively, damaged over one-third of the island's housing or over 400,000 houses (Brown 2018). Over the past two decades, building codes in Puerto Rico have grown increasingly standardized in response to hurricane damage (FEMA 2018a). However, roughly 55% of Puerto Rican residential and commercial construction is constructed informally (Hinojosa and Meléndez 2018), as a result of formal processes being inaccessible due to cost, land tenure requirements, and other barriers (Talbot et al. 2020). The typical informal construction practices consist of family, neighbors, or friends building or repairing their housing without explicit design, supervision, or inspections (Goldwyn et al. 2021). As a result, most households do not benefit from building code improvements and standardization. After Hurricanes Irma and Maria, the vast majority of this damaged or destroyed housing was reconstructed informally and often built on land for which the households did not hold tenure, leading the U.S. Federal Emergency Management Agency (FEMA) to reject 60% of applications for assistance (Acevedo 2018). Nongovernmental organizations (NGOs) were also relatively absent in Puerto Rico, leaving thousands of households to repair or rebuild their houses on their own, using whatever post-disaster resources and construction knowledge they could access, and deepening their reliance on the informal building sector. The combination of the high frequency and intensity of hurricane winds, the strong reliance on local construction capacity due to high percentage of informal construction practices in residential settings, and the relative absence of nongovernmental organizations motivated our selection of Puerto Rico to study the performance of informal construction and potential design modifications.

Many of the informally constructed houses in Puerto Rico are one-story, light-framed wooden houses with corrugated galvanized iron (CGI) roof panels (Cruzado and Pacheco-Crosetti 2018). These wooden houses generally have either gable or hipped roofs with plywood walls, have connections are generally nailed, and use wooden 2×4 s for both purlin and truss members. The other common housing type is heavy concrete construction, which includes a first floor with a reinforced concrete frame and masonry walls, and a second story built with either concrete or light-framed wood (Prevatt et al. 2018); these houses may have wood roof systems or concrete slab roofs. Houses typically have slatted Jalousie windows, or shutters; glass windows are uncommon due to cost (FEMA 2018a). The choice between wood and concrete as the primary residential construction material is often driven by economic considerations, with residents with greater financial means tending to build concrete/masonry houses and more likely building in compliance with building codes (FEMA 2018a).

3 Background

Our understanding of the performance of informally constructed housing comes primarily from post-disaster reconnaissance reports published by FEMA and NGOs. Throughout the Caribbean, reconnaissance reports show consistent failure modes for informally constructed housing and also indicate similarities in housing typologies across the region. For example, loss of roof panels is a common failure mode for wood-framed roofs with metal covering in high wind events due to insufficient number or type of fasteners and the use of thin metal panels (FEMA 2018a; FEMA 1999; Build Change 2016). Additionally, many reports from Caribbean hurricanes have found nailed roof connections, whether at purlin connections in the roof or between roof trusses and walls, are insufficient to resist the shear and uplift forces that are experienced during a high wind event, producing many of the roof failures (FEMA 2018a; FEMA 1999; Build Change 2016; Kijewski-Correa et al. 2019). Wood deterioration due to insect infestation or moisture and metal roof panel corrosion have also contributed to failures (Build Change 2016).

In Puerto Rico, after Hurricanes Irma and Maria, FEMA's reconnaissance team observed that wood-frame buildings that were damaged by wind typically had failures within the roof system due to insufficient connections between structural members (FEMA 2018a), as exemplified in Fig. 1. Weak connections caused failures to occur at the connection holding the metal roof panels to the roof structure, the connection between structural members in the roof structure, or at the connections holding the roof to the walls. These types of issues arise almost exclusively in informally constructed houses (FEMA 2018a). Of these, the most common failure mode in Puerto Rico was the loss of roof covering in structures with wooden roof systems. This roof covering loss was due to the use of improper fasteners, metal panels with an insufficient gauge, a lack of redundancy, and excessively wide truss and purlin spacing (FEMA 2018a). In some cases, metal roof panels were nailed to wooden roof members with no consideration of increased wind pressures at

Fig. 1 Illustration of roof panel loss in Puerto Rico due to Hurricane Maria (Source: FEMA 2018a)

the ends, ridges, or corners of the roof, which also contributed to failures (FEMA 2018a). Additionally, these panels were often heavily corroded due to improper coatings, inadequate material selection, or age, which likely weakened connections. These connection failures resulted in the roof covering partially missing on many houses, leading to further destabilization and water intrusion. Although less prevalent, metal roof panels have also been found to be pried from a house with wooden purlins still attached (Ginger et al. 2010). FEMA's reconnaissance team observed that houses with structural decking beneath the metal panels outperformed those without it in Puerto Rico and that adjustments such as using thicker (superior gauge) metal panels or reduced fastener spacing improved roof performance (FEMA 2018a).

Other studies have found similar damage types in resource-limited communities worldwide in hurricanes, including roof cladding loss (Prevatt et al. 2010; Shanmugasundaram et al. 2000), global roof system loss due to failure of the connections between the roof trusses and walls (Mukhopadhyay and Dutta 2012; 2016), and wall failures (Build Change 2014; Kijewski-Correa et al. 2017). In general, reconnaissance reports demonstrate that informally constructed block masonry and concrete structures better withstand hurricane winds compared to housing structure typologies built primarily with wood materials (FEMA 2018a; Build Change 2016). Even so, some structural vulnerabilities, such as insufficient reinforcement or the lack of a ring beam, can lead to the failure of masonry and concrete structures in hurricanes, as was observed in Haiti after Hurricane Matthew (Build Change 2016). More recent building practices of reducing the number of internal walls and using lighter roofs may also have increased vulnerability to wind damage, relative to older non-engineered construction (Sparks et al. 1989).

Beyond the reconnaissance studies, limited research has formally evaluated the safety of this informally constructed housing through structural analysis and performance-based engineering. We found only one study that used structural analysis to assess the performance of informally constructed housing in wind events, which assessed the wind performance of typical bamboo and thatch housing in Bangladesh and provided minimum design recommendations to increase strength in wind events (Alam et al. 2017).

Previous work by the authors (Venable et al. 2021) quantified the expected wind performance of post-disaster housing typologies constructed by government agencies and NGOs in the Philippines after Typhoon Yolanda, investigating the performance of different designs using performance-based wind engineering methods. For these typologies, we found that roof panel loss, either from failure at the connection of the roof covering to the purlins, or at the connections between the purlins and trusses, is the most common governing failure mode and is expected at wind speeds equivalent to a Category 2 hurricane. Venable et al. (2021) found that in a few housing designs with wooden frames and woven wall materials, roofs were over-strengthened compared to the strength of walls, leading to wall racking and collapse. Venable et al. (2021) also assessed how design changes could improve the performance of this post-disaster housing, finding that strengthening wall capacity, designing with hip roofs, using thicker roof panels, installing hurricane straps, and decreasing fastener spacing improved performance. Roof improvements were recommended only if walls had also been strengthened. However, in the Puerto Rican context, it is unlikely that limited-resource households and informal builders have access to the same imported materials organizations use to rebuild houses after disasters, and we thus expect different structural vulnerabilities.

Taken together, the reconnaissance reports and the previous wind assessments provide significant insight into the structural vulnerabilities that likely led to damage in hurricanes. However, these do not address modifications that can be made to improve wind performance in informal housing construction, nor evaluate the relative improvements associated with various possible design modifications.

4 Methods

In this study, we conduct performance-based wind assessments of four housing typologies, each with multiple variations, to capture the variability in design and construction among informally constructed housing in Puerto Rico. This section describes the housing typologies and variations, followed by the performance-based wind assessment. The wind assessment is used to identify when roof or wall failure occurs, detailing the quantification of wind loads, component capacities, and treatment of uncertainties.

4.1 Establishing housing typologies and variations

Due to the wide variation in housing design details in Puerto Rico, we first sought to characterize informal housing construction across the island based on a literature review of housing characteristics across the Caribbean and fieldwork/exploratory interviews. During fieldwork in July 2019 and February 2020, we measured structural dimensions and took photographs of the exterior of typical houses built with reinforced concrete and wood (Goldwyn et al. 2021). During these interviews, households were asked to show and describe any damage to their houses due to Hurricane Maria and the 2019–20 earthquakes (only in the 2020 interviews). Engineers, architects, and reconstruction program staff and volunteers also shared photographs and videos of typical damage to different, common housing types. We also examined inventory at hardware stores across Puerto Rico during this fieldwork to determine material availability and prices. In interviews, many informal builders also explained the structural vulnerabilities that are commonly produced by unsafe construction practices or design choices of other informal builders that they viewed as unacceptable yet commonplace. Figure 2 includes photographs of several typical houses taken across these fieldwork trips. We used this information to establish four main housing typologies and variations therein to reflect the most common construction practices and materials observed in Puerto Rico's informally constructed housing.

4.1.1 Base house typologies

The initial base case, denoted *Gable 1* (detailed in Fig. 3), represents a one-story wood-frame house with a corrugated metal roof. Three additional base typologies were defined to reflect common variations in the number of stories, primary housing material, and roof shape. These four base typologies are defined in Table 1.

Fig. 2 Photos of Puerto Rican informally constructed houses (Photographs: Polly B. Murray and the authors)

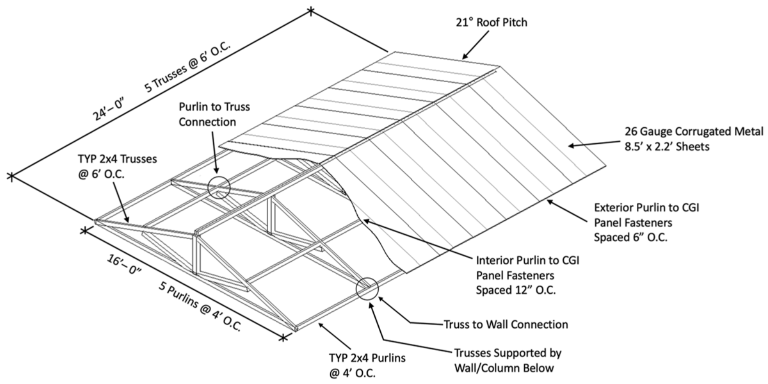

Fig. 3 Base house typology, *Gable 1*, showing roof system plan view and 3D schematic (1 in = 25.4 mm; 1 ft = 0.305 m)

Table 1 Base house typologies

	Gable 1	*Hip 1* (Hip roof variant)	*RC 1* (RC variant)	*Gable 2* (Two-story variant)
Characteristics determining typology				
Roof shape[a]	Gable	Hip	Gable	Gable
Column material	Lumber	Lumber	RC	RC, Lumber
Wall material	Plywood	Plywood	Unreinforced Masonry	Unreinforced Masonry, Plywood
Total height	8 feet (2.4 m) 1-story	8 feet (2.4 m) 1-story	8 feet (2.44 m) 1-story	16 feet (4.9 m) (2 stories)
Common characteristics across house typologies				
Plan dimensions	16feet by 24 feet (4.9 × 7.3 m)			

[a]Although flat roofs do appear in Puerto Rican houses, they are typically constructed from concrete, making them less vulnerable to wind events and outside our scope here

Although housing size varies across Puerto Rico, all base house variations were taken as 16 feet by 24 feet (4.9 by 7.3 m) based on fieldwork observations, photographs, and interviews with local professionals. The houses considered in this study were assumed to be either one or two stories in height, with a total height of 8 feet (2.4 m) and 16 feet (4.9 m), respectively (Enterprise Community Partners 2019; FEMA 2018a).

Much of Puerto Rico's informal construction consisted of light, wood-frame houses (FEMA 2018a, Wells 2020). We assumed that one-story houses in this study had wood framing with plywood sheathing, or reinforced concrete (RC) columns with unreinforced concrete masonry unit (CMU) infill walls. We assumed two-story houses had concrete or masonry walls on the first floor, with plywood walls on the second floor. This is common among two-story, informally constructed houses because the stories are often not constructed simultaneously (FEMA 2018a; Goldwyn 2021). The most common roof type was a wood-frame roof with corrugated metal panels, which we assume for all the typologies. While some houses did have tile or concrete roofs, these materials are more expensive and thus less common (FEMA 2018a). We assumed the purlin length to be 10 feet (3.1 m) with two purlins per line (parallel to the roof gable) based on local material availability and the size of the houses being considered (Fig. 3).

4.1.2 Common component variations

To model the performance of a wide range of informally constructed housing, additional variations to critical components, including CGI panels, fasteners connecting panels to the roof structure, connections between purlins and roof trusses, and connections between roof trusses and walls were considered for each of the four housing typologies. The details of the components for each base typology are provided in Table 2, with the additional variations considered shown in parentheses. Though some connection alternatives are more expensive than others, the variations evaluated in this study all represent feasible, relatively affordable options that are and can be used in informal construction.

4.2 Wind performance assessment

We assessed the likelihood of failure under wind loading by evaluating the performance of informally constructed houses subjected to wind speeds ranging from 55 mph (90 kph) to 250 mph (405 kph), where wind speeds are quantified by 3-s wind gusts. This range corresponds to the range from a Category 1 to a Category 5 storm (NOAA 2021b).

To determine possible component and system failures at a specified wind speed, we checked:

$$\mathbf{R} < \left(\mathbf{W_U} - \mathbf{D}\right), \tag{1}$$

where R = capacity of the given component, W_U = wind force on the component, and D = force from the dead load acting on the component. W_U is an uplift force on the roof system/components, and a lateral force on the wall system/components. The analysis focused on initial failures and does not redistribute pressures for either internal or external pressures as components fail. As a result, this analysis is most useful for identifying the first component failure because there is considerable load redistribution and changes in pressures after failure occurs.

The wind performance assessment identifies roof failures due to: panel failure due to failures at the panel-fastener interface, panel failure due to failures at the purlin-to-truss connections, and failure at the truss-to-wall connections. We assumed that a panel fails if ten percent, or two, of its fasteners fail, whichever is greater (Henderson et al. 2013; Stewart et al. 2018). To relate purlin-to-truss connection failure to panel failure, we assumed that all purlin-to-truss connections on a single purlin needed to fail for the purlin to fail, and the purlin at the edge of a roof panel must fail for the panel to fail. A failure of a single truss-to-wall connection was considered a roof failure.

To account for uncertainty in both the wind loads and the component capacities, a Monte Carlo simulation was used throughout the analysis.

4.2.1 Wind loading on houses

We used ASCE/SEI 7 procedures for low-rise buildings to statically determine wind pressures, as a function of wind velocity, according to Eq. 2 from ASCE/SEI 7 (ASCE/SEI 2016)

Table 2 House component variation details (1 ft = 0.3035 m; 1 in = 25.4 mm)

Component	Base typology component or configuration (Variations considered)	Rationale
Roof slope	21° (15°, 28°)	Variations based on fieldwork and Enterprise Community Partners (2019); variations chosen to span the roof slope categories in ASCE 7 (ASCE/SEI 2016). Steep roofs are less common in Puerto Rico, but were included as a possible design modification
Roof panel material	Corrugated Metal or CGI (Trapezoidal Metal)	Material variations based on Enterprise Community Partners (2019), FEMA (2018a), FEMA (2018b), interviews, fieldwork, and material availability in local hardware stores. We did not consider plywood roof decking, as that is uncommon in informal construction
Panel gauge[a]	26-Gauge (24-, 28-Gauge)	Variation in gauge was determined based on FEMA (2018a) and local material availability
Fastener type	Nail: 0.28in head (Umbrella Nail: 0.87 head)	Types chosen based on availability in local hardware stores, fieldwork, and Enterprise Community Partners (2019)
Fastener spacing	6in Exterior and 12in Interior (6in Exterior and Interior, 12in Exterior and Interior)	Variations based on exploratory interviews, Enterprise Community Partners 2019, FEMA (2018a), FEMA (2018b)
Eaves	0.5 ft (1.5 ft, No Eaves)	Variations taken from fieldwork observations, exploratory interviews, FEMA (2018a), and FEMA (2018b)
Purlin and truss lumber	Nominal 2×4 s	Based on Enterprise Community Partners (2019), FEMA (2018a), FEMA (2018b), interviews, and fieldwork
Purlin-to-truss connection	Nailed (Cleat, Hurricane Strap)	Variations based on fieldwork observations, Venable et al. (2021), and FEMA (2018a). We included hurricane straps, which are available at stores, but not often seen in informally constructed houses, as an aspirational design modification. We assumed that hurricane straps were wrapped around both the purlin and the truss to connect the two members
Truss-to-wall connection	Toe-nailed (Cleat, Bolt, Hurricane Strap)	
Truss spacing	6 ft (4 ft, 12 ft)	Enterprise Community Partners (2019) advises 2 ft spacing for purlins and trusses, but fieldwork, and FEMA (2018a) suggest much wider spacing exists
Purlin spacing	4 ft (2 ft, 8 ft)	
Wall bracing	Plywood sheathing (Additional Diagonal Bracing)	Plywood sheathing was assumed on all houses with wood walls. In-plane-diagonal bracing was additional. Variations based on fieldwork, Enterprise Community Partners (2019), and past work of authors (Venable et al. 2021)

Table 2 (continued)

Component	Base typology component or configuration (Variations considered)	Rationale
Material deterioration	None (Moderate, Severe)	In a tropical climate like Puerto Rico, wood deterioration can result from fungi, decay, rot, insects, and weathering (Ibach and Lebow 2014). Metal roof covering panels are also prone to corrosion due to improper coatings on the panels and age, and high temperature and humidity values reduce the time to onset of the corrosion process (Castañeda et al. 2013). Fieldwork observations and FEMA (2018a) revealed material (metal and wood) deterioration on the island
Masonry walls	No ring beam, Unreinforced CMU infill (Ring Beam with height of 0.7ft, Reinforcement in CMU infill)	Masonry wall variations were based on FEMA (2018a), fieldwork observations, and exploratory interviews

[a]Panel gauge is inversely related to thickness

$$W = q_h[GC_p - GC_{pi}], \tag{2}$$

where q_h = velocity pressure at the mean roof height, G = gust factor, C_p = external pressure coefficient, and C_{pi} = internal pressure coefficient. The velocity pressure (N/m^2) is determined by

$$q_h = 0.613 K_z K_{zt} K_d K_e V^2, \tag{3}$$

where K_z = velocity pressure exposure coefficient, K_{zt} = topographic factor, K_d = directionality factor, K_e = ground elevation factor, and V = 3-s gust wind speed (m/s). K_z is based on the height of the structure and the exposure classification. We determined external pressure coefficients C_p for houses using ASCE/SEI 7 Chapters 28 (Main Wind Force Resisting System–Envelope Procedure) for walls and truss-to-wall connections and 30 (Components and Cladding) for panels, fasteners, and purlin-to-truss connections (ASCE/SEI 2016). We assumed all houses have an exposure B classification due to their location in built-up terrain consistent with suburban exposure. Because we wanted to represent a range of houses at a range of locations on the island, the specific location and topography of each house were unknown. Thus, wind speed-up effects were not accounted for and K_{zt} was assumed to be 1.0. K_d was taken to be 0.85 to account for the likelihood that the wind direction does not align with the worst-case angle of attack. We considered all houses at sea level, making K_e equal to 1.0. None of the houses considered in this study were airtight due to potential gaps between the top of the wall and the roof, as well as inherently open window systems. Thus, we assumed all houses to have a partially enclosed status with an internal pressure coefficient, C_{pi}, of 0.55. This was likely a conservative estimate for the internal pressure of the intact structure. We assumed the wind loads varied according to a normal distribution with a coefficient of variation of 0.2, based on Li and Ellingwood (2006).

4.2.2 Dead loads

We considered dead loads including the self-weight of the CGI panels, the wooden purlins, and the wooden roof trusses. Uncertainty was not included for the dead load because the variability in the self-weight was low compared to wind loads.

4.2.3 Loads on components

We determined the forces on each component using structural analysis based on the loads and the tributary areas of the components based on the assumed connectivity (boundary conditions) in the roofs. We assumed plywood walls retained their integrity, forming a diaphragm that transferred the wind pressures acting over the surface to the perpendicular wall framing. Masonry uplift forces conservatively assumed a 60° angle from the point at which the concentrated uplift load to estimate the area is affected by the uplift force (Bright and Roberts 2005).

4.2.4 Component capacities

The capacities of the components considered in this study are summarized with reference sources in Table 3, with details specific to informally constructed housing in Puerto Rico explained next.

Table 3 Component capacities (1 kip = 4.45 kN; 1 ksi = 6.89 MPa)

Component	Mean capacity	Source
CGI panels	Ultimate tensile strength: 30 ksi	(Venable et al. 2021)
Fasteners	Tear-out capacity: Function of head diameter, CGI thickness, and ultimate tensile strength of the CGI Pullout Capacity: 0.3 kips	(Mahendran and Tang 1999) (Thurton et al. 2012)
Purlin-to-truss connections	Toe-nailed: 0.4 kips Cleat: Nail for single shear Hurricane Strap: 0.5 kips	(Cheng 2004) (Khan 2012) (ANSI/AWC 2015) (Simpson Strong-Tie 2019)
Truss-to-wall connections	Toe-nailed: 0.7 kips Cleat: Nail for single shear Hurricane Strap: 1.3 kips	(Cheng 2004; Khan 2012) (ANSI/AWC 2015) (Ellingwood et al. 2004) (Li and Ellingwood 2006)
Wooden wall frames	Plywood: 0.2 kips/ft 50% Reduction for windows, doors Diagonal In-Plane Braces: 5.6 kips	(Doudak and Smith 2009) (Erikson and Schmidt 2003) (Salenikovich 2000) (Li and Lam 2009)

Two failure mechanisms at the panel-fastener interface were considered, with capacities detailed in Table 3: fastener pullout and CGI tear-out around the fasteners. Fastener tear-out always governed. We assumed that not all fasteners would be properly placed during construction, meaning that some fasteners were not aligned with the center of the purlin, reducing their capacity. We assumed that three percent of all fasteners were improperly installed, changing both the pullout and tear-out capacities according to the triangular distribution from Stewart et al. (2018); according to this model, a fastener that is improperly installed has (on average) 80% lower capacity.

For the connections within the roof system, we assumed purlin connections have one nail per connection, and the nails are inset 0.8 inches (0.02 m) on both interior and edge purlins based on field observations and our own past analysis of housing in the Philippines (Venable et al. 2021). The cleat connection at both the purlin-to-truss and the truss-to-wall connection was assumed to have two nails, one into the purlin and another into the truss. The failure mechanism of these connections was assumed to be nail shear, with the governing shear failure mode being fastener yielding (Venable et al. 2021). The hurricane strap connections at both the purlin-to-truss and truss-to-wall connections were assumed to have a single hurricane strap attached to each member, with capacities based on hurricane straps available locally.

We based wall frame capacities for the wood light-frame houses on past studies that have found wall failure can result from racking under strong winds (Liu et al. 1990; Venable et al. 2021). Racking resistance is provided by the frame, the wall sheathing, and any additional bracing that may be included in the house. We did not include lateral wall assessments for the RC typology as hand calculations showed that the lateral capacity of these walls is sufficient to resist wind loads (Venable et al. 2021). However, Kijewski-Correa et al. (2017) documented tension failures in the wall due to uplift forces at truss-to-wall connections as a possible failure mechanism of unreinforced masonry walls in hurricanes, particularly where there is no ring beam. The potential for this failure mode was also indicated by our exploratory interviews. The weakest point in a CMU wall is the masonry-mortar bond, rather than the masonry block or mortar itself, which results in tensile failures in CMU construction occurring along horizontal joints (Sparks et al. 1989). Cement-lime mortar is used most commonly in CMU housing construction, which has a tensile capacity of 0.03–0.065 ksi (0.21–0.45 MPa) (Sparks et al. 1989). Thus, we conservatively assumed the tensile capacity of the masonry-to-mortar bond was 0.03 ksi (0.21 MPa). We assumed that houses with adequate reinforcement and ring beams would not experience tension failures due to uplift forces (Venable et al. 2021).

To represent the cases with material deterioration, we assumed varying percentages of fasteners, purlin-to-truss connections, and truss-to-wall connections were deteriorated and had a reduced capacity. Based on our observations, we modeled a moderate case of material deterioration as 30% of connections being affected and a severe case of material deterioration as 50% of connections being affected by the capacity reduction. We again used the triangular distribution from Stewart et al. (2018) to randomly apply capacity reductions, resulting in a reduction in capacity between 40 and 100% for those components that received a capacity reduction. Since deterioration was modeled using a reduction of connection capacity, it was assumed to represent both metal and wood degradation.

We accounted for uncertainty in the component values through a Monte Carlo simulation, where component capacities were assumed to be normally distributed. We refer the reader to Venable et al. (2021) for further details on how component capacities were determined and the distribution parameters specific to each component.

5 Findings

In this section, we discuss the effects of housing typology characteristics on the overall wind performance and show the effect of design modifications on performance. For each house typology assessed, we quantified the median wind speed at which roof failure occurred. This median wind speed is the 3-s gust wind speed at which failure occurs in 50% of the Monte Carlo realizations, determined separately for each possible roof failure mode. The failure mode with the lowest median wind speed failure is referred to as the *governing failure mode* for that house. The governing failure mode is important because it indicates which component or system is likely to fail first in each house and because some governing failure modes are more severe than others.

All four of the base housing typologies are expected to have failures occur at wind speeds much lower than those experienced in Hurricane Maria, failing even in a Category 1 storm. For these base typologies, the initial governing failure mode was roof panel loss due to fastener tear-through. Three of the four typologies failed in the same way at the same wind speed of 85 mph (137 kph) because they have identical gable roof structures. For the fourth typology, *Hip 1*, the governing failure mode was the same, but this occurred at a slightly higher wind speed of 92 mph (148 kph), due to the hip-shaped roof. For these typologies, wall failures were not governing, and walls were much less vulnerable than roofs. These findings were consistent with post-hurricane observations and reconnaissance reports, which indicated that many houses were missing roof panels after Hurricane Maria (FEMA 2018a).

After we analyzed the four base house typologies, we made alterations to one component at a time in each typology, based on the variations listed in Table 2. We quantified the percent change in the median wind speeds at failure to interrogate the performance of these modifications. When a building's design was improved to the point that its median wind speed at failure occurred at a higher wind speed than the median wind speed of another failure mode, the governing failure mode for the house changed. For example, as fasteners were modified, the wind speed associated with the fasteners' failure mode exceeded that of the failures at the truss-to-wall connection, changing the governing failure mode to the connections between trusses and walls. We refer to changes in design that change the governing failure mode as *sufficient modifications*. The concept of *sufficient modifications* enables a systems perspective to examine how governing failure could change, in some cases to a more severe failure. For example, if the panels are the first component to fail in the roof, due to tear-through at the fasteners, repair to the roof would require replacement of the lost panels. However, if there is a failure at the connection of the truss and wall, the entire roof system is lost. Thus, although the initial governing failure mode indicates the panel-fastener interface should be improved, improvements should not be made that result in a more severe governing failure, without corresponding upgrades elsewhere.

5.1 Roof system changes for wind performance improvement for existing roofs

Due to the high cost of complete roof reconstruction or replacement, we first examine feasible modifications to *existing* as-built roofs. Here, we outline the various failure modes associated with roof system failure and the effect of potential modifications on these failures, as well as the wind speed at which they occur.

5.1.1 Effects of fastener-panel interface

Given the characteristics of the gable roof on three of the four base house typologies, the governing failure was loss of roof panels due to fastener tear-out, which occurred at a median wind speed of 85 mph (137 kph). Considering this governing failure mode, several design/construction decisions can potentially improve the performance at this interface, including reducing fastener spacing, changing fastener type, choosing a thicker-gauge roof (CGI) panel, and choosing a different panel shape. Figure 4 shows the component changes that can be made to this interface, as well as their impact on the median wind speed at which the panels fail due to faster tear-out, as compared to the base case of the *Gable 1* house typology.

Figure 4 shows only the *sufficient modifications*, which include reducing fastener spacing on interior purlins, using thicker CGI (24-Gauge), using umbrella nails, and using

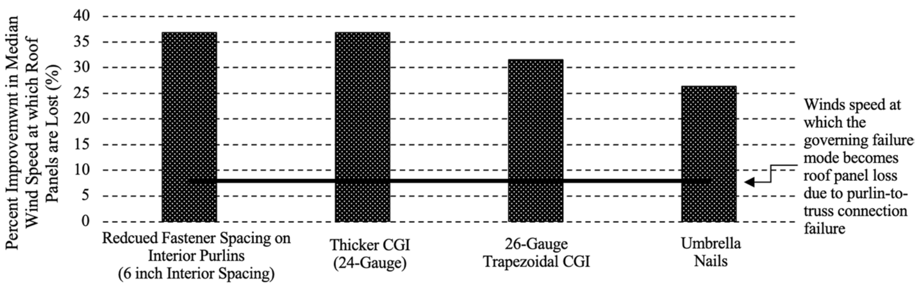

Fig. 4 Changes to median wind speed at which roof covering is lost due to modifications at the panel-fastener interface on roofs. Note: Percent improvement from base case failure for *Gable 1* at 85 mph (Base structure: 12 in interior/6 in exterior spacing of fasteners, 26-Gauge CGI, corrugated metal, standard nails)

26-Gauge Trapezoidal CGI. These materials are widely available in most hardware stores and therefore are feasible modifications to this interface. Trapezoidal CGI is commonly recommended by local builders and hardware stores; we hypothesize that it has superior performance in part because of the flat area where fasteners are attached. These all change the failure mode to roof covering loss due to failures at the purlin-truss connections. Thus, the improvement possible in roof performance is only 8% (or up to 92 mph), unless improvements are also made to the purlin-truss connections. In other words, the panels will start failing due to the purlin-to-truss connections before the full level of improvement from these modifications can be observed. However, the overall safety of the roof system can be bettered, given other component improvements.

5.1.2 Effect of purlin-to-truss connections

When the panels or the fasteners undergo any one of the changes shown in Fig. 4, panel loss due to the purlin-to-truss connections becomes the governing failure mode. These types of connections were assumed to be nailed in the base typology and can be improved by using a wooden cleat or a hurricane strap at the connection. Cleat performance depends upon the diameter of the nail used in the cleat connections. Figure 5 shows at least a 0.25 inch (6.4 mm) or greater diameter nail in a wooden cleat connection or use of a hurricane strap results in a change in the governing failure mode to the truss-to-wall connection (which occurs at a median wind speed of 101 mph (162 kph)).

5.1.3 Effect of truss-to-wall connections

Field observations and interviews revealed that some houses with concrete/masonry walls and a wooden roof do not have any truss-to-wall connections at all; the roof just rests atop the walls. In this case, this connection would be the first to fail, and adding a connection, even if it is just a nailed connection, is a top priority for improving the house's wind performance. Even in houses that do have a nailed connection, these results indicate the improvement of the truss-to-wall connection is a top priority due to the catastrophic nature of this failure that results in the loss of the entire roof structure. Like the purlin-to-truss connection, possible improvements to the truss-to-wall connection include replacing the nailed connection with a wooden cleat connection or a hurricane strap. Relative to a case with a toe-nailed truss-to-wall connection, a wooden cleat performs 36% better, and the hurricane strap performs 62% better.

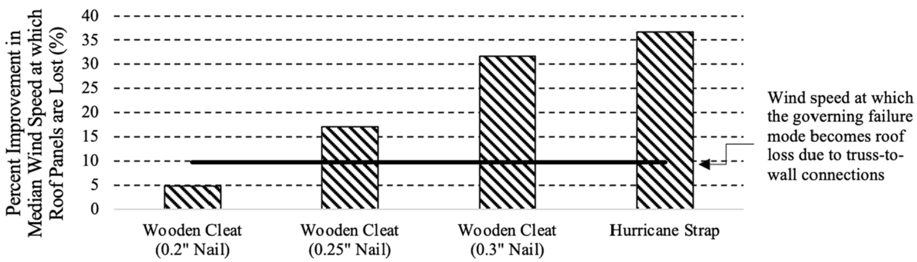

Fig. 5 Changes to median wind speed at which roof covering is lost due to modifications at the purlin-to-truss connection. Note: Percent improvement from the previous case at 92 mph (Base structure: nailed purlin-to-truss connections)

5.1.4 Effect of material deterioration

Corrosion of the metal CGI panels affects fastener behavior, with increased corrosion and deterioration causing tear-out failures to occur at lower wind speeds. In the case of moderate CGI panel corrosion, the median wind speed at which roof panels were lost decreased by 29% when compared to the case with no corrosion; this percent decrease grew to 34% in the case of severe corrosion. The main way to address CGI panel corrosion is to replace roof panels that have been corroded, which is possible on an existing roof structure. Furthermore, thicker-gauge CGI panels and the use of umbrella nails as fasteners would decrease the negative impact of CGI corrosion. The thickness of the thicker-gauge CGI allows for the panels to maintain strength even when some corrosion occurs at the faces of the panel, thus improving performance, and the wide head of the umbrella nail resists tear-out, even if the CGI is partially corroded.

We examined cases of mild and severe wood deterioration, which affected all connections within the roof system. On average, moderate wood deterioration caused median wind speeds at failure to decrease by 15%, and in the case of severe wood deterioration, 22%.

5.1.5 Combined effect of modifications to an existing gable roof

Given the above modifications, the performance of an informally constructed house can be greatly improved in a wind event. Median wind speeds at roof failure can be delayed from 85 mph (137 kph) to 107 mph (173 kph) (moving from failure expected in a Category 1 storm to almost a Category 3 storm) if all of the above improvements are undertaken, including changing fastener type and spacing, CGI type and gauge, and installing hurricane straps at purlin-to-truss and truss-to-wall connections. The governing failure mode given these improvements is panel loss due to failures of the hurricane straps at the purlin-to-truss connections. Although these failures still occur below the wind speeds experienced in Hurricane Maria, their combined improvement would have a significant effect in future storms with lower wind speeds.

5.2 Roof system changes for wind performance improvement for new or reconstructed roofs

Other roof design variations that will influence performance, such as purlin and truss spacing, roof shape and slope, and eave size and placement, are more substantive and impractical for existing roofs. These characteristics are more likely to be changed during the design process when newly constructing or reconstructing a roof.

5.2.1 Effect of roof member spacing

We considered three variations in purlin and truss spacing to determine the effect of roof member spacing on roof system performance, with results provided in Fig. 6. Overall, decreasing the spacing between roof members results in performance improvement at the panel-fastener interface, the purlin-to-truss connection, and the truss-to-wall connection because of greater load distribution. In the base case with all else equal, reducing spacing increased wind speed at governing failure up to 107 mph (173 kph).

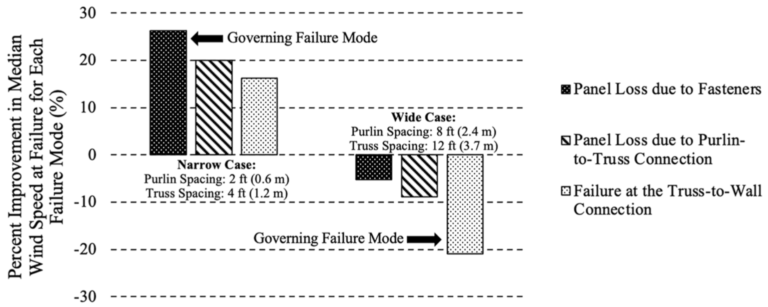

Fig. 6 Changes to median wind speed at which various failure modes occur due to modifications in purlin and truss spacing. Note: Percent improvement from base case at 85 mph (Base structure: 4 ft purlin spacing, 6 ft truss spacing)

Conversely, if purlin and truss spacings are larger than that in the base gable roof, premature truss-to-wall connection failures may occur at a median wind speed of only 76 mph (122 kph).

5.2.2 Effect of roof shape and slope

Changing the shape of the roof from a gable roof to a hip roof improves the performance of all significant roof components by reducing the wind uplift demands, including on panel-fastener interfaces, purlin-to-truss connections, and truss-to-wall connections. The initial governing failure mode in the hip roof – panels due to fastener tear-through – was the same as the gable roof, but all else equal in the base typology cases, wind speed at median failure of the panels due to fastener tear-out increased by 8% from the gable case to the hip case. Regardless of the quality, eave size, member spacing, slope, etc., hip roofs were able to withstand higher wind speeds.

With improvement to the panel-fastener interface (through the strategies shown in Fig. 5), the governing failure mode in the hip roof becomes the truss-to-wall connection. This order of failure, which contrasts that observed for the gable roofs, is significant, as improving the panel-fastener interface in a hip roof without improving other components could potentially lead to complete roof system loss. The truss-wall connection failure mode is potentially catastrophic, pointing to the importance of cleat or hurricane straps connections at these locations.

Considering roof slope, all else equal, a roof with a 28° slope outperformed a roof with a 21° slope, which in turn outperformed a roof with a 15° slope because of lower wind pressure coefficients associated with gable roofs with a pitch between 28° and 45° according to ASCE/SEI 7–16 (ASCE/SEI 2016). The improvements in median wind speed are consistent in both the gable and hip roof cases. However, we did not test roofs above 28° because they are impractical and not found in Puerto Rico, and we expect that even steeper roofs may actually perform worse.

5.2.3 Combined effect of modifications to newly constructed or reconstructed roof

These results show that the performance of an informally constructed house can be greatly improved in a wind event. Given the above modifications, which include a hip roof shape, decreased spacing between the purlins and trusses, and a higher roof slope, in addition to the modifications to each of the connections discussed for existing roofs, the median wind speed at which the governing failure occurs can be delayed from 85 mph (137 kph) to 166 mph (267 kph), or a Category 4 hurricane. Roof slope has the smallest impact on this value; if all modifications except roof slope are adopted, median wind speed at governing failure remains high, at 161 mph (259 kph). In both of these cases, the governing failure is the truss-to-wall connections. Although this is a more severe failure mode than the failure of the panels, the failure of this component is occurring at wind speed comparable to gust wind speeds in Hurricane Maria, so we believe these modifications to be beneficial, despite the severity of the failure mode.

5.2.4 A note on eaves

We also considered variations in the size and placement of the eaves, i.e., the roof overhangs. As expected, results in Fig. 7 showed that larger eaves caused the median wind speed at roof failure to decrease due to larger pressures, whereas having smaller eaves, or no eaves at all, resulted in improved performance. Changing the eave length increased the uplift on the panels and affected the wind speed at which panels were lost (due to either the purlin-to-truss connections or fastener tear-through). Eave size did worsen the performance of the truss-to-wall connections, but these changes were minor when compared to the effect on the panel failures, because of the greater tributary area of loads on the truss-to-wall connections.

Although the reduction in eave size, or better yet the elimination of eaves, would be beneficial in the structural performance, eaves protect against water intrusion and provide shade. In addition, the space under the eaves is often used for social gatherings, cooking, and other cultural activities, and households elsewhere have been found to be reluctant to eliminate eaves due to these benefits (Venable et al. 2021). Therefore, rather than suggesting the elimination or reduction in eaves, which we have assumed to be infeasible, this study instead suggests methods that strengthen other roof components to resist the increased uplift forces found in housing with eaves.

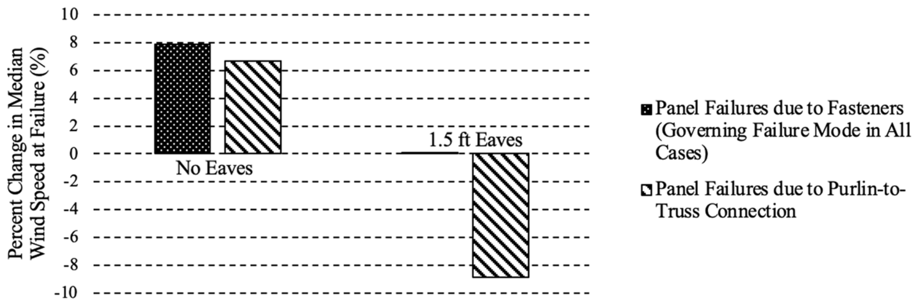

Fig. 7 Changes to median wind speed at which various failure modes occur due to modifications in eave size. Note: Percent improvement from base case (Base structure: 0.5 ft eaves on all sides)

5.3 Wall system changes

In-plane wall failures of plywood walls with no extra bracing in a one-story house occur initially at 170 mph (273 kph), which is a much higher wind speed than initial failures of any other components, even with the most-improved roof conditions tested in this study. Therefore, these wall failures are very unlikely. Adding in-plane wood diagonal members would further improve wall performance by 22%, increasing wall failure median wind speeds to 207 mph (333 kph).

Venable et al. (2021) found that over-strengthening of roofs could have the adverse effect of leading to complete collapse of homes due to wall failures. The findings of the present study differ for one-story houses, as roof failures, even in improved cases, still occurred at wind speeds lower than any wall failures. The difference between these two findings is likely due to the wall materials commonly used; plywood, which is the most common in Puerto Rico, greatly outperforms amakan, which is a woven-bamboo material, which is common in the Philippines (Venable et al. 2021). These results suggest that improvements to the roof system and roof connections for one-story houses are a higher priority than improvements to the walls in informally constructed Puerto Rican houses.

For the two-story house (Gable 2), the median speed at wall failure is 148 mph (238 kph), meaning that in almost all cases, roof component failures will govern. However, in the case of the most-improved roof, in which initial failures occur at 166 mph (267 kph), wall failures could potentially govern. Thus, substantial roof improvements in two-story houses should not be undertaken unless in-plane wood diagonal members are included.

Similarly, in cases of unreinforced masonry walls with no ring beam at the top of load-bearing walls, uplift failures can occur. Nevertheless, even in this case, uplift failures occur at wind speeds of 141 mph (227 kph), which is after roof failures in the majority of cases tested. However, this failure mode could occur if the roof is improved through greatly improved CGI panels, fasteners, purlin-to-truss connections, and truss-to-wall connections. Substantial roof improvements in masonry houses therefore should not be undertaken unless a ring beam is provided at the top of the walls or the masonry wall is reinforced.

6 Discussion and recommendations

The findings of this study point to some feasible, actionable recommendations for improving the performance of informally constructed houses in wind events, with a focus on roofs. These recommendations can be split into two categories: modifications to existing roof structures (Table 4) and design/construction details for new or reconstructed new roof structures (Table 5). These lists are prioritized based on modification importance, considering the wind performance (median wind speed at which the governing failure occurs) and the resulting severity of failure. We also assess the feasibility of the modification by providing relative cost estimates. These cost estimates are obtained from cost data from local hardware stores and informal builders across Puerto Rico, collected by local research assistants, along with information from *RS Means* construction estimating software (RSMeans 2021) based on material costs for construction in San Juan, Puerto Rico using 2021 USD. Although RS Means costs are for formal construction processes, they provide insight into relative cost differences.

Table 4 Prioritized modifications to existing roof structures

Prioritized modifications to existing roof structures	Rough cost estimates corresponding to recommended modifications
1. Strengthen truss-to-wall connections. Avoid using toe-nails to attach the truss-to-wall, as well as cases in which the roof sits atop the walls with no connection. Hurricane straps are recommended	Cost of installing hurricane straps at every truss-to-wall connection when trusses are at 4 foot spacing: ~ $40.00 (materials only)
2. Strengthen purlin-to-truss connections. Particularly if fastener spacing, type, or panel gauge has been improved, weak purlin-to-truss connections are often the governing failure mode. Hurricane straps are recommended, but if they are not available, using a cleat connection with a nail with a diameter of at least 0.2 inches (5.1 mm) will improve performance	Cost of installing hurricane straps at every purlin-to-truss connection with 2ft purlin and 4ft truss spacing: ~ $40-$50/house (materials only)
3. Improve the panel-fastener interface	
A. Reduce fastener spacing to 6 in (0.15 m) on interior and exterior purlins. Regardless of the type of nail and the head diameter, reducing the spacing of the fasteners improves performance of roof panels	A. Cost difference between improved fastener spacing of 6 in interior and exterior, rather than standard fastener spacing of 6″ interior and 12″ exterior: Under $5 (materials only)
B. Install 26-Gauge CGI or thicker. This change, or better yet, the use of 24-Gauge CGI, can greatly improve the behavior of panel-fastener interface, which is commonly the governing failure mode. Making this change also reduces the potential impacts of panel corrosion and deterioration	B. Cost of 26-Gauge CGI panels for base houses: $400-$500/house (materials only)
C. Use umbrella nails to fasten panels to purlins. The switch to the greater head diameter of the nails used greatly reduces the risk of panel loss	C. Cost difference between 26-Gauge standard CGI roofing panels and 26-Gauge standard CGI roofing panels: $5/panel or $150-$200/house (materials only)
D. Install trapezoidal instead of corrugated metal roof panels. Trapezoidal panels outperform corrugated panels, all else equal	D. Cost difference between 26-Gauge standard CGI roofing panels and trapezoidal panels: $250-$350/house (materials only)
E. Replace roof panels when corroded or paint with rust-resistant protectant. Corrosion and rust can lead to greatly decreased strength and performance and can be prevented by painting or by replacing roof panels regularly	E. See costs listed for improvements B and D, roof panels often replaced every 10–15 years

When modifying existing roofs to improve performance, there are three main target areas: truss-to-wall connections, purlin-to-truss connections, and panel-fastener interfaces. In each of these cases, there are several possible improvements, as shown in Table 4. Our findings suggest that the changes to these components should be addressed in the prioritized sequence shown in Table 4 to avoid inadvertently increasing the severity of the governing failure mode (e.g., leading to the loss of the entire roof structure rather than a single panel). Most of these changes are relatively inexpensive (from a materials cost perspective), except for buying thicker metal roof panels and replacing them more often. In addition, modifications to existing roof structures can be made to improve performance with minimal requirements for specialized skills and tools.

For the construction or reconstruction of roofs, the recommendations for the truss-to-wall connections, the purlin-to-truss connections, and the panel-fastener interface in

Table 5 Prioritized recommendations for the construction of new roof structures

Recommendations for the construction of a new roof structure	Rough cost estimates and requirements corresponding to recommendations
1. *Reduce spacing between purlins and between trusses.* Regardless of component variations used, reducing the spacing between purlin and truss members improves roof performance. Reducing spacing of purlins and trusses to at most 2 ft (0.6 m) and 4 ft (1.2 m), respectively, is preferred	Cost difference between a house with purlin spacing of 2 ft, rather than 4 ft: \$80–85/house*; Cost difference between a house with truss spacing of 4 ft, rather than 6 ft: **\$200–250*** **Including labor costs from RS Means (2021)*
2. *Use a hip roof instead of a gable roof.* Reduced wind pressures on a hip roof lead to overall reductions in demand and improved component performance	Hipped roofs cost more than gable roofs and require more construction experience and training to build
3. *Increase the roof slope for both gable and hip roofs when possible.* Roofs with slopes up to 28° outperformed lower slope roofs, all else being equal	Higher roof slopes cost more than lower roof slopes due to the greater material quantity required
4. *Replace wood members when necessary.* Wood deterioration was shown to reduce performance, and can be prevented through replacement of deteriorated members with treated wood members	Several informal contractors indicated wooden roof materials needed to be replaced every 10–15 years

Table 4 still apply, in addition to the recommendations listed in Table 5. These more substantial modifications, which address member spacing, roof slope, roof shape, and wood deterioration can lead to additional improvements in the performance of these types of houses. The most affordable option is to provide additional purlin or truss lines.

Although the results revealed that the most substantially improved roof performance would result from combining all modifications and recommendations listed in Tables 4 and 5, we aim to display these results in a way that allows individuals to prioritize specific modifications when they are financially or otherwise unable to combine all modifications and recommendations. In other words, individual modifications and recommendations in the order shown in Tables 4 or 5 will still improve performance if builders are unable to complete all of those listed.

Material costs, and even material and labor costs, are only one measure of the feasibility of the improvements. Several of these modifications, for example, construction of a hip roof, require additional construction expertise and tools. In addition to costs, our fieldwork indicates that other factors, such as material availability and lack of training on hazard-resistant housing construction practices, may be barriers to these modifications.

7 Limitations

The most crucial of the study's limitations are as follows. First, informally constructed housing is neither uniform across a specific region nor regulated. Thus, this study does not evaluate the structural performance of any particular house in Puerto Rico, but instead makes assumptions based on our fieldwork related to housing design details and component variations to capture the wide range of different housing types, as well as variations between those housing types. In addition, the wind performance assessment is based on static wind pressures and does not consider load redistribution after failure. Finally, the cost estimates do not include regional differences in cost or information regarding the specialized tools or skills required from builders to change their specific design and construction practices.

8 Conclusions

In this study, we established and tested the wind performance of four housing typologies representing informal construction practices in Puerto Rico. We used a component-based static wind performance assessment method to identify the median wind speeds at which these failures occurred, as well as how design and construction modifications affect these wind speeds. There is limited past research that has formally evaluated the safety and performance of informally constructed housing using structural analysis or performance-based engineering. Furthermore, although reconnaissance reports and previous wind assessments provide insight into structural vulnerabilities and types of failure, they do not evaluate the effect of potential modifications or make recommendations for improved wind performance. To address this knowledge gap, this study contributes information on the performance of houses built through informal construction practices under wind loads and the effects of potential modifications.

We find that roof failure modes generally occurred at lower wind speeds than wall failures in both wood-frame houses with plywood walls and those with unreinforced masonry walls, occurring at wind speeds corresponding to even a Category 1 storm. Performance of existing roofs can be improved by installing hurricane straps at truss-to-wall and purlin-to-truss connections and improving the panel-fastener interface by reducing fastener spacing, installing a thicker panel, using umbrella nails, or using trapezoidal panels. We recommend prioritizing the truss-to-wall connections first due to the severity of this failure mode, followed by the purlin-to-truss connections, then the panel-fastener interface. Modifications to existing roof structures like these can be made to improve performance for a relatively low cost with minimal requirements for specialized skills and tools. During construction or reconstruction, roof performance can be improved by reducing spacing between purlins and between trusses, using a hip roof shape, and increasing the roof slope when possible. With these changes, the roofs studied can withstand wind speeds corresponding to a Category 4 storm.

Extensive roof improvements can result in masonry uplift failure in unreinforced masonry houses without a ring beam and wall failure in two-story houses with plywood walls. Wall failures are more severe of a failure mode, and thus, substantial roof improvements in an unreinforced masonry houses and two-story plywood houses should not be undertaken unless the wall structure is also improved.

This study shows the improvement in hurricane wind performance possible for informally constructed houses, either in the renovation or construction of a roof. Past work on housing performance has mostly focused on the types of housing found in high-income countries, and the modifications and construction techniques that are available in these locations are oftentimes not feasible in areas with fewer resources. The house typologies examined in this study were based on field observations, informational interviews, and reconnaissance reports specifically focused on Puerto Rico to reflect the context-specific nature of impacts and produce effective, targeted recommendations, as described by

Méheux et al. (2007). These results, which will be shared with local, community-based organizations and community members, provide actionable, affordable, and realistic modifications that can be implemented to make informally constructed houses safer and more resilient to hurricanes as a form of climate adaptation.

In addition, we observe that informally constructed housing typologies we studied are prevalent across much of the Caribbean (FEMA 2018b; Build Change 2016). Prevatt et al. (2010) provides data on houses on six Caribbean islands, revealing significant similarities between informally constructed homes with those studied here, including low sloped gable roofs, wood exterior walls, metal roof panels fastened using nails, and wooden purlins and trusses, which are typically toe-nailed. These similarities in housing typologies and materials indicate that although the typologies and results were developed for Puerto Rico, the recommendations and prioritization may be applicable in similar types of housing across the Caribbean.

Acknowledgements We thank our research assistants, Yarelis González, Juneilis Mulero Oliveras, and Nicolle Teresa Ramos, and also Tracy Kijewski-Correa, Polly Murray, Yesenia Rosario Ramos, and Hailey Rae Rose.

Authors' Contributions M. Lochhead, C. Venable, and A. Liel led the study concept and design. Material preparation, data collection, and analysis were performed by M. Lochhead, B. Goldwyn, A. Liel, and A. Javernick-Will. The first draft of the manuscript was written by M. Lochhead and B. Goldwyn and all others commented on subsequent versions. All authors read and approved the final manuscript.

Funding This study is supported by the US National Science Foundation Award No. 1901808 and a University of Colorado Innovative Seed Grant. The opinions, findings, and conclusions expressed in this study are those of the authors and do not necessarily reflect the National Science Foundation.

Data Availability Detailed results are available from the first author, upon request.

Declarations

Conflicts of Interest The authors declare that they have no conflict of interest.

Code Availability MATLAB code files for wind analysis are available from the first author, upon request.

Ethics Approval The fieldwork described herein was approved through the University of Colorado IRB.

References

Acevedo N (2018). FEMA has either denied or not approved most appeals for housing aid in Puerto Rico. *NBC News*

Alam M, Alam K, Mushtaq S (2017) Climate change perceptions and local adaptation strategies of hazard-prone rural households in Bangladesh. Clim Risk Manag 17:52–63

ANSI/AWC (2015) National design specification for wood construction *2015 Edition.* American wood 623 council, Leesburg, VA

ASCE/SEI (2016) Minimum design loads and associated criteria for buildings and other structures. ASCE/SEI 7–16, Reston, VA

Bright N,Roberts J (2005). The treatment of concentrated loads in masonry design codes. In: 10th Canadian masonry symposium, Banff, Alberta

Brown N (2018). Special report: In Puerto Rico, a Housing Crisis US. Storm Aid won't Solve. *Reuters*

Build Change (2014) Post-disaster reconnaissance report: damage assessment and housing and markets survey 2013 Bohol Earthquake and Typhoon Yolanda. Build Change, Philippines

Burgess CP, Taylor MA, Spencer N, Jones J, Stephenson TS (2018) Estimating damages from climate-related natural disasters for the Caribbean at 1.5° C and 2° C global warming above preindustrial levels. Reg Environ Change 18(8):2297–2312

Castañeda A, Howland JJ, Corvo F, Pérez T (2013) Corrosion of steel reinforced concrete in the tropical coastal atmosphere of Havana City, Cuba. Química Nova 36(2):220–229

Change Build (2016) Post-disaster reconnaissance report: hurricane matthew. Build Change, Puerto Rico

Cheng J (2004) Testing and analysis of the toe-nailed connection in the residential roof-to-wall system. For Prod J 54(4):58–65

CRED, and UNISDR (2018) Economic losses, poverty, and disasters 1998–2017. UNISDR, Geneva

Cruzado HJ, Pacheco-Crosetti GE, (2018) General overview and case studies of damages in Puerto Rico Due to Hurricane Maria. *Forensic Engineering 2018*, Austin, Texas, 986–996

Doudak G, Smith I (2009) Capacities of OSB-sheathed light-frame shear-wall panels with or without perforations. J Struct Eng 135(3):326–329

Edmond C (2020) These are the top risks facing the world in 2020. World Economic Forum, Davos, Switzerland

Ellingwood BR, Rosowsky DV, Li Y, Kim JH (2004) Fragility assessment of light-frame wood construction subjected to wind and earthquake hazards. J Struct Eng 130(12):1921–1930

Enterprise Community Partners. (2019). Guía para la Protección y Construcción de Viviendas Resistentes a Huracanes en Puerto Rico

Erikson RG, Schmidt RJ (2003) Behavior of traditional timber frame structures subjected to lateral load department of civil and architectural engineering. University of Wyoming, Laramie, WY, pp 1–229

FEMA. (1999). Building performance assessment report - Hurricane Georges in Puerto Rico: observations, recommendations, and technical guidance

FEMA. (2018a). Mitigation assessment team report. Hurricanes Irma and Maria in Puerto Rico: building performance, observations, recommendations, and technical guidance

FEMA. (2018b). Mitigation assessment team report. Hurricanes Irma and Maria in the US. Virgin Islands: building performance, observations, recommendations, and technical guidance

Ginger J, Henderson D, Edwards M, Holmes J, (2010). Housing damage in windstorms and mitigation for Australia. In: Proceedings of 2010 APEC-WW and IG-WRDRR joint workshop: wind-related disaster risk reduction activities in asia-pacific region and cooperative actions, Incheon, Korea, 1–18

Goldwyn B, Javernick-Will A, Liel A (2021) Dilemma of the tropics: changes to housing safety perceptions, preferences, and priorities in Multihazard environments. Nat Hazard Rev 22(3):04021012

Henderson D, Williams C, Gavanski E, Kopp G (2013) Failure mechanisms of roof sheathing under fluctuating wind loads. J Wind Eng Ind Aerodyn 114:27–37

Hendricks E, Luyten L, Parrack C (2018) Knowledge exchange and adoption to enable safer post-disaster self-recovery. IDRiM J 8(2):1–23

Hinojosa J, Meléndez E, (2018). The housing crisis in Puerto Rico and the impact of Hurricane Maria. *Centro,* 24

Ibach RE, Lebow PK (2014) Strength loss in decayed wood. McGraw-Hill Encyclop Sci Technol 2014:368–371

Khan M (2012) Load-sharing of toe-nailed, roof-to-wall connections under extreme wind loads in wood-frame houses. University of Western Ontario, Ontario, Canada

Kijewski-Correa T, Kennedy A, Prevatt D, Taflanidis AA (2017). Field reconnaissance following the passage of Hurricane Matthew over Haiti's Tiburon Peninsula. In: 13th Americas conference on wind engineering, Gainesville, Florida

Kijewski-Correa T, Alagusundaramoorthy P, Alsieedi M, Crawford S, Gartner M, Gutierrez SM, Heo Y, Lester H, Marshall J, Micheli L, Mulchandani H, Prevatt D, Roueche D, Tomiczek T, Mosalam K, Robertson I (2019). StEER - Hurricane Dorian: preliminary virtual reconnaissance report (PVRR). DesignSafe-CI

Knutson TR, Sirutis JJ, Vecchi GA, Garner S, Zhao M, Kim H-S, Bender M, Tuleya RE, Held IM, Villarini G (2013) Dynamical downscaling projections of twenty-first-century Atlantic Hurricane activity: CMIP3 and CMIP5 model-based scenarios. J Clim 26(17):6591–6617

Lallemant D, Burton H, Ceferino L, Bullock Z (2017) A framework and case study for earthquake vulnerability assessment of incrementally expanding buildings. Earthq Spectra 33(4):1369–1384

Li Y, Ellingwood BR (2006) Hurricane damage to residential construction in the US: importance of uncertainty modeling in risk assessment. Eng Struct 28(7):1009–1018

Li M, Lam F (2009) Lateral performance of nonsymmetric diagonal-braced wood shear walls. J Struct Eng 135(2):178–186

Liu H, Gopalaratnam VS, Nateghi F (1990) Improving wind resistance of wood-frame houses. J Wind Eng Ind Aerodyn 36:699–707
Mahendran M, Tang RB (1999) Pull-through strength of high tensile steel cladding systems. Austr Struct Eng Trans 2(1):37–50
Means RS (2021) 2021 Building construction costs book. Gordian, Greenville, SC
Méheux K, Dominey-Howes D, Lloyd K (2007) Natural hazard impacts in small island developing states: a review of current knowledge and future research needs. Nat Hazards 40(2):429–446
Mukhopadhyay P, Dutta SC (2016) Rapid visual screening of earthquake-susceptible buildings. In: Proceedings of the institution of civil engineers - Municipal Engineer, ICE Publishing, 170(2): 71–84
Mukhopadhyay P, Dutta SC (2012) Strongest cyclone of the new millennium in the Bay of Bengal: strategy of RVS for nonengineered structures. Nat Hazard Rev 13(2):97–105
NOAA (2021a) NCH data archive: past track seasonal maps. National Hurricane Center and Central Pacific Hurricane Center. https://www.nhc.noaa.gov/data/#tracks_all. Accessed 28 Aug 2021
NOAA (2021b) Saffir-simpson hurricane wind scale. National Hurricane Center and Central Pacific Hurricane Center. https://www.nhc.noaa.gov/aboutsshws.php. Accessed 28 Aug 2021
Parrack C, Flinn B, Passey M (2014) Getting the message across for safer self-recovery in post- disaster shelter. Open House Int 39(3):1–15
Prevatt DO, Dupigny-Giroux L-A, Masters FJ (2010) Engineering perspectives on reducing hurricane damage to housing in CARICOM Caribbean Islands. Nat Hazard Rev 11(4):140–150
Prevatt DO, Roueche DB, Aponte-Bermúdez LD, Kijewski-Correa T, Li Y, Chardon P, Cortes M, del Puerto CL, Mercado A, Muñoz J, Morales A (2018) Performance of structures under successive Hurricanes: observations from Puerto Rico and the US Virgin Islands after Hurricane Maria. *Forensic Engineering 2018*, Austin, Texas, 1049–1059
Puerto Rico Hurricane Center (2005a). Hurricanes and tropical storms in Puerto Rico from 1900–1979. < https://huracanado1.tripod.com/history3.html> (Accessed 28 August 2021).
Puerto Rico Hurricane Center (2005b). Hurricanes and tropical storms in Puerto Rico from 1980–2005. < https://huracanado1.tripod.com/history2.html> (Accessed 28 August 2021).
Rentschler JE (2013) Why resilience matters: the poverty impacts of disasters. World Bank, UK
Rodgers JE (2012). Why schools are vulnerable to earthquakes. In: Proceedings of the 15th world conference on earthquake engineering, Lisbon, Portugal, 24–28
Salenikovich A (2000) The racking performance of light-frame shear walls. Virginia Tech, Blacksburg, VA
Shanmugasundaram J, Arunachalam S, Gomathinayagam S, Lakshmanan N, Harikrishna P (2000) Cyclone damage to buildings and structures — a case study. J Wind Eng Ind Aerodyn 84(3):369–380
Sparks PR, Liu H, Saffir H (1989) Wind damage to masonry buildings. J Aerosp Eng 2(4):186–198
Stewart MG, Ginger JD, Henderson DJ, Ryan PC (2018) Fragility and climate impact assessment of contemporary housing roof sheeting failure due to extreme wind. Eng Struct 171:464–475
Strong-Tie Simpson (2019) Wood construction connectors catalog 2019–2020. Simpson Strong-Tie, Pleasanton, CA
Talbot J, Poleacovschi C, Hamideh S, Santos-Rivera C (2020) Informality in postdisaster reconstruction: the role of social capital in reconstruction management in post-Hurricane Maria Puerto Rico. J Manage Eng 36(6):04020074
Thurton DAW, Sabnis G, Raval P (2012) Performance of various semi-engineered roof deck systems under high velocity winds. Scientia Iranica 20(1):34–43
Venable C, Liel AB, Kijewski-Correa T, Javernick-Will A (2021) Wind performance assessment of postdisaster housing in the philippines. Nat Hazards Rev 22(4):0401033
Vosper EL, Mitchell DM, Emanuel K (2020) Extreme hurricane rainfall affecting the Caribbean mitigated by the Paris agreement goals. Environ Res Lett 15(10):104053
Wells M (2020) Evaluating the impacts of Hurricane Maria on the residential construction industry in Puerto Rico and the effectiveness of reconstruction efforts. Theses and Dissertations. https://scholarsarchive.byu.edu/etd/8535
Zorn M (2018). Natural disasters and less developed countries. *Nature, Tourism and Ethnicity as Drivers of (De) Marginalization: Insights to Marginality from Perspective of Sustainability and Development*, Perspectives on Geographical Marginality, S. Pelc and M. Koderman, eds. Springer International Publishing, Cham, Switzerland, 59–78