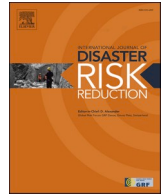




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Potential for mitigating hurricane wind impact on informally-constructed homes in Puerto Rico under current and future climate scenarios

D. Valdivieso^{a,b,c,*}, B. Goldwyn^a, A.B. Liel^a, A. Javernick-Will^a,
D. Lopez-Garcia^{b,d}, P. Guindos^{b,c,e}

^a Department of Civil, Environmental and Architectural Engineering, University of Colorado, Boulder, USA

^b Department of Structural & Geotechnical Engineering, Pontificia Universidad Catolica de Chile, Santiago, Chile

^c Centro Nacional de Excelencia para la Industria de la Madera (CENAMAD) & Centro de Innovación en Madera (CIM UC-CORMA), Santiago, Chile

^d Research Center for Integrated Disaster Risk Management (CIGIDEN) ANID FONDAP 1523A0009, Santiago, Chile

^e Faculty of Architecture and Centro de Innovación Tecnológica en Edificación e Enseñaría Civil (CITEEC), Universidade da Coruña, A Coruña, Spain

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ABSTRACT

This study investigates the resilience of informally-constructed light-frame timber houses in Puerto Rico, a region where households with limited resources face significant risks from climate hazards, notably hurricanes. This study conducts a component-based, performance-based wind engineering assessment of informally-constructed house typologies, defined based on extensive fieldwork, under both existing and projected future climate conditions. Key findings highlight the effectiveness of certain mitigation strategies, such as reinforcing roof-to-wall connections, in significantly reducing the probability of failure. Fully-mitigated cases, which involve applying mitigation measures to the roof envelope, roof-to-wall connections, and shear walls, exhibited annual probabilities of failure that are much closer to, but do not necessarily meet, the threshold targeted by American building standards (i.e., ASCE 7). The results also show a dramatic increase in probability of failure of these houses projected by the adopted climate change model scenarios, driven by the increased frequency and intensity of hurricanes in Puerto Rico. Results from feedback from those working in the informal construction sector also identify challenges hindering the effective implementation of mitigation measures in Puerto Rican communities, including a lack of knowledge about how to implement the mitigation strategies and barriers related to real and perceived costs. Taken together these results underscore the urgent need for changes in building practices and revising building standards and suggesting potentially feasible mitigation strategies to improve those practices.

1. Introduction

Worldwide, there are growing threats to housing from weather and climate disasters, jeopardizing community safety and prosperity. In 2023 alone, the U.S. experienced 28 distinct weather and climate disasters that incurred costs of at least \$1 billion, a record-

* Corresponding author. University of Colorado, 1111 Engineering Dr, Boulder, USA.

E-mail address: diego.valdivieso@colorado.edu (D. Valdivieso).

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breaking number [1]. Hurricanes, which are our focus here, and also known as typhoons and cyclones in other parts of the world, have been a major contributor to the economic impact of climate-related hazard events in the U.S., accounting for about 52 % of the total economic impacts of these events since 1980 [1]. A significant part of the economic impacts of these events comes from the destruction of or damage to homes, which has a profound and lasting impact on community recovery [2,3] and a disproportionate impact on resource-limited communities [4]. With the projected escalation of hurricane threats due to global climate change [5–9], addressing the vulnerabilities of these communities in regions prone to hazards by changing design and construction practices to mitigate these risks is crucial for fostering community resilience and reducing the impacts of future disasters.

In many places, large portions of the housing stock are constructed through informal processes. Here, we use the term “informally-constructed” to refer to housing erected by builders without formal training or by residents themselves, often with the assistance of friends and family. This form of construction stems from households’ efforts to address personal housing needs within the constraints of available resources and local building practices; this construction typically occurs without the support of an architect or engineer, and typically does not align with building codes and standards [10–12]. As a result of this process, the risk perceptions of the residents, their construction knowledge, preferences and needs, and available resources play a pivotal role in shaping design and construction decisions, creating a diverse array of housing types and construction techniques, which in turn can either reduce or intensify the potential damage to the housing [2,12–15].

Over the past three decades, Puerto Rico—a U.S. Caribbean archipelago with an estimated population of more than 3 million in 2023—has experienced several catastrophic hurricanes, including Hugo, Georges, Irma, and Maria. These hurricanes caused extensive damage to millions of homes (see Fig. 1), and major disruption to everyday life [2,16]. Hurricane Fiona, which occurred in September 2022, caused significant flooding, disrupting infrastructure and transportation connectivity, as well as damaging thousands of homes, exacerbating the situation of communities still in the process of recovering from Hurricane Maria in 2017. Typical housing typologies in Puerto Rico include light-frame timber houses with corrugated metal panels as roof envelopes, as shown in Fig. 1, which are particularly vulnerable to hurricane winds [17]. Housing construction in Puerto Rico, and, likewise, post-hurricane recovery and construction efforts, are often informally-constructed, and predominantly self-initiated and funded by homeowners [15,18,19].

This study assesses the hurricane wind performance of informally-constructed light-frame timber houses in hurricane scenarios, with a specific focus on the typical informal construction styles found in Puerto Rico, examining the extent to which possible mitigation strategies can improve this performance. Our study design recognizes that the development of climate-resilient and adaptive housing needs engineering assessment that is locally grounded, community-based and interdisciplinary [2,20,21]. First, we define housing typologies that consider local building materials and building practices considering both existing practices and potential mitigation measures. We then assess the housing performance using a component-based static wind assessment procedure that considers these materials and practices and the uncertainties therein. Hurricane performance is quantified by wind structural fragility curves and the calculation of failure probabilities for both baseline and mitigated light-frame timber house typologies; these failure probabilities are determined considering both the current climate scenario and a range of projections that are anticipated to increase risks. We also explore local builders’ and hardware store employees’ perceptions of the feasibility of the mitigation measures, interrogating challenges to implementing these measures.

2. Points of departure

Light-frame residential construction accounts for the majority of single-family housing in the U.S. (e.g., accounting for 94 % of that constructed in 2022) [21–24]. These light-frame timber houses also contribute to much of the economic losses from hurricanes, which average \$5.4 billion (total direct economic losses) annually in the U.S [25]. These losses have been increasing over time, due to the growing coastal population, and climate change [26]. During hurricanes, the most vulnerable component of a light-frame timber house is typically its envelope. Damage to the envelope can result in additional harm to the interior of the building from wind and

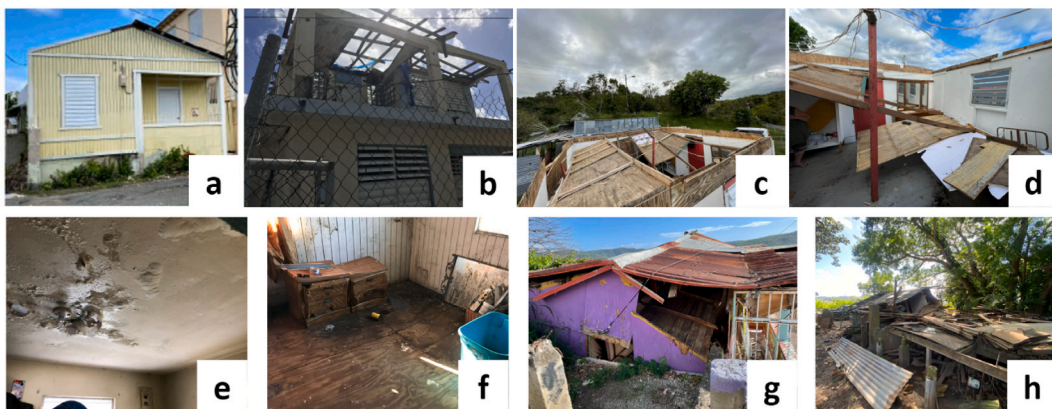


Fig. 1. (a) Example of undamaged Puerto Rican informally-constructed timber house [Photo from Polly Murray] and failure modes observed in housing structures in Puerto Rico from 2017’s Hurricane Maria: (b) roof envelope damages; (c, d) failures in roof-to-wall connections; (e, f) rain intrusion damage due to roof envelope failure; and (g, h) shear wall failures and sliding. [Photos from Emily Alfred].

wind-driven water intrusion [25,27,28]. For U.S. construction, typical envelope failure modes observed are the uplift of roof panels, failures in the connections between the roof and walls due to uplift, and the breaking of windows and doors because of intense wind pressures or debris impact [25]. Focusing specifically on the hurricane-prone state of Florida, Pinelli et al. [29] and Torkian et al. [30] confirm these results, using loss assessment to show that reinforcing the roof envelope, roof structure, roof-to-wall connections, and shear walls with uplift retrofitting are important, but more cost-effective in some parts of the state. For Australian houses, Henderson & Ginger [31] likewise showed that the majority of damage occurs in roof cladding, but that the roof structure itself is also critical. Two studies of housing in the Philippines [32,33] showed that roof panel losses due to panel or purlin connection were the critical failure mode, with some houses exhibiting structural collapse from racking failures in wood and bamboo walls, worsened by roof reinforcements that inadvertently increased vulnerability. Nishijima et al. [34] and Zhang et al. [35] similarly show that the expected failure modes in Japan also relate to the envelope, including roof tile loss, window breakage, and roof sheathing failures.

Extensive research has been conducted on the response of residential structures in the U.S. to hurricane and tornado winds, using component-based performance-based wind engineering approaches (e.g. Refs. [22,25,36–40]). These studies typically rely on established literature to quantify the capacities and demands of the key components and define performance limit states used to construct structural fragility curves. These curves, incorporating elements like the roof envelope, roof-to-wall connection, and shear walls, represent the probability of failing performance states of interest. van de Lindt & Dao [23] defined four performance states of interest for light-frame timber houses under hurricane winds as including occupant comfort, continued occupancy, life safety, and collapse prevention. Other studies have examined building performance accounting for the significant consequences of wind-driven rainwater intrusion on interior components [28,41–43]. Many of these studies confirm the findings above that the roof envelopes are critical.

Some of the past work has also assessed the performance of light-frame timber houses against certain established thresholds for performance, mostly showing that performance goals may not be met. For example, Stoner & Pang [40] explored established thresholds for acceptable failure probabilities under tornado loads, referencing threshold failure probabilities in standards such as ASCE 7, the Eurocode, and the Netherlands. The ASCE 7 Standard defining *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* [44], which is relevant for this paper because it applies to U.S. construction, sets its target annual failure probability at 3.0×10^{-5} per year. However, Stoner & Pang [40] find that residential light-frame timber housing design in 60 % of the U.S. area would fail to meet the ASCE 7 [44] threshold for tornados following current practice. They argue that reconsideration of the acceptable target probabilities may be appropriate. To assess the reliability of low-rise light-frame timber houses in hurricane-prone areas of the U.S., Li & Ellingwood [38] developed a probabilistic framework, incorporating both structural fragility models and hurricane wind hazard models. They look specifically at one-story single-family light-frame timber houses and roof panel uplift failure, roof-to-wall connection failure due to uplift, and breakage of windows and doors under excessive wind pressure as limit states. From their results, we infer that the thresholds for roof-to-wall connection (i.e., life safety) do not meet ASCE 7 [44] in most of the evaluated cases for both toe-nail and hurricane strap roof-to-wall connection types.

Climate change and coastal development are expected to significantly increase hurricane damage worldwide due to increased hurricane intensity and/or frequency [45]. Several studies have examined how climate change affects the risk of failure and other limit states at both component and community (i.e., regional) scale levels (e.g. Refs. [7,34,35,46–50]). At the component level, climate change has the potential to impact long-term structural reliability due to both increased wind speeds and degradation (e.g., carbonation, corrosion, fatigue, aging) of mechanical properties over the lifecycle of a structure [47,49]. At the regional scale, efforts have focused on developing frameworks to estimate losses, with a general consensus that climate change significantly increases community losses, and proposing models assist decision-makers in managing projected risks [7,46,48]. For example, Esmaeili & Barbato [7,8] expanded the performance-based hurricane engineering framework to include climate change effects on hazard non-stationarity, estimating structural losses due to increased hurricane risks. Their study found that the mean of the total expected losses for benchmark single-family homes in Pinellas Park, Florida, could increase by 13.2%–38.1% over a 50-year design life relative to the same case without climate change. For instance, buildings closer to the shore are likely to sustain more damage over time due to increased storm surge impacts, as rising sea levels from climate change exacerbate flooding risks compared to wind damage. Effective adaptation strategies, such as elevating buildings, can significantly mitigate future damage, potentially shifting the damage profile from flood impacts to wind impacts [50].

In Puerto Rico, housing and construction differ from that in other parts of the U.S. During recent hurricanes, envelope-related failure modes have been commonly observed in light-frame timber houses [17,27,51], as depicted in Fig. 1. Window failures are less likely due to the use of jalousie-type windows. In addition, some wall lateral and sliding failures have been observed in past hurricanes in Puerto Rico. Of these shear wall failures, the predominant failure is the lateral failure due to the shear failure of the OSB or plywood sheathing-to-wood frame connection.

There have been a few studies that examine the hurricane performance of informally-constructed houses in Puerto Rico. For instance, Lochhead et al. [52] found that the typical governing failure mode is roof panel loss due to tear-through at the fasteners used for attaching the corrugated metal panels to the roof structure. If this failure mode is avoided, failures at the purlin-to-truss connections and of the roof-to-wall connections also occur. To mitigate these issues, Lochhead et al. [52] suggested two main strategies: enhancing the attachment of corrugated metal panels to the roof structure and the installation of hurricane straps at critical connections. Using the Hazus Hurricane Model, Vickery et al. [27] further showed that utilizing hurricane straps instead of toe-nails for the roof-to-wall connection and appropriate screws instead of nails for securing the corrugated metal panels to purlins lead to a significant reduction in annualized average hurricane losses. However, these studies faced limitations due to the absence of connection-level test data for these mitigation measures, leading to approximations in the typologies of buildings considered and the failure analysis. Further, Lochhead et al. [52] did not account for the implications of progressive failure and load redistribution as per Stewart et al. [53], which are crucial

for a more accurate assessment of structural failure. Moreover, our fieldwork revealed that some proposed improvements for purlin-to-truss connections were not feasible at construction sites due to space restrictions. Thus, further research is needed to develop fragility curves considering performance levels for Puerto Rican informally-constructed house typologies, demonstrating the effectiveness of locally feasible mitigation measures for improving performance.

3. Hurricane wind performance assessment

The performance of both baseline and mitigated housing typologies, defined below, was evaluated using a component-based performance-based wind engineering approach.

3.1. Wind demands

The wind loads acting on structures were computed using the ASCE 7 [44] methods and wind pressures for low-rise buildings, consistent with the approach taken by others (e.g. Refs. [38,52,54]). We use the 3-s wind speed gust, referred to as velocity, V , as the intensity measure representing wind severity. The velocity is measured in miles per hour (mph), where 1 mph equals 0.447 meters per second (mps). From the velocity, we compute the velocity pressure at the average roof height, q_h , as detailed by Equation (1). In Eqn (1), q_h is in pounds per square foot or psf (1 psf = 47.88 N/m²).

$$q_h = 0.00256 K_z K_{zt} K_e V^2 \quad (\text{Eq. 1})$$

In Equation (1), K_z is the velocity pressure exposure coefficient, K_{zt} is the topographic factor and, K_e represents the ground elevation factor. Table 1 provides the distributions of these factors used to define the wind. The value of K_z is determined based on the structure's height and its exposure classification. Our assessment was primarily location-independent, due to the similar housing forms across the island. As such, we initially used a topography factor of 1.0 for computing wind structural fragility curves. However, to account for the acceleration effect caused by complex topography, such as hilly or mountainous landscapes, we considered topographic effects on the wind hazard, following the approach outlined by Vickery et al. [55] for Puerto Rico.

From the velocity pressure at the average roof height, we determine the wind pressures, W , on the components of the houses, as outlined in Equation (2).

$$W = q_h K_d (G C_{pf} - G C_{pi}) \quad (\text{Eq. 2})$$

In this equation, K_d is the directionality factor, G is the gust factor, C_{pf} denotes the external pressure coefficient, and C_{pi} is the internal pressure coefficient. Pressure coefficients from Chapter 28 (Main Wind Force Resisting System–Envelope Procedure) were applied for shear walls and roof-to-wall connections and from Chapter 30 (Components and Cladding) for panels, fasteners, and purlin-to-truss connections [44]. The envelope procedure considers the worst-case pressures over all wind orientations.

Based on these wind pressures, we use structural analysis to calculate the wind uplift forces on the roof panels and components and shear forces in the lateral force-resisting system, considering the compensating effects of dead loads. As components failed, the wind uplift forces were modified to account for load redistribution, recognizing the evidence provided by those on the island, including engineers, that some roof failures in Puerto Rico occurred progressively. This redistribution has two aspects: 1) reduction in internal pressures due to the loss of components of the roof envelope (in this case, the corrugated metal panels, thereby reducing loads on the remaining components; and 2) redistribution of loads from a failed component to other nearby components in the load path. To account for the redistribution, the wind pressure calculations for the components of the light-frame timber houses were refined by adapting a methodology developed by Stewart et al. [53], which was based on Henderson and Ginger [57] and Konthesingha et al.'s [58] experimental results. Initially intended for industrial buildings, this procedure has been adapted here for light-frame timber houses [58]. The approach, as developed by Stewart et al. [53], is suitable for roofs that involve the direct attachment of corrugated metal panels to purlins, which is appropriate for the construction practices observed in informally-built houses in Puerto Rico. Fig. 2a shows the assumed reduction in internal pressure on the basis of the number of failed corrugated metal panels. The only modification from the curve from Stewart et al. [53] is the starting initial C_{pi} value of 0.55 instead of 0.65. We made this modification to establish an initial C_{pi} that is consistent with ASCE 7 pressure coefficients [44]. The negative constant C_{pi} for the scenario of four or more panels failing was then scaled by a factor of $0.55/0.65 = 0.85$ times the Stewart et al. [53] model. To account for the load redistribution, when a component fails, the load is redistributed to neighboring components, as depicted in Fig. 2b. This redistribution is based on static analysis.

Table 1
Parameter values defining wind demands.

Variable	Mean Value	Coefficient of Variation	Distribution Type	Data Source
K_z	by structure	0.14	Normal	Amani & van de Lindt [39]
K_{zt}	1.0; by location	Deterministic	–	ASCE [44]; Vickery et al. [55]
K_d	0.85	Deterministic	–	ASCE [44]; Stoner & Pang [56]
K_e	1.0	Deterministic	–	ASCE [44]; Stoner & Pang [56]
$G C_{pf}$	by panel	0.12	Normal	Amani & van de Lindt [39]
$G C_{pi}$	0.55 (partially enclosed)	0.33	Normal	ASCE [44]; Lee & Rosowsky [37]
Dead load	by component	0.10	Normal	ASCE [44]; Lee & Rosowsky [37]

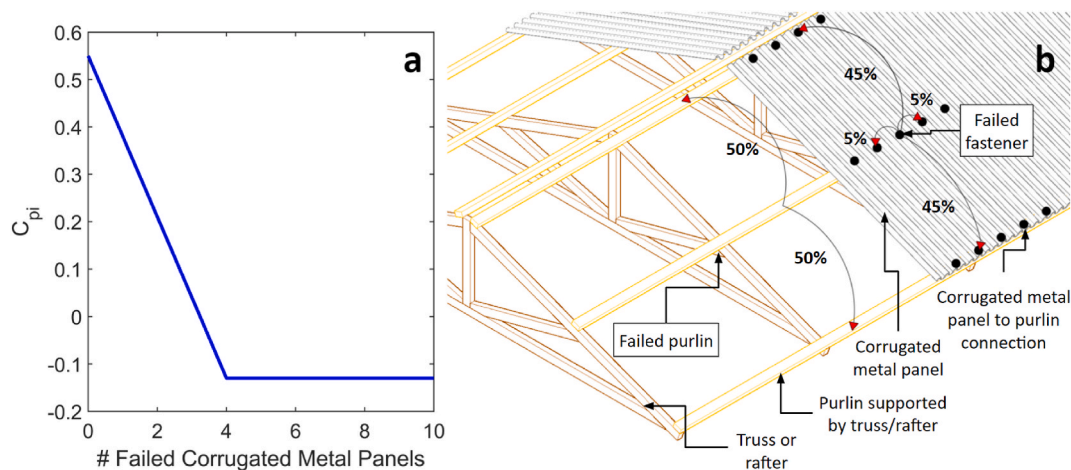


Fig. 2. Implemented methodology for (a) reducing the internal pressure coefficient, C_{pi} , in response to failed corrugated metal panels in roof envelope, and (b) redistributing load on corrugated metal panels-to-purlins connections and purlins after failure of a purlin or fastener.

3.2. Components and component capacities

The wind loads are used to determine whether the components of interest, namely fasteners, roof panels, rafters, purlins, roof trusses, roof-to-wall connections, and/or shear walls have failed, by comparing the demand and capacity. These components are considered because they are linked to specific hurricane failure modes of housing that have been observed in Puerto Rico and elsewhere. To determine the component capacities (defined in Table 2), we built on Lochhead et al. [52] and sourced data on component capacities from the existing literature. In addition, we conducted additional tests to refine the capacities used for hurricane straps with different fastener arrangements (see Fig. 3). We also gathered test results provided by Simpson Strong-Tie, to characterize the capacities of the hurricane straps with other fastener arrangements and screwed roof-to-wall and purlin-to-truss (or rafter) connections. Simpson Strong-Tie is the leading supplier of hurricane straps in the region.

3.3. Performance assessments

The outcome of this study is an assessment of hurricane performance for baseline and mitigated housing typologies, represented by a set of fragility curves and, subsequently, an assessment of the annual probability of failure, which can be compared to target risk

Table 2
Parameter values defining component capacities.^a

Variable	Component	Mean Value	Coefficient of Variation	Distribution Type	Data Source
Wood strength	Bending	$F_b = 7.2$ ksi	0.16	Normal	ASTM [59]
	Shear	$F_s = 0.9$ ksi	0.15	Truncated ^g	
Corrugated metal panel to purlin connections ^{b,c}	by limit state		0.40–0.25	Normal	Tear-out capacity (Mahendran et al. [60]); Pull-out capacity (Thurton et al. [61]), COV (Li & Ellingwood [38]; Stewart et al. [62])
Purlin-to-truss ^d connections	Cleat	by calculation	0.40	Normal	ANSI/AWC NDS [63]
	SDWS22500 ^e	0.5 kip	0.10	Truncated ^g	
Roof-to-wall connections	Toe-nailed	0.3 kip	0.30	Normal	test data provided by Simpson Strong-Tie Cheng [64]
	Hurricane Strap	1.7 kip	0.10	Truncated ^g	Test data from authors (Fig. 3) and/or provided by Simpson Strong-Tie
Shear wall Strength	SDWC15600 ^f	1.9 kip			Test data provided by Simpson Strong-Tie
	Baseline case (Table 5)	0.16 klf	0.12	Normal	Test data as per report N-191 Vasquez et al. [65], Doudak and Smith [66]
	Mitigated case (Table 5)	0.90 klf		Truncated ^g	ANSI/AWC SDPWS [67], Valdivieso et al. [68]

^a Unit conversion: 1 ksi = 6.895 MPa; 1 kip = 4.448 kN; 1 klf = 14.594 kN/m.

^b Our assumption considered the likelihood of improper fastener installation during construction. Specifically, we estimated that around 3 % of all fasteners might not align correctly with the purlin, thereby diminishing their capacity. Following Stewart et al. [62], we modeled this scenario using a triangular distribution, where a misaligned fastener has a mean capacity 80 % lower than a correctly installed fastener.

^c The failure of corrugated metal panel-to-purlin connections is contingent upon assessing the uplift limit state, which is based on the tear-out and pull-out capacity of the connection.

^d These values also apply to purlin-to-rafter connections.

^e Timber screw with a 0.22 in (5.6 mm) shank diameter, 5 in (127.0 mm) in total length, and 3 in (76.2 mm) of thread length.

^f Fully-threaded screw with a shank diameter of 0.155 in (3.9 mm) and a length of 6 in (152.4 mm).

^g To prevent negative values in component capacity, a normal truncated distribution was employed, which cuts off at zero capacity, while maintaining a valid probability density function.

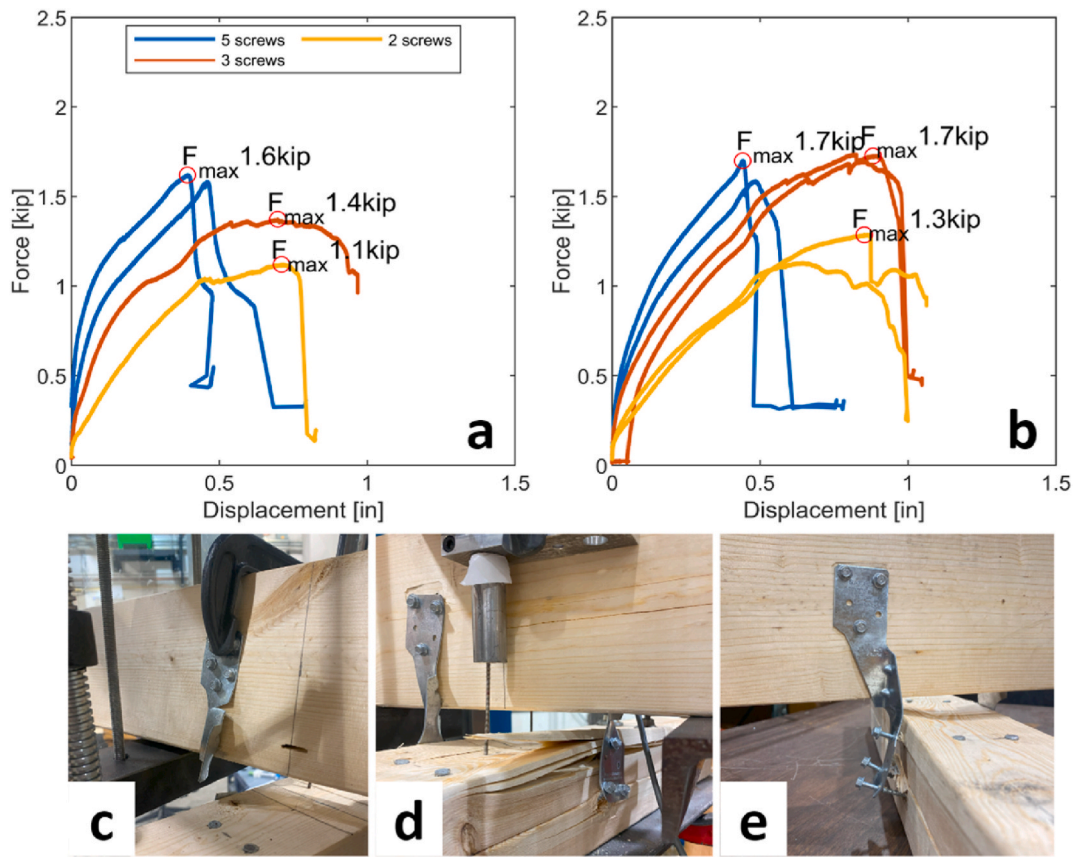


Fig. 3. Monotonic uplift test results used to define the component capacities for hurricane straps used at roof-to-wall connections: with (a) SD screws, as recommended by Simpson Strong-Tie, and (b) Gripe Rite brand screws, which are commonly found in Puerto Rican hardware stores. These tests also identify the various failure modes in the uplift tests of hurricane straps, including (c) tensile failure of the connector, (d) plate splitting, and (e) screw pull-out. Unit conversion: 1 kip = 4.448 kN; 1 in = 25.4 mm.

levels in established codes and standards.

3.3.1. Performance levels of interest

Table 3 details the performance levels considered for evaluating the response of informally-constructed light-frame timber houses in Puerto Rico. These levels quantify *Roof Envelope*, *Roof Structure*, and *Shear Wall* performance (see Fig. 4). Recognizing the difficulty in setting performance expectations, their definition was informed by definitions in Vickery et al. [69] and van de Lindt & Dao [23]. For example, the *Roof Envelope* failure impedes continued occupancy because it induces excessive water intrusion in the house [23]. This failure mode occurs if there is loss of 4 or more roof panels. The *Roof Structure* failure is taken as a failure of life safety because it causes the entire detachment of the roof from the shear walls, and the *Shear Wall* failure is a failure of collapse prevention because it causes the entire collapse of the house.

3.3.2. Wind fragility curves

The wind fragility curves represent the probability of exceeding a specified performance level (i.e., failure of that performance level), as a function of wind speed. We employed a Monte Carlo simulation approach to incorporate uncertainties in wind loads and component capacities in the development of the fragility curve. Tables 1 and 2 identify the load and capacity parameters treated as



Fig. 4. Damage photos showing (a) roof envelope, (b) roof-to-wall connection, and (c) shear wall failure modes after Hurricane Maria (2017). [Photos from Emily Alfred].

uncertain, respectively. The key uncertain variables on the loading side are GC_{pf} , GC_{pi} , and K_z , based on Lee and Rosowsky [37]. Other variables, i.e., K_d and K_e , are less influential and are therefore treated deterministically. For the capacities, the key uncertain variables are roof envelope-to-purlin connection capacities, roof-to-wall connection capacities, and shear wall strengths as they highly influence the defined performance levels (see Table 3).

For each structure of interest, the analysis was repeated at multiple wind speeds, with each wind speed associated with 500 realizations of the load and resistance variables, generated independently. We verified that 500 realizations were sufficient to yield stable values for the annual probability of failure. In each realization, the failure mechanisms associated with each performance level are assessed. For a performance level encompassing multiple criteria or sub-criteria, the occurrence of any one of these is sufficient to constitute a failure at that performance level. Subsequently, the instances of failure at each wind speed are tallied and normalized by the total number of simulations (i.e., 500) to calculate the failure probability for each performance level.

3.3.3. Roof failure probabilities

The annual probability of failure, $P_{f,1}$, for the light-frame timber house typologies represents the annual probability of failure of the structure, considering the wind hazard curves and the fragilities. The calculated annual probability of failure for specific locations, focusing on the *Roof Structure* performance level (i.e., life safety), is evaluated against the threshold stated in Table 1.3–1 of ASCE 7 [44] for Risk Category II buildings $P_{f,1}$ of 3.0×10^{-5} per year. This comparison is based on a failure scenario that is not abrupt and does not lead to extensive progressive damage. Risk Category II buildings include residential, office buildings, and commercial structures not designated as essential facilities.

The annual probability of failure is calculated under the assumption that hurricane occurrences each year follow a Poisson distribution. This assumption is consistent with the hurricane arrival process model adopted by other studies (e.g. Refs. [5,8]). The suitability of this process model for hurricane wind speeds was also verified by Esmaili & Barbato [70]. The annual probability of failure is calculated following Equation (3).

$$P_{f,1} = 1 - e^{-\lambda_f} \quad (\text{Eq. 3})$$

The mean annual probability of exceedance, λ_f , is derived by convolving the hazard curve with the fragility curves. Given the lack of a closed-form solution for this convolution, we employ a numerical approximation, as detailed in Equation (4):

$$\lambda_f = \sum_{i=1}^N P(F|v_i) \left| \frac{d\lambda(v_i)}{dv_i} \right| \Delta v_i \quad (\text{Eq. 4})$$

where $P(F|v_i)$ represents the fragility curve, i.e., the probability of failure for a specific performance level at a given wind speed v_i . Here, $\lambda(v_i)$, denotes the annual probability of exceedance associated with the hazard curve at any given wind speed v_i . N represents the total number of intervals on the hazard curve used for the numerical approximation, with each interval spaced equally at increments of 0.01 mph (0.004 mps).

3.3.4. Wind hazard curves: current and future climate

We considered the wind hazard curve at multiple locations across Puerto Rico, selected based on their representation of diverse damage levels observed after Hurricane Maria in 2017, as reported by Severino et al. [51]. We developed the hazard curve using the

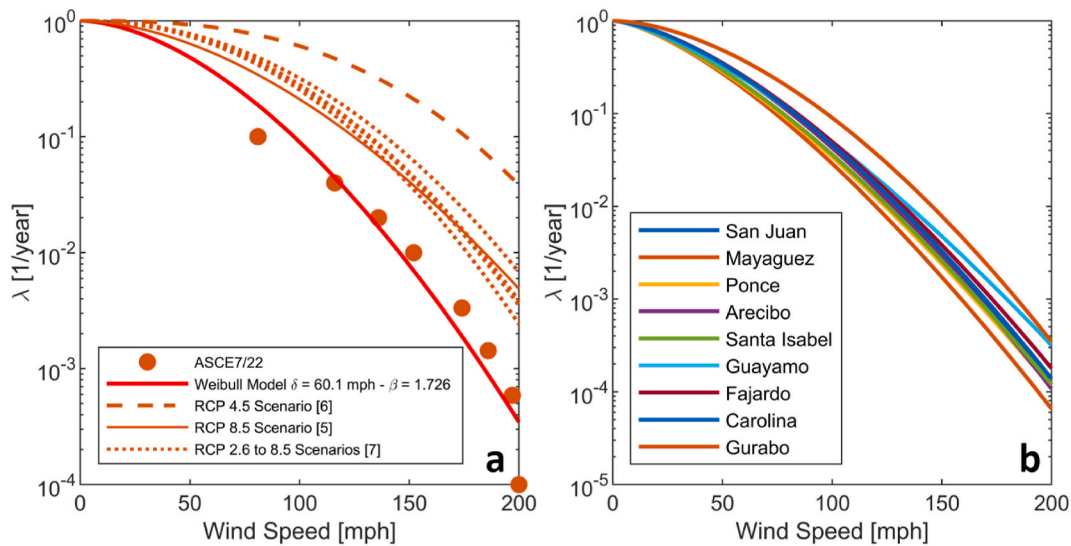


Fig. 5. Wind hazard curves (a) in Gurabo, showing the derivation of the current climate Weibull model, and as adjusted for climate change, and (b) for the current climate in all the considered locations. The locations are mapped in Fig. 12. Unit conversion: 1 mph = 0.477 mps.

ASCE 7 [44,71] online hazard tool, which reports wind speeds for return periods of 10, 25, 50, 100, 300, 700, 1700, 3000, and 10,000 years. These speeds account for the topographic factor as per Vickery et al. [55]. Subsequently, we fitted a Weibull distribution to the data points based on past research showing its suitability [7,8,38,70]. Although applying the Weibull distribution to lower (non-extreme) wind speeds may need further validation, these wind speeds contribute minimally to the probability of failure of mitigated cases. We used the fitted Weibull distributions to derive the annual probability of exceedance, λ , for wind speeds of interest ranging from 0 mph to 200 mph, as demonstrated in Fig. 5a for Gurabo, Puerto Rico. This hazard curve is representative of our current climate, considering the historical record [27]. Fig. 5b provides the Weibull distributions for each location (see parameters reported in Table S1). The wind hazard is more significant in the eastern coast (i.e., Gurabo) and slightly less in the western coast (i.e., Mayagüez), indicating the geographical variation in hurricane risk exposure across Puerto Rico.

Due to climate change, wind speeds are likely to increase in the North Atlantic Ocean because of increased sea temperatures leading to more frequent tropical storm formation [7]. To incorporate the effects of climate change on the computed hazard curves, we make use of research by Mudd et al. [5], Esmaili & Barbato [7], and Bhowmik et al. [6], which are based on the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report [9]. Mudd et al. [5] used the high-forcing Representative Concentration Pathway (RCP) 8.5 scenario to quantify expected hazards for the year 2100 at the Northeast US coastline, specifically for New York City. Esmaili & Barbato [7] projected the effects of climate change on hurricane hazards up to 2060 along the US Atlantic basin from Texas to Maine (a total of 27 locations), considering scenarios from RCP 2.6 to RCP 8.5. Bhowmik et al. [6] focused on the RCP 4.5 scenario to project the hurricane hazard curve for the year 2060 for a site in South Carolina. Despite different scenarios and locations of interest, all of these studies show increases in wind speeds for different hurricane return periods, with results indicating a consensus on wind speeds increasing by a factor of 1.1–1.4 for a 700-year return period hurricane event. Due to the absence of specific studies for Puerto Rico, we applied scaling factors from these studies for the North Atlantic Ocean to adjust the local hazard curves to provide an illustration of the range of future climate scenarios. We applied a uniform scaling factor across all locations, though not uniformly across all wind speeds. Instead, we adjusted the scaling factor for each wind speed based on the findings from the reference studies [5–7]. The impact of these scenarios on hurricane hazards in Gurabo is illustrated in Fig. 5a. Table S1 provides the assumed hazard curves considering climate change.

As noted previously, we assume a Poisson model for hurricane occurrence for both current and future projected climate scenarios, which is consistent with Esmaili & Barbato [70], among others. However, this assumption requires further investigation due to the non-stationarity of climate change impacts on hurricane frequency.

4. Light-frame timber house typologies

We defined typologies of informally-constructed houses based on our field observations and insights shared with us by NGOs involved with post-hurricane reconstruction efforts in Puerto Rico. Our fieldwork consisted of site visits, interviews, a survey, and capacity-building trainings conducted between 2019 and 2023 [12,14,73,74].

In particular, during fieldwork in July 2019 and February 2020 [14,73–75], we collected structural data and photographed typical reinforced concrete and light-frame timber houses in Puerto Rico. This data collection [73] included interviews with households about damage from Hurricane Maria and the 2019–2020 earthquakes, with engineers, architects, and reconstruction staff contributing

Table 3
Definition of the performance levels and failure criteria.

Performance Level	Associated Failure Mode	Component-Specific Mechanism	Criteria ^a	Sub-criteria ^a
<i>Roof Envelope</i> (Continued Occupancy)	Loss of 4 or more roof panels ^b	Failure of panel-to-purlin connection (fastener pullout or panel tear-out) or	A minimum of two panel-to-purlin connections, or ten percent of the panel-to-purlin connections, whichever is higher ^c	–
		Failure of purlin at the edge of the panel ^c	Shear or bending failure of purlin material or Failure of all purlin-to-truss ^d connections at edge purlin	– Failure of the connection or shear/bending failure of the connected truss material
<i>Roof Structure</i> (Life Safety ^e)	Loss of uplift capacity of the roof	Failure of 3 or more roof-to-wall connections	Uplift failure of roof-to-wall connection	–
<i>Shear Wall</i> (Structural Integrity)	Loss of shear wall lateral capacity	Failure of at least one shear wall line	Lateral failure of the shear wall line	–

^a For a criterion or sub-criterion that encompasses multiple possibilities, the fulfillment of any one criterion is sufficient to classify the performance level as failed.

^b Following Vickery et al.'s [69] definition of damage state 1 for roof cover failure.

^c Lochhead et al. [52] assumed that the failure of a purlin at the edge of the roof is sufficient to engage the failure of the associated corrugated metal panel. This assumption is founded on engineering principles and the understanding that failure at the edge of the corrugated metal panel could lead to excessive uplift, thereby precipitating its failure.

^d This criterion also applies to purlin-to-rafter connections.

^e In this study, we argue that the failure of three or more roof-to-wall connections is sufficient to jeopardize the entire roof's attachment to the wall. Our assertion is based on observations that the fragility curve remains unchanged beyond this threshold of three failed connections.

additional evidence of damage. These studies also assessed material availability and pricing in hardware stores, and surveyed hardware store employees and builders about housing safety and mitigation strategies [14,73–75]. Based on these results, the team co-designed a capacity-building initiative focused on safer housing practices with local NGOs, aiming to increase local knowledge and self-efficacy in implementing mitigation measures, especially the use of hurricane straps [12]. Later fieldwork monitored progress towards implementing mitigation measures and also highlighted challenges with mitigation measures. One of the benefits of this fieldwork was the definition of representative building typologies, and the definition and subsequent feasibility assessment of mitigation measures.

4.1. Baseline typologies

The dimensions of the baseline typologies, outlined in Table 4, reflect typical one-story light-frame housing construction in Puerto Rico. The dimensions for the light-frame timber house baseline typology are 16 ft by 24 ft (4.88 m by 7.32 m), with a story height of 8 ft (2.44 m) and a roof slope of 21°. We consider baseline typologies with both gable and hip roof shapes (see Fig. 6). The roof envelope consists of corrugated metal panels connected to the purlins. The designation of flat 2 × 4 purlin means that the purlin is installed horizontally, with the wider side lying flat against the truss or rafter, providing a broader surface area for support, but less bending resistance. We found this to be the most common configuration during fieldwork. The roofs extend to 0.5 ft (0.15 m) eaves. The roof structural system is assumed to be wood trusses in most cases, though we also consider a case with rafters for the gable roof. We consider only light-frame timber houses. Even so, the fragility results for *Roof Envelope* and *Roof Structure* performance levels are applicable to houses with wood frame roofs and masonry-infilled reinforced concrete frames because the roofs and roof-to-wall connections have the same capacity (based on data we gathered for connections used in those situations, as well statements in Refs. [27,74]). However, we did not calculate the fragility curves for the *Shear Wall* performance level for masonry-infilled reinforced concrete frames due to the lower likelihood of wall (lateral) failure. Southern Yellow Pine is assumed for all wood in the roof structures, as it is the most locally available material. All cases are classified as partially enclosed, based on fieldwork observations; windows are typically of the miami or jalousie type.

4.2. Mitigated typologies

The mitigation measures proposed in this study draw on findings from surveys previously conducted with those involved in the informal construction industry [14] and focus group conversations with Puerto Rican builders during training exercises [12]. Surveys of individuals in the construction industry highlighted the significance of mitigating light-frame timber houses, with 89 % of respondents anticipating damage or destruction due to hurricane winds. Those respondents expressed particular concern about reinforcing the roof envelope, showing interest in thicker panels, additional fasteners, or tie-down cables, drawing on their personal experiences from past hurricanes [14]. In relation to hurricane straps and enhancing the roof-to-wall connection, only 45 % of respondents identified strengthening this connection as crucial for hurricane mitigation [75]. Despite the widespread availability of hurricane straps in Puerto Rican hardware stores, survey results [14] and subsequent capacity-building sessions [12] revealed uncertainty about the choice of fasteners (nails vs. proprietary screws vs. conventional screws) and concerns about the number of fasteners needed, especially in terms of its effects on the integrity of the wooden components of the roof. Trainees at capacity-building events explained their confusion with existing catalogs on hurricane straps and other mitigation materials sold at hardware stores, saying “It’s more complicated than it should be” and “It’s not accessible to people” [12]. Although NGOs are beginning to implement the use of hurricane straps, during fieldwork in March and October 2022, we observed several examples of residents and local NGO staff incorrectly installing hurricane straps horizontally (rather than vertically, see labels “a” and “b” in Fig. 7) at the purlin-to-truss connection due to space limitations. NGO staff also noted that implementing the mitigation measures on roofs, which result in stronger and heavier roof structures, could require them to replace shear walls rather than simply retrofitting them. This decision depends on the evaluation of each individual case, considering factors such as severe damage or structural weaknesses. Examples of the training exercise conducted in June 2023 are illustrated in Fig. 7.

This study proposes incremental mitigation strategies for the roof envelope, roof structure, and shear walls in both existing and new buildings, informed by the previously described survey data from the informal construction sector and dialogues with Puerto Rican builders [12,14], as well as damage observations post-Hurricanes Maria and Fiona [17,51]. These mitigation measures are intended to address the interests of the local building community, and to investigate mitigation measures that are not well understood. Accordingly, the proposed mitigation measures include improving corrugated metal panel-to-purlin connections, roof-to-truss connections,

Table 4
Baseline typology matrix^a.

Item	Baseline Typology		
	Gable 1	Gable 2	Hip
Roof shape	Gable	Gable	Hip
Roof structure	Wood trusses	Wood rafters	Wood trusses
Shear wall	2 × 4 Wood frame studs and 0.5 in plywood	2 × 4 Wood frame studs and 0.5 in plywood	2 × 4 Wood frame studs and 0.5 in plywood
material	sheathing	sheathing	sheathing
Shear wall	8 ft	8 ft	8 ft
height			

^a Unit conversion: 1 in = 25.4 mm; 1 ft = 0.305 m.

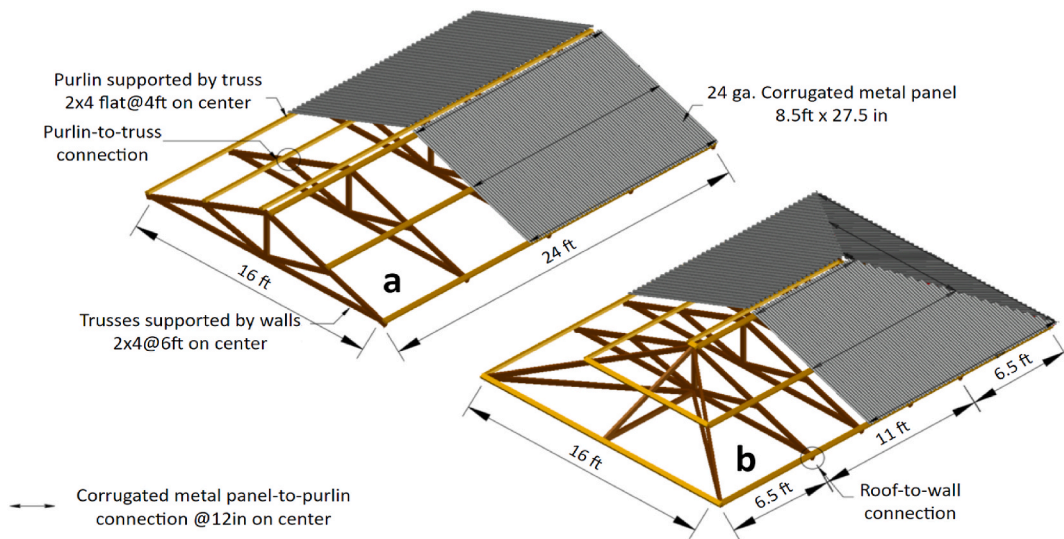


Fig. 6. Baseline (a) gable and (b) hip roof typologies. Unit conversion: 1 ft = 0.305 m; 1 in = 25.4 mm.

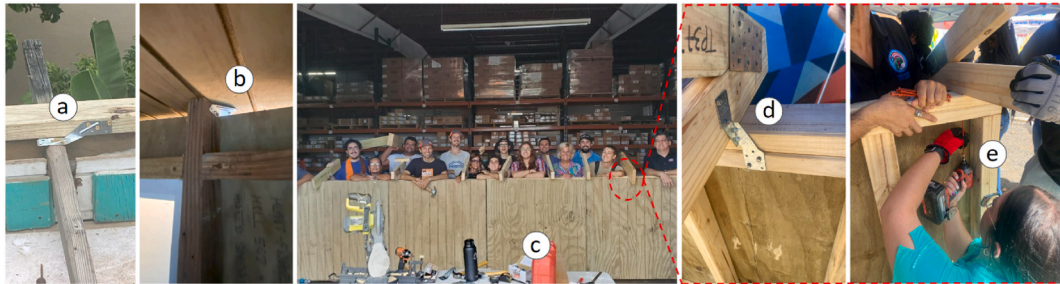


Fig. 7. Observed incorrect installation of hurricane straps at connections between (a) purlins and rafters, and (b) roofs and walls during fieldwork. Collaborative Training and Practical Workshops with two key local NGOs in Puerto Rico focusing on reconstruction efforts after Hurricane Maria. Examples of hands-on activities demonstrating the application of mitigation measures to (c) shear walls and to roof-to-wall connections using (d) hurricane straps and (e) fully-threaded screws.

Table 5

Mitigated typology matrix^{a,b}.

Group	ID	Item	Baseline	Mitigated
Roof Envelope and Structure (RE ^c)	RE ₁ ^d	Corrugated panel-to-purlin connection	nail	screws
		Corrugated panel-to-purlin connection spacing	12 in exterior/12 in interior	4 in exterior/4 in interior
	RE ₂ ^d	Purlin and truss/rafter member size	2 × 4	2 × 6
		Purlin-to-truss ^e connection	nailed	screwed ^f
	RE ₃ ^d	Truss/Rafter spacing	6 ft	2 ft–3 ft ^g
Roof-to-Wall		Purlin spacing	4 ft	2 ft
	R2W	Roof-to-wall connection	toe-nailed	hurricane straps or fully-threaded screws
Shear Wall		Shear wall sheathing layers	one-side	both-sides
	SW	Shear wall overturning restraint system	none	conventional hold-down

^a The term “Fully-Mitigated” is used to denote the combined implementation of the RE, R2W, and SW mitigation measures.

^b Unit conversion: 1 in = 25.4 mm; 1 ft = 0.305 m.

^c The term “RE” refers to the combined action of RE₁, RE₂, and RE₃.

^d RE₁ aims to provide a strong attachment of the roof envelope to the wood frame. In contrast, RE₂ and RE₃ focus on strengthening the wood frame of the roof using two different approaches. RE₂ enhances the structure by increasing the strength of both connections and member sizes, whereas RE₃ achieves this by incorporating additional members and providing more redistribution of forces within the structure.

^e This item also applies to mitigation of purlin-to-rafter connections.

^f In Lochhead et al. [52] hurricane straps were considered for purlin-to-truss connections. However, our subsequent fieldwork in Puerto Rico found that there is not enough space to place hurricane straps making them less effective than screwed connections.

^g For hip roof designs, we considered typologies with the spacing of trusses at 2 ft and 3 ft. In contrast, for gable roof configurations, trusses or rafters are spaced at 2 ft. This distinction in spacing reflects the structural differences and requirements between the two roof shapes.

truss/rafter and purlin spacing, purlin-to-truss/rafter connections, corrugated metal panel thickness, and lateral strength of shear walls. We established eight enhanced typologies, based on the baseline typologies in Table 4, each progressively integrating the proposed mitigation measures. Table 5 provides detailed descriptions of the proposed mitigation measures, including the specific combinations considered.

Reflecting the reality of informal construction, none of these mitigated typologies explicitly satisfy design loads and criteria of American building standards adopted in Puerto Rico (i.e., in IRC 2018, IBC 2018, ASCE 7). Yet, the fully-mitigated case is more consistent with the requirements of these documents, including corrugated metal panels attached to purlins using screws, with purlin spacing not exceeding 2 ft (0.6 m), roof-to-wall connections reinforced with hurricane straps or screws, and shear walls reinforced with sheathing panels at least 3/8 in (9.5 mm) thick, complemented by hold-downs as an overturning restraint system. However, the fully-mitigated gable case does not entirely meet the building code standards regarding truss and rafter spacing—mandated to be no more than 2 ft (0.6 m). Neither the fully-mitigated hip nor the gable cases align with building codes requiring OSB panels for roof sheathing.

5. Results: hurricane wind performance of housing typologies

5.1. Performance of baseline typologies

Figs. 8–10 present fragility curves for baseline and mitigated light-frame timber house typologies, including gable truss, hip truss, and gable rafter cases. In general, the baseline typologies show poor performance, with *Roof Envelope* failures possible with wind speeds less than a Category 1 storm, and *Roof Structure* failures likely in a Category 2 storm. These observations are consistent with field observations after Hurricanes Maria and Fiona made by the authors, NGO workers, and Severino et al. [51].

Among the baseline typologies, the gable cases with trusses and rafters (Figs. 8a and 10a) exhibited similar performance, suggesting that wood failure in the roof structure is not a significant factor in hurricane wind resistance. The hip truss case demonstrated superior baseline *Roof Structure* performance to the gable in terms of annual probability of failure (up to 76 % better in median wind speed) due to the lower pressures on hip roofs and the larger number of roof-to-wall connections. For the baseline cases, the *Roof Envelope* failure occurs at the lowest wind speed, followed by the *Roof Structure* and *Shear Wall* failures. However, the sequence of these failure modes depends on a systematic consideration of the load transfer from one component to another. If any link in the path is weaker, then the sequence of the failure modes can be altered. For example, in the hip-roof baseline case, the *Roof Envelope* performance is slightly worse than the gable roof cases, due to longer purlin spans associated with the roof geometry impacting roof envelope integrity (see the comparison between Figs. 8a and 9a).

The fragility curves shown in Figs. 8–10 were derived from numerical simulations with wind speed increments of 0.2 mph (0.1 mps). We did not smooth the results by fitting the results to a probability distribution model. As a result, we note that, in some cases, the fragility curve is not monotonically increasing (e.g., Fig. 8a for the *Roof Structure* failure). This perhaps surprising result occurs because the sign of C_{pi} changes due to failure of the roof envelope (see Fig. 2a), and, in such a scenario, the probability of uplift failure of the corrugated metal panel actually decreases.

The fragility curves developed for gable and hip roof baseline typologies in our study indicated less favorable outcomes across all performance levels when compared to those of typical formally-constructed American light-frame timber houses. We specifically compared our baseline fragility curves to those developed by Li & Ellingwood [38] and van de Lindt & Dao [23], which incorporate roof panels with overhangs, roof-to-wall connections, and the lateral capacity of shear walls (specifically for a case where 20 % of the wall length is shear walls). This comparison specifically contrasted Puerto Rican residential housing with that in the Southeast, Gulf

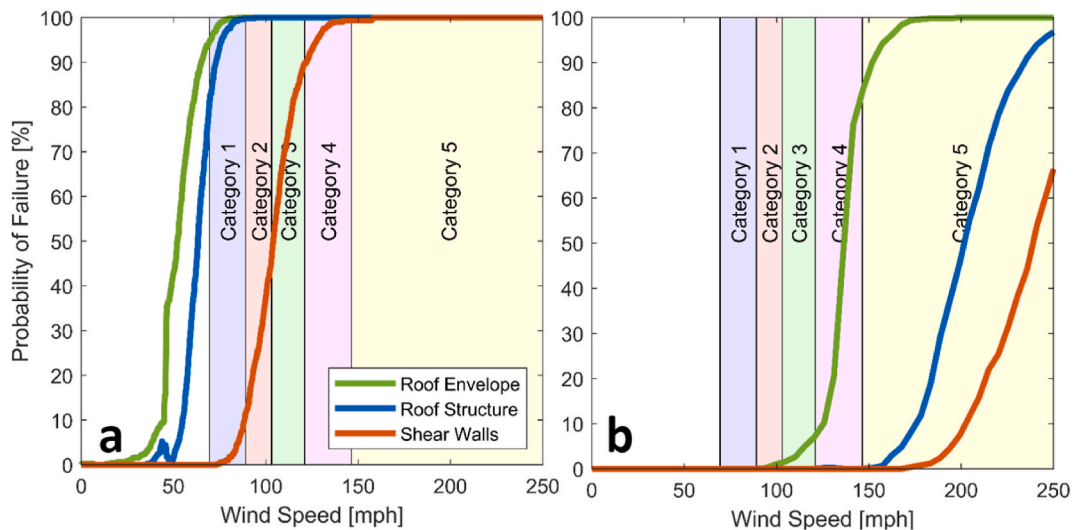


Fig. 8. Wind fragility curves for gable roof with trusses: (a) baseline and (b) fully-mitigated cases. (On this figure and subsequent figures, wind speed is delineated into storm categories, based on the Saffir-Simpson [72] scale). Unit conversion: 1 mph = 0.477 mps.

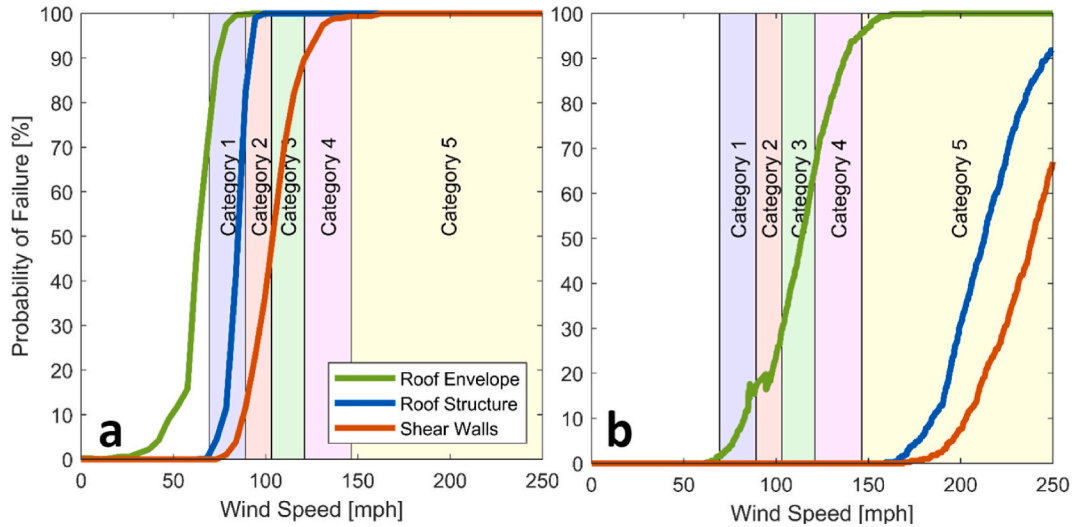


Fig. 9. Wind fragility curves for the hip roof with trusses: (a) baseline and (b) fully-mitigated cases with trusses at 3 ft on center. Unit conversion: 1 mph = 0.477 mps.

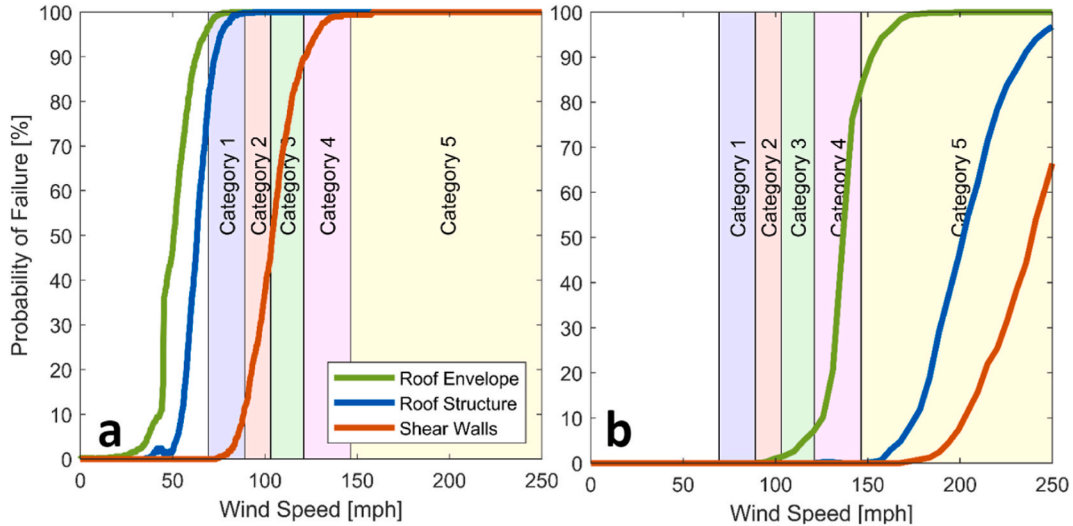


Fig. 10. Wind fragility curves for gable roof with rafters: (a) baseline and (b) fully-mitigated cases. Unit conversion: 1 mph = 0.477 mps.

Coast, and Eastern Seaboard states of North America.

This comparison shows that our baseline informally-constructed typologies performed up to 200 % worse in terms of the median wind speed at failure for the *Roof Envelope* and *Roof Structure* performance levels, and up to 60 % worse for the *Shear Wall* performance level. These discrepancies are largely due to several factors in Puerto Rican housing that differ significantly from other North American typologies: the absence of OSB sheathing in the roof envelope, where corrugated metal panels are instead fastened directly onto purlins without intermediate sheathing; wider truss and purlin spacing; and less frequent nailing with a lack of an overturning restraint system in shear walls. In contrast, typical formal construction in other regions uses sheathing, narrower spacing of roof support structures, and an overturning restraint system in shear walls, which contribute to a denser nailing pattern for attaching corrugated metal panels to purlins and higher lateral capacity of shear walls. Although there are differences in assumptions between our study and the comparison studies, this difference is significant and meaningful.

5.2. Performance of mitigated typologies

The effect of the mitigation measures is to dramatically improve performance, leading to up to 140 %, 220 %, and 135 % increase in median wind speeds at the *Roof Envelope*, *Roof Structure*, and *Shear Wall* limit states, respectively, relative to the baseline typologies. In particular, the median speed at *Roof Envelope* failure changes from occurring below a Category 1 wind speed, to a Category 3 or 4 wind speed. The mitigation measures delay the median speed of failure for the *Roof Structure* and *Shear Wall* to that of a Category 5 hurricane. In mitigated cases, despite the expectation of increased stress on the wood frame of the roof because the envelope failure is

delayed, wood failure does not significantly impact the response of the houses to hurricane winds because the roof structures are strong enough. This observation is again evidenced by the similar responses observed between gable cases with trusses and those with rafters (see Figs. 8b and 10b), even though the rafters are much weaker.

For the mitigated cases, our *Shear Wall* fragility curves show levels of failure probability comparable to the intermediate case presented by van de Lindt & Dao [23] (i.e., a case where 40 % of the wall length consists of shear walls). These results demonstrate that augmenting the lateral capacity of shear walls through sheathing on both sides, integrating hold-downs as an overturning restraint system, and accounting for the effects of finish layers effectively enhance the performance level of *Shear Wall*.

5.3. Annual failure probabilities

Fig. 11 provides the average annual probability of failure for the *Roof Structure* (life safety) performance level for all selected sites for the cases considering all mitigation measures. (These results include only the gable with truss, as the rafter results are similar; the full set of results is provided in Tables S2–S4). The baseline cases have terrible performance, with annual failure probabilities several orders of magnitude over those found in previous studies and established targets. However, our results for the fully-mitigated cases of informally-constructed light-frame timber house typologies indicate a lower annual failure probability than those reported for typical houses by Li & Ellingwood [38]. Even so, only the fully-mitigated hip case with trusses spaced 2 ft on center meets the criteria set in the ASCE 7 [44] standards, which limits the annual probability of failure to 3.0×10^{-5} per year.

Fig. 12 examines the annual probability of failure for fully-mitigated gable and hip cases across different locations. Focusing here on results for the current climate, the results for the fully-mitigated gable case indicate that southern/western locations are closest to reaching the target of the ASCE 7 [44] failure probabilities, while northern/eastern areas have more vulnerability due to the greater wind hazard in those areas. This failure pattern aligns with the damage observed on the island following Hurricane Maria in 2017, as noted by FEMA [17] and Severino et al. [51], and the differences in hurricane hazard (Fig. 5). The fully-mitigated cases showed annual probabilities of failure that are closer to, but do not necessarily meet the ASCE 7 [44] target criteria, as indicated by the greener dots in Fig. 12. The hip roof case with trusses at 3 ft on center is the closest to the target across all locations (neither over or undershooting). As highlighted by prior studies [51,55], Gurabo is uniquely vulnerable due to topographical factors that amplify wind speeds, resulting in increased damage.

To further explore the design implications of the failure probabilities, we also disaggregate the wind speeds to examine the ranges of wind speed that most contribute to the failure risk. The vertical axis in the disaggregation figures represents the probability of failure for a specific limit state, $P(F|v_i)$, at a given wind speed, v_i , derived from the fragility curves and multiplied by the likelihood of that wind speed occurring according to the hurricane hazard curve, as in Equation (4). The area under the curve of these disaggregation figures is the mean annual probability of exceedance, λ_f . We refer to the wind speed range that contributes 90 % of the failure (i.e., from 5th to 95th percentile) as the “critical failure range”. This disaggregation is illustrated in Figs. 13 and 14 for the gable cases, and Figs. S1 and S2 for the hip cases, while Table 6 provides a summary of the critical failure range for each typology and performance level. These results show that the baseline cases fail well below the design wind speed. Likewise, the implementation of all proposed mitigation strategies led to significant increases in the wind speed range for both roof types. In contrast, the fully-mitigated cases’ critical failure range encompasses or is above the design wind speed, despite not being explicitly designed. Mainly the *Roof Envelope*

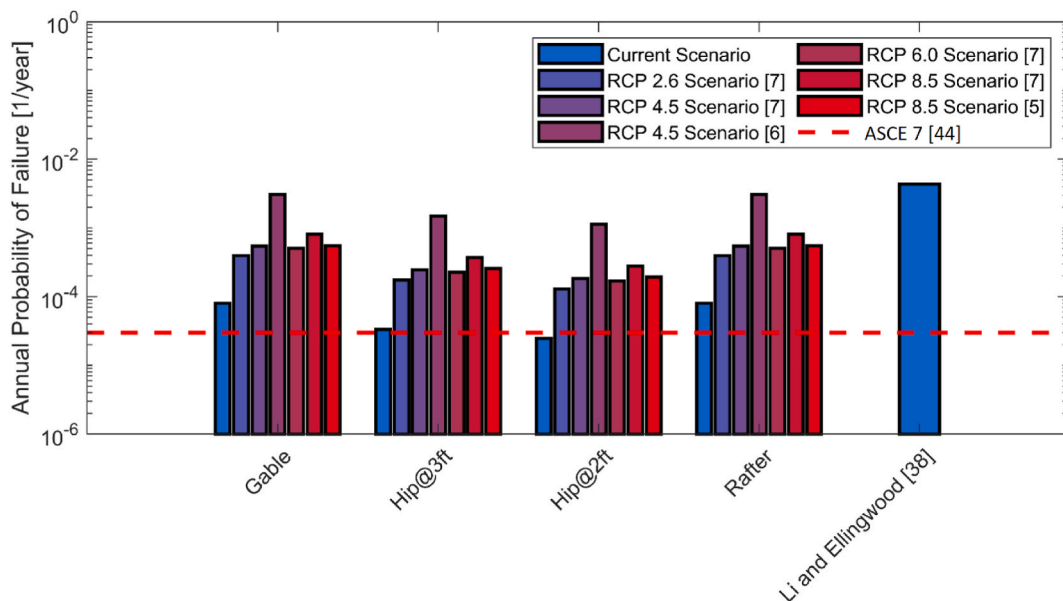


Fig. 11. Comparison of the computed annual probability of failure (average across locations) of *Roof Structure* (life safety) performance level for the fully-mitigated cases to results from Li & Ellingwood [38] for formally-constructed light-frame wood housing, and to ASCE 7 [20] acceptable risk thresholds. For comparison, baseline cases have annual probabilities of failure ranging from 1.4×10^{-1} to 3.4×10^{-1} [1/year] and are illustrated in Fig. 15.

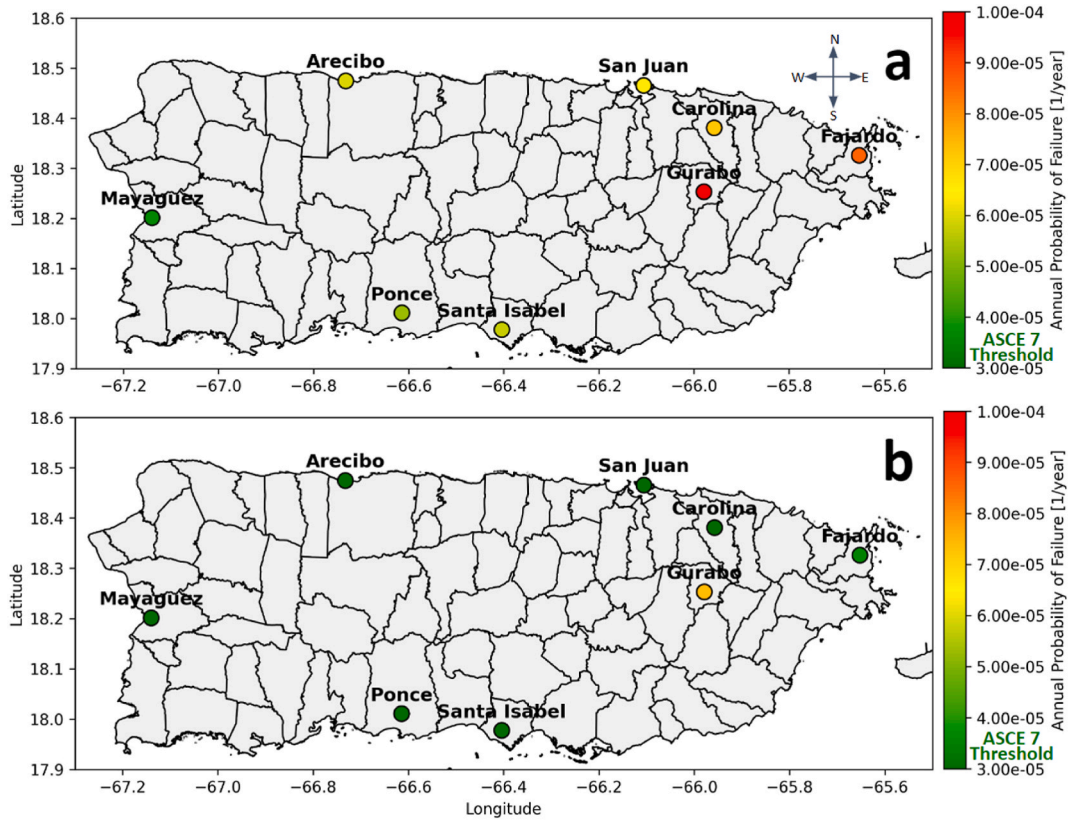


Fig. 12. Annual probability of failure related to the *Roof Structure* (life safety) performance level across various locations on the island for mitigated (a) gable case and (b) hip case with trusses at 3 ft on center.

performance level is below the design wind speed. For the baseline cases, in comparison to the gable case, the hip case demonstrates a critical failure range that is 10 % higher across all performance levels, indicating again the higher wind speeds associated with failure in the hip cases.

5.4. Contribution and feasibility of the proposed mitigation measures

In order to explore the effectiveness of individual mitigation strategies, Fig. 15 showcases the impact of each proposed mitigation measure, both individually and in combination as outlined in Table 5, on the annual probability of failure for the *Roof Structure* performance level.

By comparing the baseline case and R2W, this figure reveals that, in both gable and hip cases, the most effective individual mitigation measure is reinforcing the roof-to-wall connection (i.e., R2W), either through the installation of hurricane straps or fully-

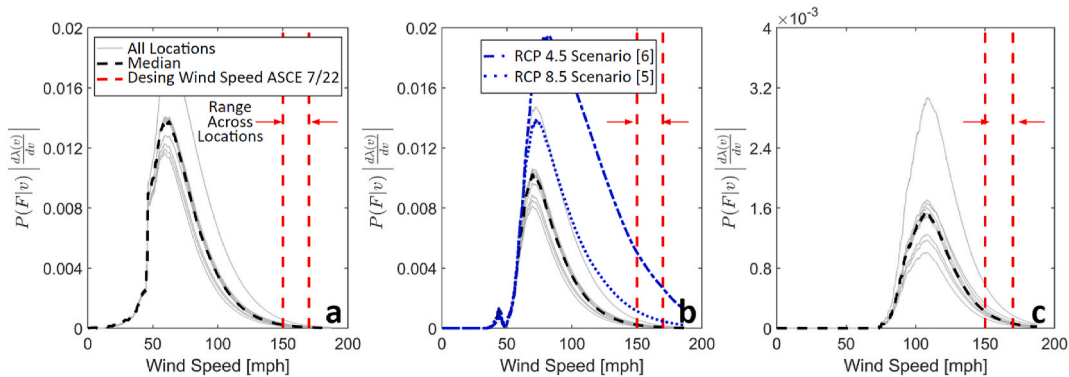


Fig. 13. For the baseline gable case, disaggregation of the wind speed contribution to the probability of failure for (a) *Roof Envelope*, (b) *Roof Structure*, and (c) *Shear Wall* performance levels under current (a,b, & c) and climate (b only) scenarios. Unit conversion: 1 mph = 0.477 mps.

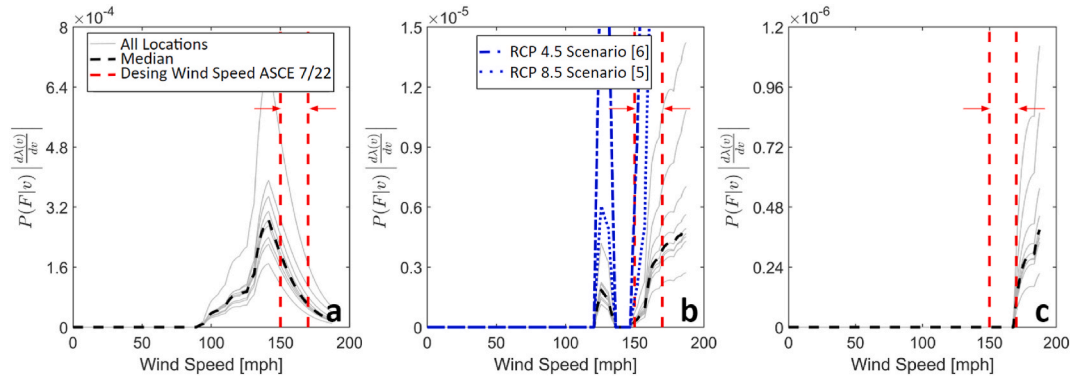


Fig. 14. For the fully-mitigated gable case, disaggregation of the wind speed contribution to the probability of failure for (a) *Roof Envelope*, (b) *Roof Structure*, and (c) *Shear Wall* performance levels under current (a,b, & c) and climate (b only) scenarios. Unit conversion: 1 mph = 0.477 mps.

Table 6

Wind speed range contributing to the 90 % of the annual probability of failure under the current climate scenario.

Performance Level	Critical failure range wind speed [5th, 95th percentiles] mph (1 mph = 0.447 mps)			
	Gable	Gable- Fully mitigated	Hip	Hip- Fully mitigated
<i>Roof Envelope</i>	[46,114]	[108,172]	[47,121]	[76,150]
<i>Roof Structure</i>	[57,122]	[127,186]	[80,137]	[163,187]
<i>Shear Wall</i>	[88,150]	[171,187]	[88,150]	[171,187]

threaded screws at this location. This approach significantly reduces the annual probability of failure by increasing the capacity of the crucial roof-to-wall connection by up to six times, making it a priority in strengthening efforts.

Regarding the roof envelope and roof structure (RE) enhancements, the most beneficial for improving the *Roof Structure* performance level compared to the baseline case is reducing the spacing of trusses (or rafters) and purlins (i.e., RE₃), for the gable (up to 67 % reduction in annual probability of failures) and hip (up to 20 %) cases. This mitigation has the effect of reducing the uplift force on the roof-to-wall connection because there are more trusses to attach to the walls, and thereby delaying the likelihood of failure. Although not shown, RE₃ also improves the fragility of the *Roof Envelope* performance level by 62 % (reduction in annual failure probability) compared to baseline performance. The second most beneficial of these mitigation measures on *Roof Structure* performance, labeled RE₂, involves: a) increasing the dimensions of wooden components in trusses (or rafters) and purlins to produce higher uplift strength

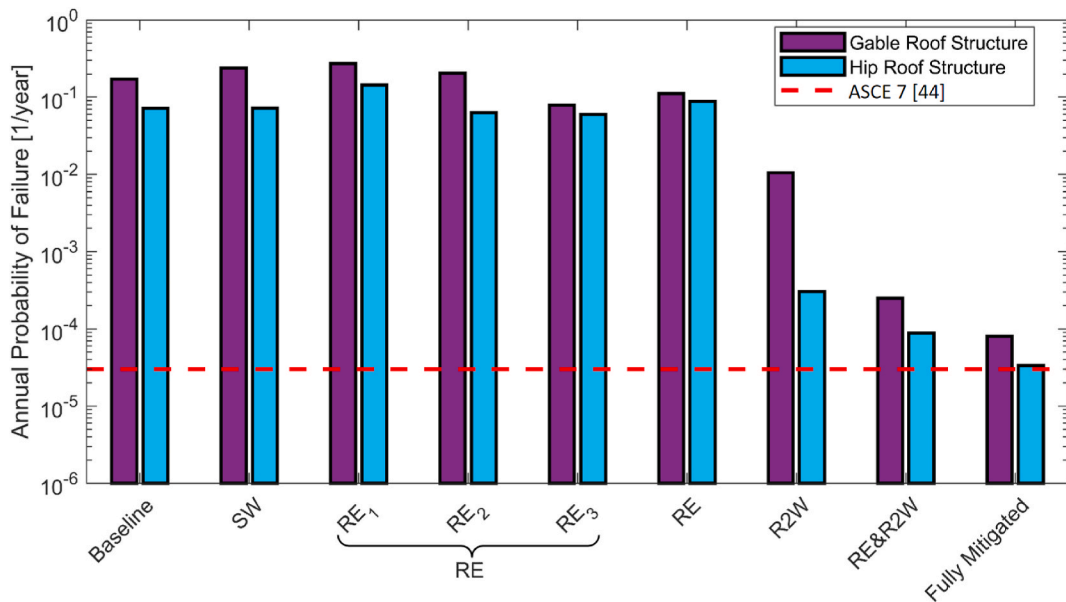


Fig. 15. Contribution of each proposed mitigation measure to reduce the annual probability of failure associated with the *Roof Structure* performance level. See Table 5 for definitions of each mitigation; RE + R2W + SW = fully-mitigated.

in toe-nails, and b) using screwed purlin-to-truss connections. However, RE₂ exhibits a negligible impact (less than 4 %) on reducing the annual probability of failure for the *Roof Envelope* performance level when compared to the baseline performance. Improving both the thickness of corrugated metal panels and the spacing of corrugated metal panel-to-purlin fasteners (RE₁) improves the *Roof Envelope* performance by 30 % for the gable case and by 66 % for the hip case. However, the RE₁ approach alone actually worsens the *Roof Structure* performance because strengthening the envelope means that larger forces are transferred to the weak roof structure and roof-to-wall connections when the envelope does not fail—unless that structure and its connections are also mitigated. All of the RE measures are more effective than the sum of the individual RE₁ and RE₂ for the *Roof Structure* performance, but are slightly less effective than implementing RE₃ alone; essentially, the more mitigated the roof structure from RE₁ and RE₂, the higher the uplift load transferred to the shear wall through the roof-to-wall connection. However, RE₃ should not be implemented alone. It needs to be implemented together with RE₁ to generate an appropriate load path within the roof structure to the roof-to-wall interface, as RE₁ provides a strong attachment of the roof envelope to the wood frame. Additionally, RE₂ is particularly needed when roofs with rafter beams are used. This ensures that the uplift force from the roof is evenly distributed over the walls.

Taken together, these results show that, to achieve the performance criteria set by ASCE 7 [44], it is essential to combine roof-to-wall reinforcement with improvements to the roof envelope and roof structure. In particular, combining roof envelope and roof structure enhancements means that the structure is able to produce a continuous and effective load path to shear walls, reducing annual failure probabilities more than if either set of modifications were made alone. This underscores the importance of adopting a system thinking approach in designing or mitigating houses.

Mitigating the roof envelope and structure is crucial, yet without applying mitigation measures to the shear walls, its performance could be compromised (refer to Table S4 to evaluate the differences between baseline, RE + R2W, and the fully-mitigated cases). Implementing shear wall mitigation measures enhances the continuity of the load path to the foundation. While not displayed here, shear wall mitigation measures (SW) improve the baseline annual probability of failure for the *Shear Wall* performance level from 1.97×10^{-2} to as small as 7.11×10^{-7} .

We conducted additional fieldwork in June 2023 to assess the feasibility of the mitigation measures explored in this engineering assessment, i.e., those outlined in Table 5 and Fig. 15. This assessment involved capacity-building workshops co-hosted with two local NGOs and surveys of 28 participants to identify builder-perspective barriers to the proposed mitigation measures. Additionally, it included visits to eight hardware stores, surveying 14 employees to assess barriers based on their customer interactions, and to check the availability and pricing of the materials needed for the proposed mitigation measures. Those surveyed shared that they believed that the proposed mitigation measures would enhance the safety of their houses, provide shelter for neighbors, and contribute to improved mental well-being by increasing preparedness for future hurricanes. These results complement the larger dataset in Goldwyn et al. [14]. However, we administered our survey after showing recommended mitigation measures, whereas Goldwyn et al.'s [14] survey was not administered in conjunction with any capacity-building materials. As a result, while Goldwyn et al.'s [14] participants considered improving the corrugated panel-to-purlin connection more important, and hurricane straps, a type of roof-to-wall connection, the least important; our participants identified roof-to-wall connections as the most critical area for fortification to improve hurricane performance. We attribute this difference to the capacity-building workshops previously conducted [12] and reported here, where the effects of roof-to-wall connection mitigation measures and their installation were illustrated, demonstrating how to improve hurricane resilience in houses. Additionally, our participants emphasized the importance of fortifying shear walls. This indicates that participants were able to identify that focusing only on the roof and roof-to-wall connections could increase the risk of failure at the shear walls. We attribute this to their understanding of workshop concepts, such as securing a continuous load path to the foundation and adopting a systems-thinking approach to mitigating structural risks.

However, the survey respondents also expressed concerns about barriers to implementing the proposed mitigation measures. We summarize the responses from local hardware store employees and builders representing two local NGOs in Fig. 16 to the question, "In what situation might a builder not incorporate the guidance for mitigation? Please choose no more than 3". Fig. 17 and S3 to S6 (detailed analysis) show results to the question: "What guidance for mitigation may be challenging for the average builder/homeowner to implement due to cost, difficulty, material availability, lack of knowledge, or time constraints? Please select all that apply." Both questions specifically addressed the mitigation measures examined in this study.

As Fig. 16 shows, 86% of builders from local NGOs (24 of 28) and 86% hardware store employees (12 of 14) cited a lack of knowledge and difficulty, respectively, as the primary reasons for not implementing the proposed mitigation measures in Puerto Rico. Notably, neither group considered cost as the primary barrier.

However, Fig. 17 indicates that cost was most frequently mentioned as the main challenge when respondents discussed specific mitigation measures. Specifically, Fig. 17 and S3 to S6 illustrate that builders highlighted cost as the main barrier to using: 1) fully-threaded screws in roof-to-wall connections (R2W), 2) screws over nails in corrugated metal panel-to-purlin connections (RE₁), and 3) 2 × 6 over 2 × 4 wood members in roofs (RE₂). Similarly, hardware store employees identified cost as a barrier for the adoption of 1) 2 × 6 wood members (RE₂), 2) fully-threaded screws for R2W connections, and 3) screw attachments for purlins to trusses (RE₂), along with 4) reducing the spacing of trusses and purlins (RE₃). Both groups also reported a significant lack of knowledge that impedes the implementation of the proposed mitigation measures (see Figs. S3–S6). They highlighted a lack of knowledge as critical for fastener type and spacing when attaching the corrugated metal panel (RE₁), spacing reductions for trusses, rafters, and purlins (RE₃), and strengthening roof-to-wall connections (R2W). The surveyed builders also noted material availability issues for the screws to attach the purlin to trusses or rafters (RE₂), for the fully-threaded screws at the roof-to-wall connection (R2W), for the 2 × 6 wood members (RE₂), and reinforcing shear walls (SW). However, surveyed hardware store employees did not report material availability as an obstacle, instead attributing the lack of adoption primarily to a lack of customer awareness around the proposed mitigation measures. Builders involved with local NGOs cited cost, difficulty, lack of knowledge, and the additional time required as barriers for implementing hip

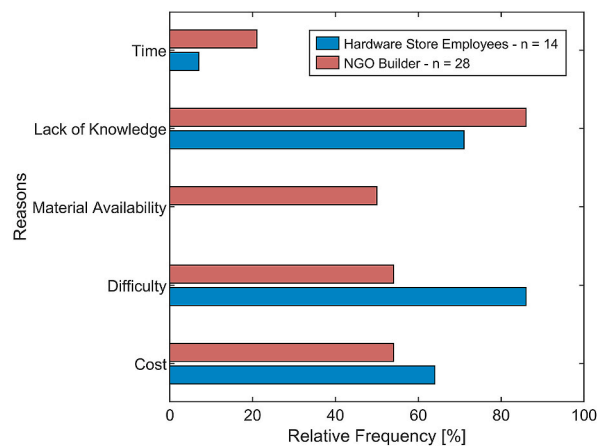


Fig. 16. Reasons given for why a builder may not implement the proposed mitigation measures from a survey conducted in June 2023.

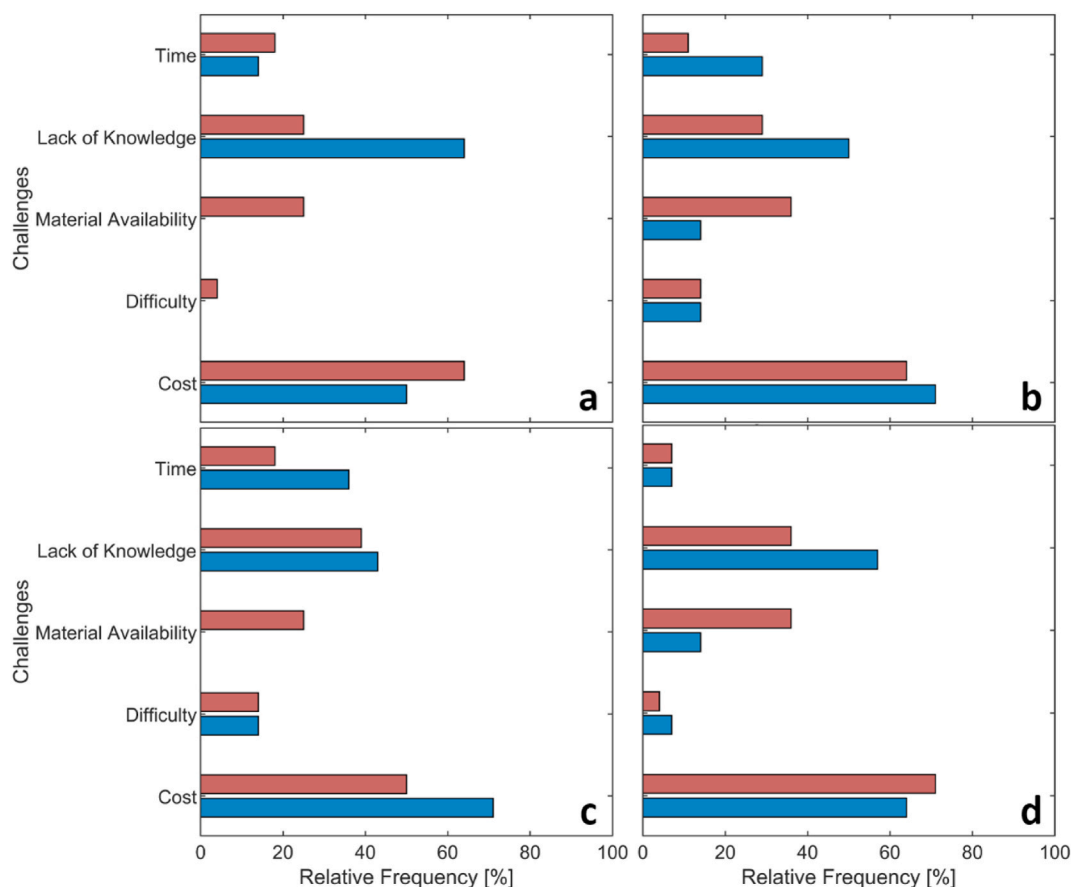


Fig. 17. Challenges to implementing (a) screws over nails in corrugated metal panel-to-purlin connections (RE₁); (b) 2 × 6 over 2 × 4 wood members in roofs (RE₂); (c) reducing the spacing of trusses and purlins (RE₃); and (d) fully-threaded screws for R2W connections, as identified in a survey conducted in June 2023 by hardware store employees and local NGO builders.

roof designs, despite our findings (and those of others, e.g., Vickery et al. [27]) suggesting hip roofs are highly advantageous over gable roofs.

The discrepancy in responses to the questions in Figs. 16 and 17 regarding cost suggests that when people are unaware of how to mitigate and respond to a general question about not mitigating (Fig. 16), they focus on lack of knowledge and difficulty as barriers. However, once they understand the specifics of the proposed mitigation measures (Fig. 17 and S3 to S6), they begin to consider cost as

a more significant barrier to mitigation. In the survey presented here, we did not investigate differences between actual and perceived cost, but Goldwyn et al. [12] previously noted that builders and households were surprised by the relatively small cost of hurricane straps, and valued sharing information about costs and the cost-to-benefit ratio of using hurricane straps to secure roof connections. These results highlight the need to develop and present a comprehensive cost-benefit analysis in future workshops, ensuring that both hardware store employees and builders understand both the true costs and benefits of the proposed mitigation measures and are equipped with the necessary tools to effectively communicate these advantages to their communities.

5.5. Effect of climate change

Climate change significantly escalates failure risks for these structures, with probabilities of failure potentially doubling to quintupling based on the roof shape and climate scenarios in both baseline and mitigated cases (see Fig. 11). This increase is derived from the amplified hazard in the climate change scenarios considered; for example, in Gurabo, a 100 mph (45 mps) wind speed's annual likelihood increases, as an example, from 8.96×10^{-2} to 2.09×10^{-1} (a factor of more than two) and to 6.05×10^{-1} (a factor of almost seven) for the Mudd et al. [5] and Bhowmik et al. [6] climate change scenarios, respectively. In addition, the critical failure range changes from [127,186] mph ([57,83] mps) in the current climate scenario to [156,187] mph ([70, 84] mps) for the fully-mitigated gable case under Bhowmik et al. [6] climate change scenario (see Table 7 and Fig. 14b). These cases represent the range of climate scenarios used here for illustration and, hence, the range of possible influences. Failing to proactively adjust for the non-stationary future climate implies that the upper and lower limits of the critical failure range of wind speeds will increase over time, leading to the obsolescence of existing design wind speeds and inadequacies of practices that may have implicitly satisfied the current design targets. This observation adds urgency to the need to mitigate, as the annualized failure risk is increasing, regardless of the future climate model considered.

6. Limitations and future work

This research focuses exclusively on the impacts of wind and does not encompass risks associated with hurricane-induced flooding, storm surges, or wind or water-borne debris. Likewise, our analysis considers only structural damage caused by hurricane winds, excluding considerations such as water intrusion and impacts from debris. In calculating the fragility curves, we did not account for potential changes in the Velocity Pressure Exposure Coefficient (K_z) across the island caused by variations in the exposure category. The house typologies were established through fieldwork observations and are confined to single-story residential homes. However, these typologies are based on a simplification of house shapes, and results could vary for unusual geometry or construction practices. Lochhead et al. [52] and Vickery et al. [27] partially addressed the limitation related to building stories in our study, showing greater risk for two-story buildings. Additionally, we recognize that the definition of the performance levels, as described in Table 3, can significantly influence the fragility curve response for the typologies under review. Moreover, the coefficients of variation used for wind demands and components, especially those not derived from experimental data, can also greatly affect the calculated probability of failure. A Puerto Rico-specific climate model would greatly improve the determination of hurricane demands on structures based on future climate change projections and the evaluation of geographical variations across the island in these projections.

Future research should focus on refining the fragility models to accommodate changing climate scenarios and tackle scenarios involving multiple hazards, as Puerto Rico has recently experienced earthquakes and floods as well as high winds. These events have placed residents in a dilemma regarding the choice of the most suitable structural system since heavier construction is preferable for winds and in many cases flooding (elevation is possible), but not earthquakes [73,75,76]. Additionally, conducting a cost-benefit analysis of mitigation measures could be valuable to prioritize among the proposed mitigation measures, taking into account future climate projections. Lochhead et al. [52] partially addressed the cost-benefit analysis of mitigation by providing a prioritized modification to existing roof structures along with a material cost estimate.

We assess the ASCE 7 [44] threshold for annual probability of failure, but we emphasize the need for a more nuanced approach for Puerto Rico, considering its specific hurricane risks and socioeconomic context. The threshold from ASCE 7 [44] applies broadly to various hazards and diverse U.S. contexts, and future research should consider how and if these targets—and the associated building code requirements—should be varied to be more aligned with building practices and the changing nature of hurricanes due to climate change on the island to meet community expectations.

While considering the applicability of our results beyond Puerto Rico, it is important to acknowledge that the procedure might require significant adaptation for other regions. Special attention must be given to contextualizing the specific house typologies and

Table 7

Wind speed range contributing to the 90 % of the *Roof Structure* annual probability of failure under various climate scenarios.

Climate Scenario	Critical failure range wind speed [5th, 95th percentiles] mph (1 mph = 0.447 mps)			
	Gable	Gable-Fully mitigated	Hip	Hip-Fully mitigated
Current	[57,122]	[127,186]	[80,137]	[163,187]
RCP 2.6 [7]	[60,134]	[128,186]	[82,146]	[163,187]
RCP 4.5 [7]	[61,138]	[129,186]	[82,149]	[164,187]
RCP 4.5 [6]	[64,160]	[156,187]	[85,166]	[165,187]
RCP 6.0 [7]	[60,137]	[129,186]	[82,149]	[164,187]
RCP 8.5 [7]	[61,143]	[131,186]	[83,153]	[164,187]
RCP 8.5 [5]	[60,141]	[132,187]	[82,154]	[165,187]

material availability in the evaluated area. Engaging with local communities is crucial to conduct a thorough feasibility analysis of our proposed mitigation measures and to integrate potentially unique, local-based techniques. Despite these regional adjustments, the foundational approach of securing a continuous load path in the development of mitigation measures and recognizing knowledge gaps as a primary barrier remains broadly applicable. This approach can serve as a foundation for conducting workshops in other parts of the world. Additionally, region-specific climate models are necessary for accurately computing hurricane demands on structures. Frameworks, like the one provided by Esmaeili & Barbato [7], could serve as a basis for these models.

7. Conclusions

This study assessed hurricane wind performance of light-frame timber houses in Puerto Rico, focusing on developing fragility curves roof three critical limit states – roof envelope failure, roof structure failure, and shear wall failures – for both gable and hip roof types. This analysis used a component-based probabilistic method that considered how wind demands would contribute to roof envelope, structure, and wall failure at a range of wind speeds. These results were used to evaluate the probability of failure for the baseline typologies and to assess how various mitigation measures reduce this probability, comparing these probabilities of failure to target performance level and findings from other studies. Additionally, the research investigated the projected impact of multiple illustrative climate change scenarios on the probability of failure of the light-frame timber house typologies.

These assessments demonstrated the poor performance of the existing informally-constructed housing stock, with high risk of roof envelope and structure failure in hurricanes. The implementation of all proposed mitigation measures significantly reduced the probability of failure. Among the mitigation measures, reinforcing the roof-to-wall connection emerged as the most effective strategy in reducing the probability of failure associated with *Roof Structure* (life safety) performance level. The results showed that improvements to the roof structure through increasing the number (smaller spacing) and the dimension of wood components are the next most effective strategy. Reinforcing the envelope through improvements to the panel and panel-to-purlin connections improve the *Roof Envelope* (continued occupancy) performance, but can have detrimental effects on the *Roof Structure* performance if pursued without increasing the quality and number of roof-to-wall connections.

The fully-mitigated cases showed substantial improvements, on par with that performance found with other more formally constructed North American housing even without fully complying with all aspects of building codes and standards. Even so, they did not consistently meet the ASCE 7 [44] target (adequately low) probability of failure. The study also revealed that the future climate change scenarios considered have the potential to dramatically increase the probability of failure across all evaluated cases and performance levels. In these scenarios, the baseline typologies' performance becomes even more unacceptable, driving the need for design and mitigation strategies that meet these future climate conditions.

The surveys we conducted identified both resource constraints and knowledge gaps as significant obstacles preventing Puerto Rican communities from adopting the suggested mitigation measures for roof-to-wall and corrugated metal panel-to-purlin connections. These findings underscore the need to develop strategies to overcome some of the real and perceived cost barriers, and to improve understanding of these mitigation measures among local builders. A key aspect of the needed capacity building is to convey the long-term advantages of these mitigation strategies and to accommodate both current and anticipated future demands resulting from climate change.

Looking ahead, this research aims to set the stage for achieving safer and more resilient informally-constructed housing within Puerto Rican communities by identifying key challenges. Overcoming these challenges will involve an active collaboration with local stakeholders to boost knowledge and transfer the application of cost-effective strategies to reinforce houses against hurricane winds, particularly those focused on the roof-to-wall connections. These efforts will be especially critical given the expected increases in the frequency of hurricane-force winds, which indicates even worse performance by the end of the century without changes in building practices. Nevertheless, the results suggest that dramatic improvements are possible in performance with available materials and technologies. The improvements may reach close to a target level performance of modern standards and that achieved by typical light frame timber housing in North America without explicitly following all the detailing requirements of codes and standards. The ultimate goal of this endeavor is to enhance the resilience of communities in Puerto Rico and similar areas, preparing them to face escalating hurricane threats in a progressively changing climate.

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CRediT authorship contribution statement

D. Valdivieso: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **B. Goldwyn:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **A.B. Liel:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **A. Javernick-Will:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **D. Lopez-Garcia:** Writing – review & editing. **P. Guindos:** Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Diego Valdivieso Cascante reports financial support was provided by Simpson Strong-Tie. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request. Some of the data supporting the findings of this study is openly available in DesignSafe-CI (Ref. [77]).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ijdr.2024.104627>.

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