Hurricane wind performance and mitigation strategies for informally constructed houses in Puerto Rico

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ABSTRACT

This paper examines the performance of wood-based informally constructed houses in Puerto Rico, where resource-limited communities are vulnerable to climate-related hazards including hurricanes. Informally constructed housing is potentially vulnerable to hurricane and earthquake events but with significant variation depending on housing characteristics. This paper assesses the hurricane performance of representative housing typologies through a component-based performance-based wind engineering assessment framework. Results show that strengthening the roof envelope and roof-to-wall connections is essential for increasing the resilience of informally constructed wood houses in Puerto Rico. These upgrades are feasible for many builders and households, but challenges related to cost, appropriate construction, and material availability remain.

INTRODUCTION

Hazard-induced disasters have caused tens of billions of U.S. dollars in economic losses on a global scale since the 1990s (Botzen et al. 2019). The loss of residential structures is particularly impactful in terms of its long-term effect on community recovery (Peacock et al. 2018). Hurricanes are climate-related hazard events that disproportionately affect resource-limited communities, such as in Puerto Rico, where much of the population lives in informally constructed housing. Given the potential for increasing hurricane risks due to global climate change, it is essential to address the vulnerability of resource-limited populations in hazard-prone regions to build community resilience and reduce disaster risk (Mudd et al. 2014). Interdisciplinary and participatory approaches that engage communities in hazard assessment, mitigation, and recovery planning are critical (Hinojosa et al. 2018).

We define informally constructed housing as buildings constructed by builders without formal training and that may not adhere to building codes or other regulations (Goldwyn et al. 2022). In Puerto Rico and elsewhere, informally constructed housing is typically the only affordable housing available. Previous research by Hinojosa et al. (2018), Cruzado et al. (2018), and Goldwyn et al. (2022) has demonstrated that housing vulnerability varies depending on the characteristics of the housing. The wide variation in housing types and construction styles on the island contributes to differences in vulnerability. To improve informally constructed housing to be future-ready, understanding the available resources, risk perceptions, and construction knowledge of households and builders is essential. These factors determine design and construction choices that may enhance or reduce housing damage and, thus, community resilience.

Puerto Rico has experienced several devastating hurricanes over the last 30 years, including Hurricanes Hugo, Georges, Irma, and Maria, which have damaged or destroyed thousands of houses and infrastructure (see Figure 1), disrupted communication and electricity, and led to significant loss of life (Enterprise 2019). Wooden houses with corrugated galvanized iron (CGI) roof panels have been particularly vulnerable. The most recent major hurricane was Hurricane Fiona in September 2022. The majority of recovery efforts post-hurricane in Puerto Rico and elsewhere have been initiated and financed by households themselves, i.e., self-recovery, and a better understanding of how to support self-recovery that reduces disaster vulnerability is needed (Opdyke et al. 2021). Researchers have called for additional studies on perceived risks and how they relate to mitigation and resilience building to intervene and improve housing safety (Goldwyn et al. 2022; Cruzado et al. 2018).

This paper quantitatively examines the impact of mitigation measures on the performance of informally constructed houses, which are representative of Puerto Rican informal construction, during hurricanes. It does so by generating structure fragility curves of typical ("baseline") and possibly mitigated ("future-ready") housing, considering the pressure change in the structure as the envelope fails, and realistic material properties of housing and roof configurations observed in the field. The scope of the paper is limited to wind effects and excludes hurricane flood risk and storm surge.

PRIOR EVALUATIONS OF WOOD HOUSES UNDER HURRICANE WIND LOADS

Residential wood-framed construction, which constitutes around 90% of housing in the United States (Ellingwood et al., 2004), is responsible for the majority of economic losses from hurricanes, averaging $5.4 billion annually (Li et al., 2009). Several studies have evaluated the behavior of these houses under hurricane and/or tornado winds (e.g., Ellingwood et al. 2004; Li et al. 2009; Van de Lindt et al. 2009; Amini et al. 2014; Lochhead et al. 2022) using a component-based performance-based wind engineering assessment framework. These studies have typically drawn from the published literature to quantify component capacities and demands.

The most vulnerable part of a building exposed to a hurricane is its envelope, with damage to the building envelope leading to damage to the building contents by wind and rain (Ellingwood et al. 2004). Envelope failure modes include roof panel uplift, failure of roof-to-wall connections due to uplift, and broken windows and doors due to excessive wind-induced pressure or projectile impact (Li et al. 2009). These are also the most common failure modes experienced in wood-frame construction in Puerto Rico in recent hurricanes (Figure 1).

Lochhead et al. (2022) previously examined hurricane performance informally constructed houses in Puerto Rico. The study found that the typical governing failure mode in an informally constructed house is roof panel loss due to tear-through at the fasteners between the panel and the roof structure. If this failure mode is avoided, panel loss due to failures at the purlin-to-truss connections and failures of the roof-to-wall connections also occur. Lochhead et al. (2022) identified two primary mitigation measures: 1) improving the fastening of the panel to the roof structure and 2) installing hurricane straps at the truss-to-wall and the purlin-to-truss connections. The authors of that study, however, faced limitations as they did not have access to connection-level test data for the proposed mitigation measures. This led to approximations in the evaluation of failure. In addition, that study did not consider the load redistribution effect that occurs when the loss of panels in the roof envelope alters the pressure distribution across the structure (Stewart et al., 2016).

Figure 1. Damage photos showing (a) roof envelope, (b) roof-to-wall connection, and (c) sliding failure modes after Hurricane Maria (2017). Photos: Emily Alfred, Protechos.

METHODS

Static Wind Analysis. The hurricane performance of the baseline and future-ready typologies, defined below, was assessed using the component-based performance-based wind engineering framework. In this analysis, component capacities were drawn from published literature and test results provided by Simpson Strong-Tie, updating the approach considered by Lochhead et al. (2022). Simpson Strong-Tie is the predominant purveyor of hurricane straps on the island.

Wind load is applied over the structure using the ASCE-7 (ASCE/SEI 2016) coefficients for low-rise buildings to statically determine wind pressures as a function of the intensity measure (i.e., 3-s wind speed gust, referred to here as velocity). Pressure coefficients Cp from Chapter 28 (Main Wind Force Resisting System–Envelope Procedure) were used for walls and truss-to-wall connections and from Chapter 30 (Components and Cladding) for panels, fasteners, and purlin-to-truss connections (ASCE/SEI 2016). The analysis does not suppose a specific location and topography to represent houses at a range of locations on the island.

The wind pressures on the roof-to-wall connections and the shear walls are updated throughout the analysis considering Stewart et al. (2016) procedure for accounting for the internal pressure change as the envelope fails. Uncertainties in capacities and demands are considered following Venable et al. (2020).

Probabilistic Performance Assessment. Hurricane performance is quantified by a structural fragility curve that shows the probability of failure as a function of wind speed. The fragility curve is characterized by the median wind speed at failure. Monte Carlo simulation was used to propagate uncertainties in the wind loads and the component capacities through the performance assessment to develop the fragility, considering 500 realizations at each wind speed. The structural fragility curves are built from component and failure mode fragility curves. The components considered are roof panels, purlins, connections between purlins and truss, roof-to-wall connections, and shear walls. The system failure modes considered are the roof envelope, roof-to-wall connection, and shear walls.

In each realization, fasteners, connections, and purlins are considered as failed if the uplift wind demands exceed the capacities, considering the countervailing effects of dead load. For the roof panel components, additional failure criteria need to be defined because these are based on the fastener and purlin failures. For informally constructed houses in Puerto Rico, Lochhead et al. (2022) defined failure criteria for roof CGI panel components corresponding to the failure of 10% or 2 fasteners fail, whichever is greater (Lochhead et al. 2022). This criterion is consistent with the evidence that suggests that the failure of a few fasteners will result in panel failure (Stewart et al. 2018). To establish the relationship between the failure of purlin-to-truss connection and roof panel failure, Lochhead et al. (2022) assumed that the failure of all purlin-to-truss connections on a single purlin is required for the purlin to fail, and the failure of the purlin at the edge of a roof panel results in panel failure.

The system failure mode fragility curves were developed by considering the fragility curves of all components in that system, assuming that each component's failure mode is independent of other components, conditioned on the wind speed, following Stoner (2020). The structure fragility curve is controlled by the envelope of the failure mode fragility curves.

BASELINE INFORMALLY CONSTRUCTED HOUSE TYPOLOGIES

Definition. The selection of representative informally constructed house typologies shown in Figure 2 was based on fieldwork observations and from information provided by nongovernmental organizations (NGOs) assisting households with rebuilding. Some of the fieldwork was previously summarized in Goldwyn et al. (2022); additional fieldwork was conducted in October 2022. In this study, the house typology plan dimensions are taken as 4.9 m by 7.3 m, a story height of 2.44 m, and a roof slope of 21 degrees. Gable and hip roof shapes are considered, with metal CGI panel roofs connected to the purlin system. The roofs have 150 mm eave extensions. Wood trusses were considered as the structural system of the roof. The analysis was limited to 1-story structures using wood-frame shear walls sheathed with 9.0 mm grooved plywood boards as the lateral system. The baseline house typologies from Lochhead et al. (2022) were redefined considering purlins installed in a flat position, which was found to be more typical in informally constructed houses. In addition, we assume Southern Yellow Pine as the raw material for wood structure, as it is the most readily available material locally. All the cases are considered to be partially enclosed structures based on field observations. Table 1 summarizes the baseline typologies.

Table 1: Baseline and future-ready typologies for both hip and gable roofs

Item	Baseline	Future Ready
CGI gauge	26	24 (thicker)
CGI-to-purlin connection	nail	screws
CGI-to-purlin connection spacing	300 mm exterior/interior	150 mm exterior/interior
Purlin size	nominal 2x4	nominal 2x6
Purlin-to-truss connection	nailed	screwed*
Truss(roof)-to-wall connection	toe-nailed	hurricane straps
Truss spacing	1800 mm	1200 mm /600 mm
Purlin spacing	1200 mm	600 mm

* Lochhead et al. (2022) considered hurricane straps at purlin-to-truss connections. However, further fieldwork in Puerto Rico indicates there is not typically enough space to place hurricane straps at these locations making them less effective than screwed connections.

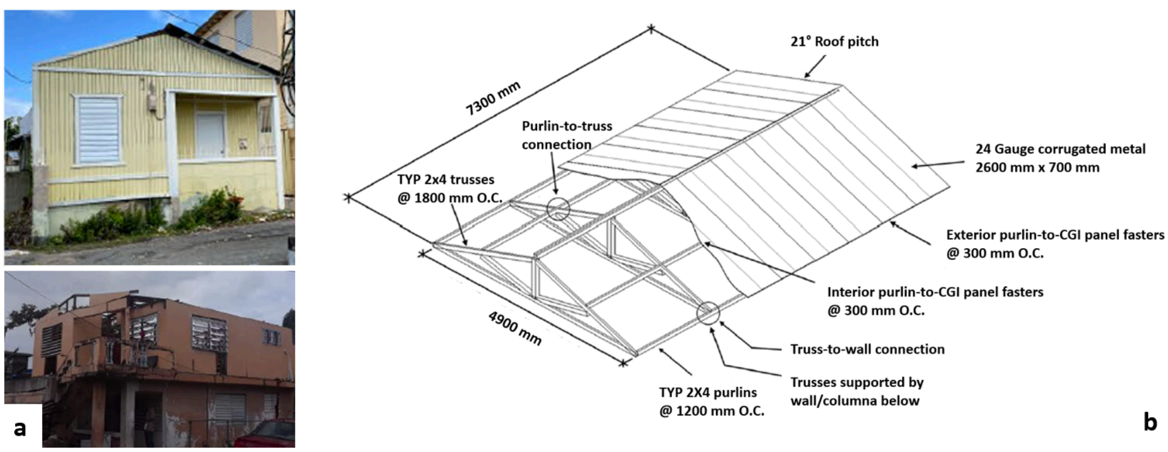

Figure 2. (a) Example of informally constructed houses in Puerto Rico and (b) 3D schematic of gable house typologies. Modified from Lochhead et al. (2022).

Hurricane Performance. Results for baseline typologies are shown in Figure 3. These results show that the CGI panel loss due to fastener failures is the main failure mode of the *Gable* typology, which is consistent with the failure modes in Hurricane Maria. As the baseline typologies use toenails for the wall-to-truss connection, this failure mode is the first most likely for the *Hip* and the second most likely in the *Gable* case. This failure mode is more catastrophic because the entire roof is compromised. Considering the median wind speed at failure, the *Gable* baseline house typology could not withstand a Category 1 hurricane; this finding is consistent with previous results (Lochhead et al. 2022). Thus, a significant improvement for future-ready houses in Puerto Rico is needed and results indicate that mitigation measures should be oriented to strengthen CGI panel-to-purlin and wall-to-truss connections for securing the structure's loading path.

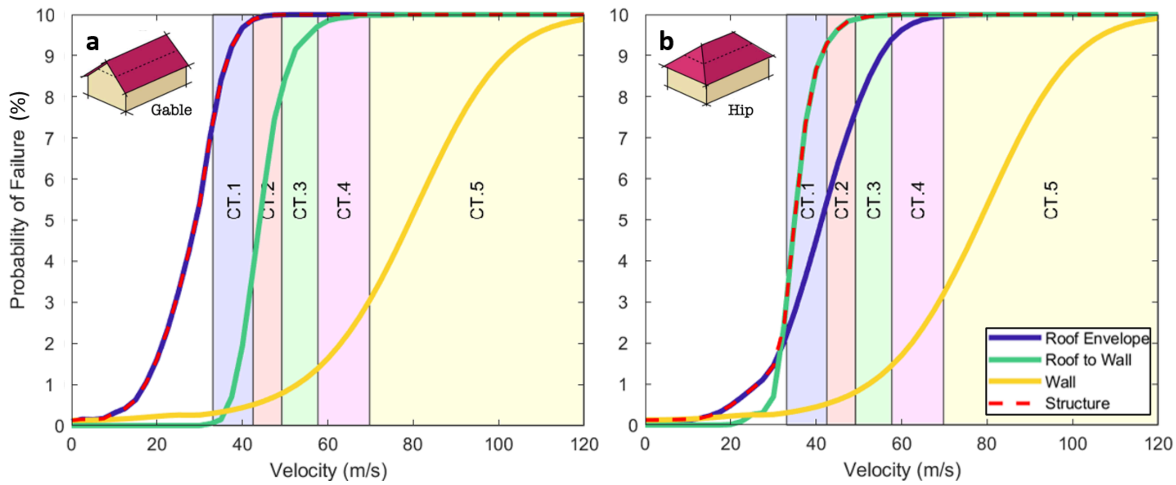

Figure 3. System failure mode and structure fragility curves for (a) gable- and (b) hip-roof baseline typologies. CT = category, defined by the Saffir-Simpson Hurricane Wind Scale.

FUTURE-READY INFORMALLY CONSTRUCTED HOUSE TYPOLOGIES

Definition. The mitigation measures consider incremental improvements for existing or new structures. Mitigation measures are focused mainly on roof structure (e.g., enhancements of connection of CGI panels to the roof structure, wall-to-truss connection, truss spacing, purlin-to-truss connection, purlin spacing, CGI panel thickness). Four future-ready house typologies were defined from the baseline typologies with a combination of mitigation measures implemented, as described in Table 1.

Hurricane Performance. Figure 4 provides results for the future-ready housing typologies. The implemented mitigation measures yielded positive results, demonstrating that *Gable* and *Hip* typologies can withstand a Category 4 (like Hurricane Maria) and almost a Category 5 hurricane, respectively, considering the metric of the median windspeed at failure. For the future-ready typologies, the median wind speed at failure doubled for both *Gable* and *Hip* typologies compared to the baseline housing typologies. The CGI panel loss -- which occurred due to detachment from the purlins -- is the main failure mode for both the future-ready *Gable* and *Hip* typologies. As a result of strengthening the roof-to-wall connection, the most likely second failure mode is the shear wall of the structure which could be a catastrophic (i.e., collapse) failure of the house.

As Figure 4 shows, reducing truss spacing has a significant effect on the roof-to-wall connection failure mode and it becomes relatively less likely to occur. However, there is no effect of truss spacing in the roof envelope and wall failure modes. If further improvement is desired above and beyond the typologies described here, additional mitigation measures could further strengthen the CGI panel-to-purlin connection and shear walls by reducing fastener spacing and providing a stronger overturning restraint system, respectively.

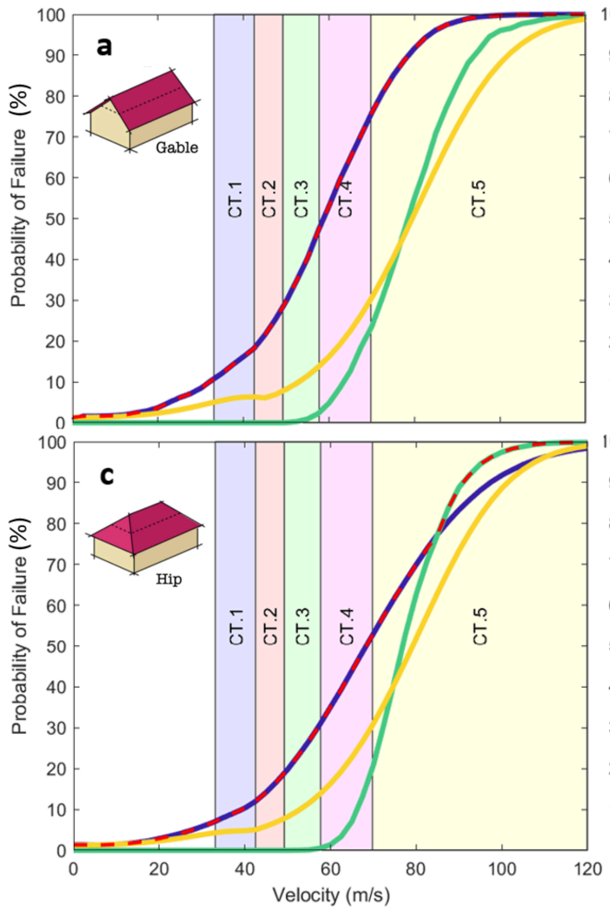

Figure 4. System failure modes and structure fragility curves of future-ready typologies for the gable roof with trusses spaced at (a) 1200 mm and (b) 600 mm, and hip roof with trusses spaced at (c) 1200 mm and (d) 600 mm.

FEASIBILITY

Previous fieldwork by our team (Goldwyn et al., in press) highlight several barriers to the adoption of these mitigation measures. These barriers include limited knowledge about their importance and appropriate installation, as well as concerns about the associated costs. For instance, during our fieldwork, we observed builders working with NGOs incorrectly installing hurricane straps horizontally (rather than vertically) at the purlin-to-truss connection, due to space limitations.

To assess the feasibility of the proposed mitigation measures, additional fieldwork was conducted in June 2023. This assessment involved training ~30 builders on the proposed mitigation measures and conducting interviews with these builders, as well as ~15 hardware store employees, to gather feedback from Puerto Ricans working in the informal building industry about their likelihood of implementing these measures before or after future events. Builders and hardware store employees believe that implementing the proposed mitigation measures will enhance the safety of their houses, provide shelter for neighbors, and contribute to improved mental well-being by increasing preparedness for future hurricanes. However, participants expressed concerns regarding the cost, lack of understanding, and material availability, which are perceived as the main barriers to adopting the proposed mitigation measures. Cost is particularly identified as the primary obstacle for most mitigation measures, particularly where the life-cycle benefits are not clearly conveyed. For the panel-to-purlin connection spacing, a lack of understanding stands out as a key challenge. Based on this valuable feedback, we will update and refine the proposed mitigation measures to address these identified barriers.

CONCLUSIONS

The study presented results for baseline and future-ready house typologies subjected to hurricane loads. Baseline typologies showed that the roof panel loss and failure of the roof-to-wall connections were the main failure modes of the *Gable* and *Hip* roof houses, respectively. Mitigation measures should, therefore, focus on strengthening the CGI panel-to-purlin and truss-to-wall connections to secure the loading path. Future-ready typologies showed that with the proposed mitigation measures, the evaluated house typologies could withstand the next Category 4 hurricane event. For these upgraded houses, the most likely failure was panel loss due to failure at the connection between the panel and purlin, while the second most likely failure mode was shear wall failure. The proposed mitigation measures were shared at training and the materials were well received, but concerns about cost, lack of understanding, and material availability persisted. The study emphasizes the need for improving house typologies to be future-ready in Puerto Rico, particularly considering the devastating Hurricane Maria in 2017.

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