Damage Assessment and Validation of a Community Resilience Model for Galveston Island under Two Historical Hurricane Scenarios

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Abstract

Coastal communities are highly vulnerable to multi-hazard events, particularly hurricanes that impose combined wind, surge, and flooding impacts. Effective community resilience planning requires validated models to assess potential damage and guide mitigation strategies. This study presents a damage assessment and validation framework applied to Galveston Island, using two historical hurricane scenarios. The Holland wind field model was employed to simulate hazard intensity, and fragility functions were mapped to a detailed building inventory for structural vulnerability assessment. Results highlight spatial patterns of damage across multiple states, supporting emergency management and resource allocation. The framework also facilitates validation by comparing simulated outcomes with historical data, enhancing confidence in community-scale resilience modeling.

Keywords: Community Resilience, Hurricane Damage Assessment, Galveston Island, Scenario Analysis, Holland Wind Model, Fragility Functions.

1. Introduction

Urban communities worldwide are increasingly exposed to the adverse impacts of natural hazards, including earthquakes, floods, tsunamis, and hurricanes. The growing frequency and intensity of such events, driven in part by climate change and urbanization, underscore the importance of enhancing community resilience. Community resilience refers to the capacity of a community to withstand, adapt to, and recover rapidly from disruptive events while maintaining critical functions (Koliou et al., 2018). Unlike traditional engineering approaches that focus on individual structures, community resilience emphasizes a holistic assessment of both physical infrastructure and social systems, aiming to minimize downtime, economic losses, and population displacement after a hazard event.

Coastal regions, in particular, face heightened risks due to their exposure to tropical cyclones and hurricanes, which present complex multi-hazard scenarios. These storms generate destructive forces through high winds, storm surges, and coastal or inland flooding, often acting simultaneously to compromise infrastructure and disrupt communities (Nofal, 2021). While integrated hazard assessments are essential, prior studies have shown that wind loads often contribute the most to structural damage in hurricane events, making wind hazard modeling a critical component of risk assessment frameworks (Guo & van de Lindt, 2019; Vickery et al., 2006, 2009).

To evaluate potential impacts and support decision-making, community-scale damage assessments typically couple hazard models with vulnerability representations, such as fragility functions or vulnerability portfolios (Lin & Wang, 2016; Zhang et al., 2018). These functions quantify the probability of damage states for different building types under varying hazard intensities. However, for such models to be reliable in practice, they must be validated against empirical data from past events. Testbed communities, where detailed building inventories and historical hazard records are available, offer an ideal platform for this validation process.

In addition to supporting scientific validation, scenario-based damage assessments play a vital role in disaster preparedness and response planning. By identifying zones of high expected damage, emergency managers can prioritize resource allocation, evacuation planning, and post-disaster recovery efforts. Furthermore, insights gained from these analyses can inform long-term mitigation strategies, such as strengthening building codes or retrofitting vulnerable structures.

This study presents a comprehensive damage assessment and validation framework applied to Galveston Island, a coastal community with a history of hurricane exposure. Using two historical hurricane scenarios, this research integrates hazard simulation, fragility mapping, and geospatial analysis to evaluate community-level impacts. The outcomes not only demonstrate the sensitivity of damage patterns to hurricane characteristics but also provide a foundation for enhancing resilience planning in similar coastal regions.

2. Methodology

The first step in conducting a community-based hurricane damage assessment is selecting a suitable case study area. An ideal candidate community should have comprehensive building inventory (BI) data and detailed historical records of past hurricanes, including track information. Coastal regions, due to their frequent exposure to tropical cyclones, are particularly appropriate for such studies. In this research, Galveston Island was selected as the testbed community, given its rich BI dataset and well-documented hurricane history (Figure 1).

The second step involves defining the hazard components to be included in the analysis. Hurricanes present multiple hazards—primarily strong winds, storm surge, and coastal or inland flooding (Ding et al., 2016; Masoomi et al., 2019). While a comprehensive multi-hazard assessment is ideal, this study focuses solely on wind-induced damage, reflecting its predominant contribution to structural impacts in past events.

Next, an appropriate hazard model must be employed to simulate wind speeds across the community during a scenario hurricane. For this purpose, stationary mathematical models, such as the Holland wind field model, are used to estimate wind intensity at building locations based on hurricane track data. Accurate representation of the hurricane's path over the community is essential for reliable hazard simulation.

Once wind speed estimations are obtained, the structural vulnerability of the community is assessed by linking the hazard model to a set of fragility functions. These functions describe the probability of buildings reaching or exceeding specific damage states under given wind intensities. A representative set of fragility curves must be selected and systematically mapped to buildings in the BI dataset based on structural characteristics.

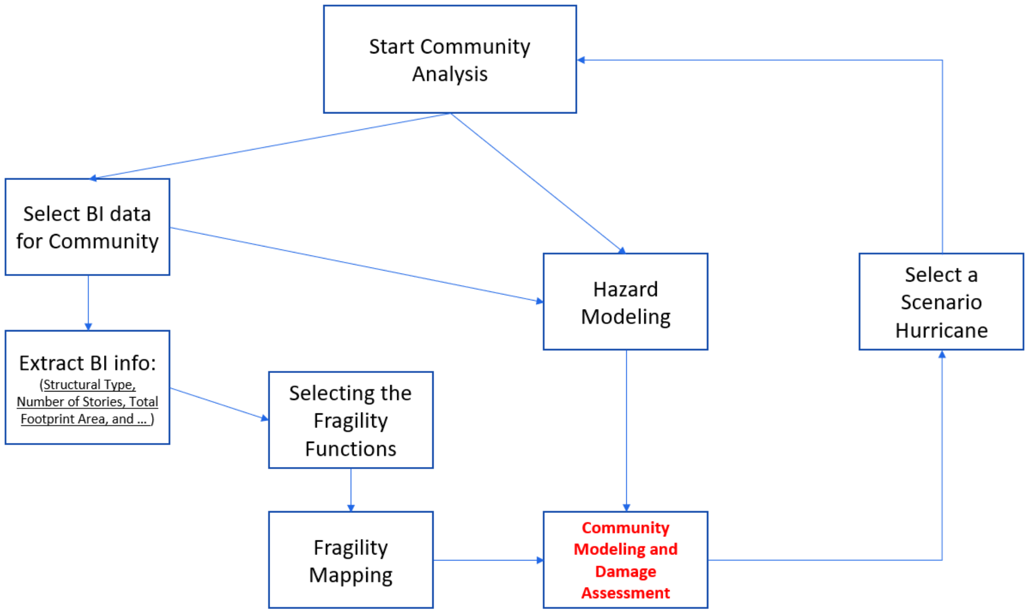

Figure 1. Workflow for community-scale hurricane damage assessment using hazard simulation and fragility mapping.

The subsequent subsections detail each component of this methodology: the building inventory of Galveston Island, the selected hazard model and scenario hurricanes, the criteria for fragility curve mapping, and the overall framework for community modeling and damage assessment. This structured approach ensures that the simulation outputs can be effectively used for both risk evaluation and validation against observed post-hurricane damage data.

2.1 Building Inventory Data of the Candidate Community

Galveston Island, a barrier island located southeast of Houston, Texas, was selected as the case study for this community-based hurricane damage assessment. The region is historically vulnerable to coastal storms, hurricanes, and flooding events, making it an ideal testbed for resilience modeling. Additionally, Galveston's socio-demographic diversity, characterized by a wide range of income levels and a racially and ethnically varied population, underscores the importance of comprehensive risk assessments in such communities.

The building inventory (BI) for Galveston comprises 18,962 residential structures. This inventory corresponds to approximately 32,501 housing units, reflecting the fact that many buildings accommodate multiple households. The distinction between building counts and housing units is critical for accurately mapping vulnerability, as structural characteristics are assigned at the building level, while social impacts may correlate with household data.

All BI data utilized in this study were sourced from the IN-CORE platform, which provides detailed, geospatially-referenced datasets for designated testbed communities, including Galveston Island. This comprehensive dataset includes structural attributes necessary for fragility mapping and supports both hazard simulation and subsequent damage assessment.

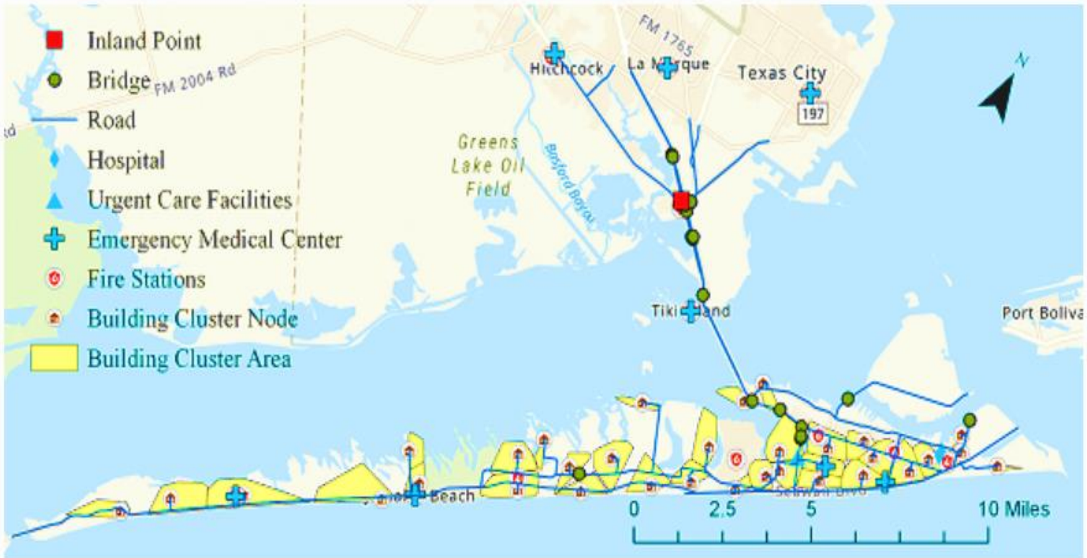

Figure 2. Geographic location of Galveston Island selected as the community testbed for resilience modeling.

2.2 Hazard Model and Scenario Hurricanes

The Holland hurricane wind field model, as refined by Vickery and Wadhera (2008), is widely recognized for simulating hurricane-induced wind hazards. This parametric model requires a limited set of input parameters—such as central pressure, maximum wind speed, and radius to maximum winds (RMW)—to generate spatial distributions of tangential wind fields. Its efficiency and reliability make it suitable for community-scale hazard assessments.

In this study, input parameters for the Holland model were derived from historical hurricane data specific to Galveston Island, obtained from NOAA's Historical Hurricane Tracks database. As illustrated in Figure 4, Galveston has experienced multiple hurricane events, confirming its status as a hurricane-prone coastal community within Texas.

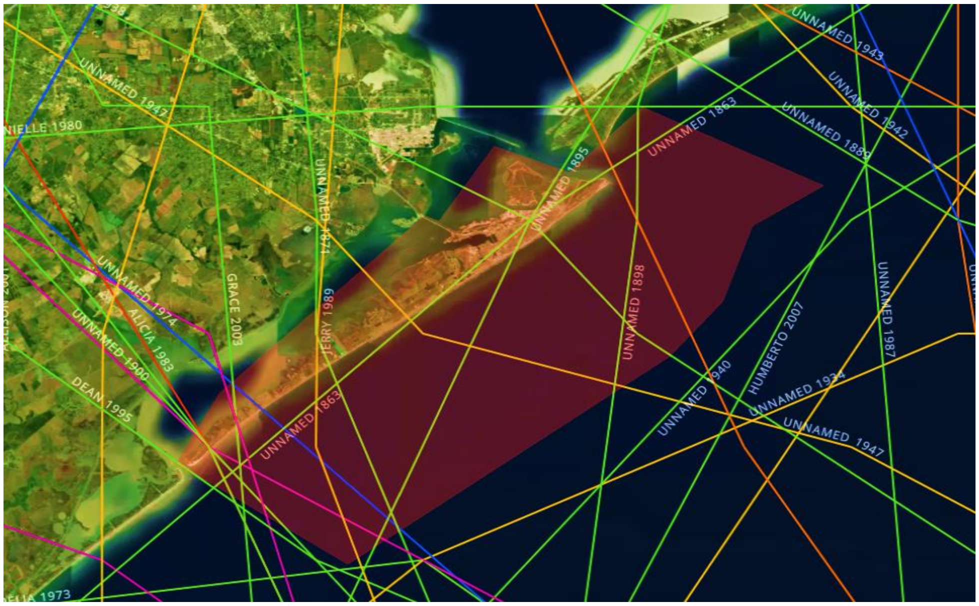

Figure 4. Historical hurricane tracks recorded over the Galveston region, highlighting its exposure to recurring tropical cyclones.

Two historical hurricanes were selected as scenario events for this analysis, chosen based on their significant impact and availability of detailed track data. The first scenario hurricane (HR1) corresponds to the event of August 23, 1915, while the second scenario hurricane (HR2) represents the storm of August 27, 1947. The recorded paths of these hurricanes are depicted in Figures 5 and 6, respectively.

Table 1. Key characteristics of the selected scenario hurricanes (HR1 and HR2), including date, maximum wind speed, minimum central pressure, and associated track reference.

Scenario hurriccanes	**Date**	**Maximum wind speed (kt)**	**Maximum pressure (mb)**	**The path recorded**
HR1	Aug 23 of 1915	125	940	Figure 5
HR2	Aug 27 of 1947	70	984	Figure 6

Key characteristics of HR1 and HR2, including maximum sustained wind speeds and minimum central pressures near the Galveston boundary, are summarized in Table 1. It is important to note that these values represent localized measurements; comprehensive datasets exist along each hurricane's full trajectory, allowing for detailed hazard modeling across the community.

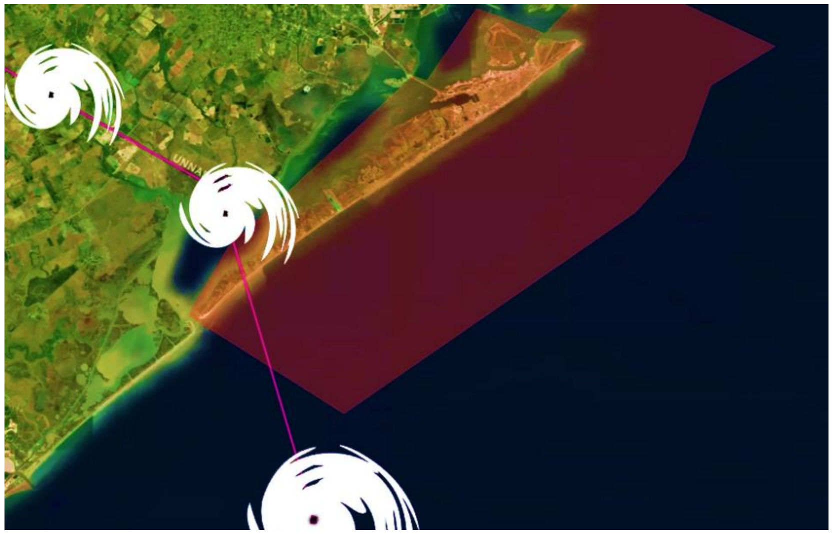

Figure 5. Track of Scenario Hurricane HR1 (August 23, 1915) across the Galveston region.

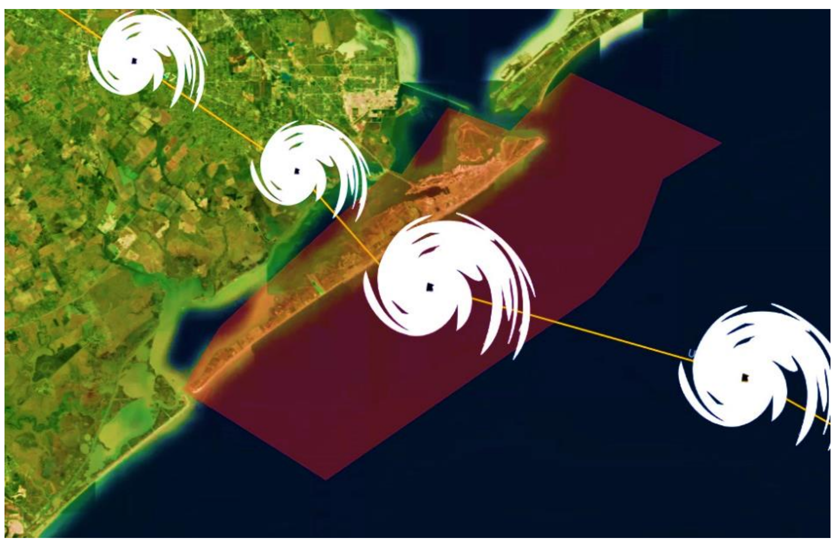

Figure 6. Track of Scenario Hurricane HR2 (August 27, 1947) across the Galveston region.

To perform the hazard analysis, the Holland model was calibrated for each scenario using these parameters. Wind speed estimations were generated for all building locations within the Galveston community footprint. Figure 7 illustrates the spatial distribution of simulated wind speeds for HR2, representing a critical input for subsequent damage assessment. This process, termed hurricane hazard analysis, provides the necessary link between historical hurricane characteristics and localized wind demand on the built environment.

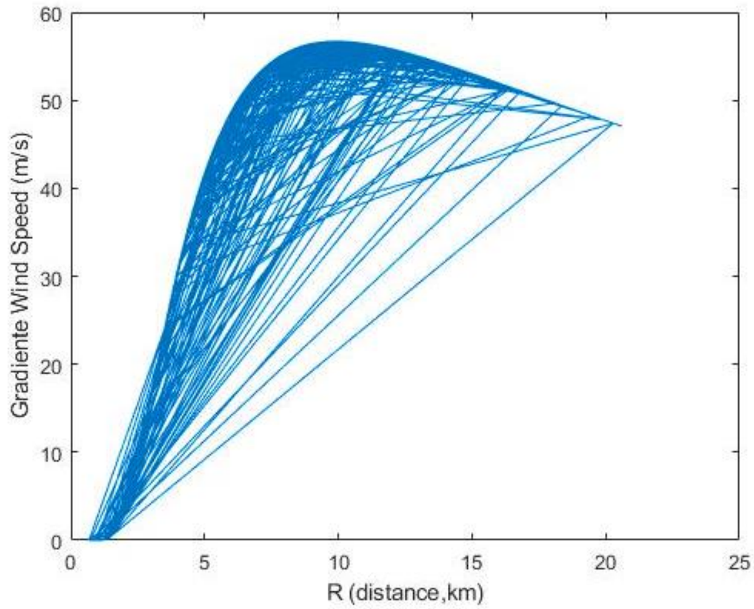

Figure 7. Simulated wind speed distribution for HR2 across building locations in Galveston using the Holland wind field model.

2.3 Mapping Criteria

As outlined in previous sections, the application of appropriate fragility functions is essential for assessing building-level damage within a community subjected to a hazard scenario. This process, known as fragility mapping, involves assigning relevant fragility curves to each building in the dataset based on its structural characteristics and attributes captured in the Building Inventory (BI).

For the Galveston community, four key parameters were identified to guide the fragility mapping process:

- **Building Type:** All structures within the testbed are classified as wood-frame buildings, simplifying the selection of applicable fragility functions.
- **Elevation of the Lowest Horizontal Structural Member:** Critical for assessing vulnerability to hazards influenced by elevation, such as flooding or surge, but also indicative of structural design practices.

- **Building Age Group:** Categorized into four groups reflecting construction era—pre-1974, 1974–1987, 1987–1995, and 1995–2008—this parameter accounts for changes in building codes and construction practices over time.
- **Total Building Height / Number of Stories:** Derived from elevation data, this parameter is directly linked to structural vulnerability under wind loading conditions.

Using these parameters, a rule-based approach was implemented in MATLAB to automate the fragility assignment. A conditional logic structure (if/elseif statements) was developed to ensure that each building was mapped to the most representative fragility curve based on its height and age classification.

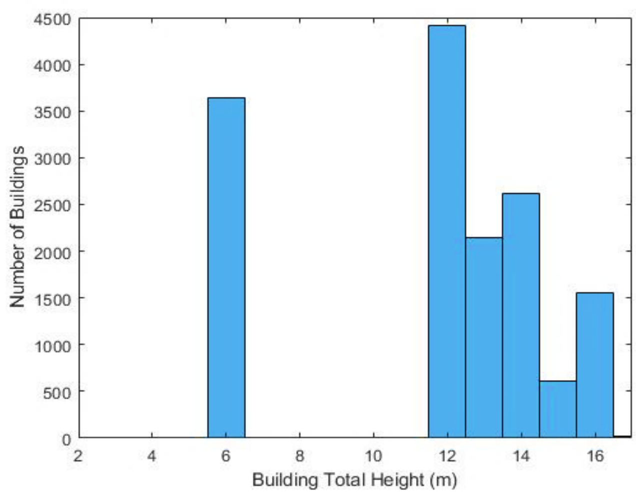

Figure 8. Distribution of total building heights for wood-frame structures within the Galveston community.

Given that all buildings in this study are wood-frame structures, the primary differentiator in fragility mapping was building height, expressed either as total height or number of stories. This parameter significantly influences wind vulnerability, as taller structures generally experience higher wind pressures and associated risks.

Figure 8 presents the distribution of building heights across Galveston Island, illustrating the prevalence of low-rise wood-frame structures within the community. This distribution informed the selection and application of fragility functions tailored to different height categories.

2.4 Fragility Functions

Fragility curves represent the probability that a structure will reach or exceed a specified damage state given a particular hazard intensity. These curves are fundamental tools in risk and resilience assessments, enabling the prediction of potential damage to built infrastructure under various natural hazards, including hurricanes, earthquakes, and tsunamis. Beyond damage prediction, fragility functions support decision-making processes across all phases of disaster management—pre-event mitigation, emergency response, and post-disaster recovery—by informing strategies to minimize economic losses and safeguard human life.

In community resilience studies, fragility curves are typically categorized into two types:

- **Empirical Fragility Functions:** Derived from post-disaster field reconnaissance and statistical analysis of observed damage data.
- **Analytical Fragility Functions:** Developed through structural engineering principles, numerical simulations, and probabilistic modeling.

For this study, analytical fragility functions developed by Memari et al. (2018) were selected, given their relevance to the structural typology of Galveston Island. Memari et al. provided a comprehensive set of fragility curves for 19 wood-frame structures subjected to wind hazards, applicable to both hurricanes and tornadoes. These curves define the likelihood of exceeding four distinct damage states, offering a robust framework for assessing wind-induced structural vulnerability in wood-frame communities.

Considering that the Galveston building inventory consists exclusively of wood-frame structures, the fragility functions tailored for hurricane hazards were directly mapped based on building characteristics, as detailed in Section 2.3. Figure 9 illustrates typical fragility curves from Memari et al. (2018), depicting the probability of damage state exceedance for both tornado (Figure 9a) and hurricane (Figure 9b) scenarios. For this analysis, only the hurricane-specific fragility functions were applied.

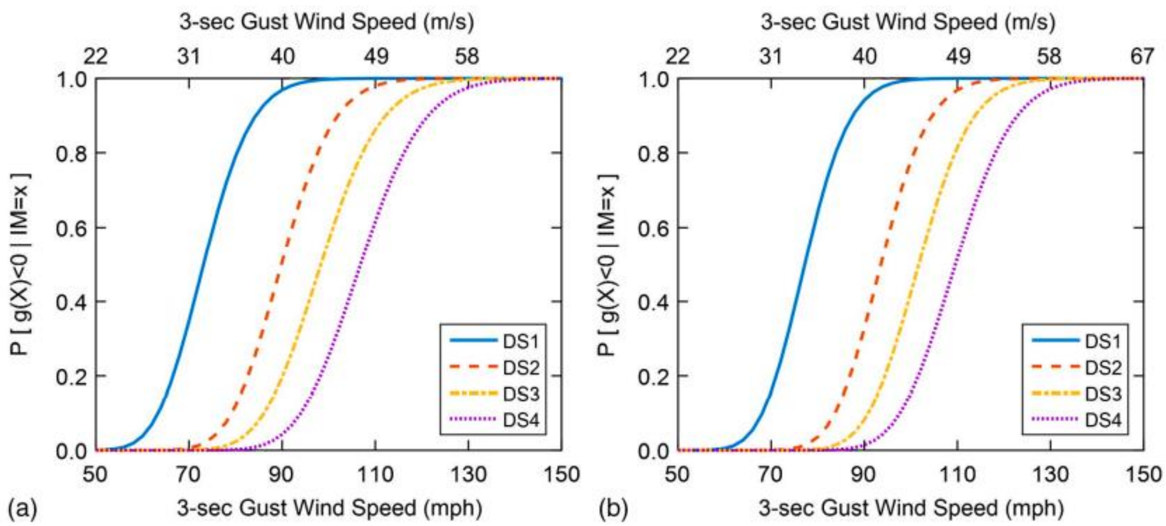

Figure 9. Example fragility curves developed by Memari et al. (2018) for wood-frame structures: (a) tornado scenario, (b) hurricane scenario.

2.5 Community Modeling

Community modeling in this study was conducted through the integration of geospatial data and hazard-vulnerability frameworks to assess potential hurricane-induced damage across Galveston Island. Geospatial variables from the Building Inventory (BI) were managed and visualized using a combination of software tools, including ArcMap for GIS-based spatial analysis, MATLAB for data processing and fragility mapping, and Excel for handling and preprocessing CSV datasets extracted from the IN-CORE platform.

The BI data, sourced from shapefiles and CSV tables associated with the Galveston testbed in IN-CORE, were mapped to represent the spatial distribution of structures across the community. As illustrated in Figure 10, the geospatial layer of building locations was visualized over the Galveston region using ArcMap, with supplementary visualization and analysis performed through Python 3 scripts and Google Earth Pro to enhance interpretability and presentation.

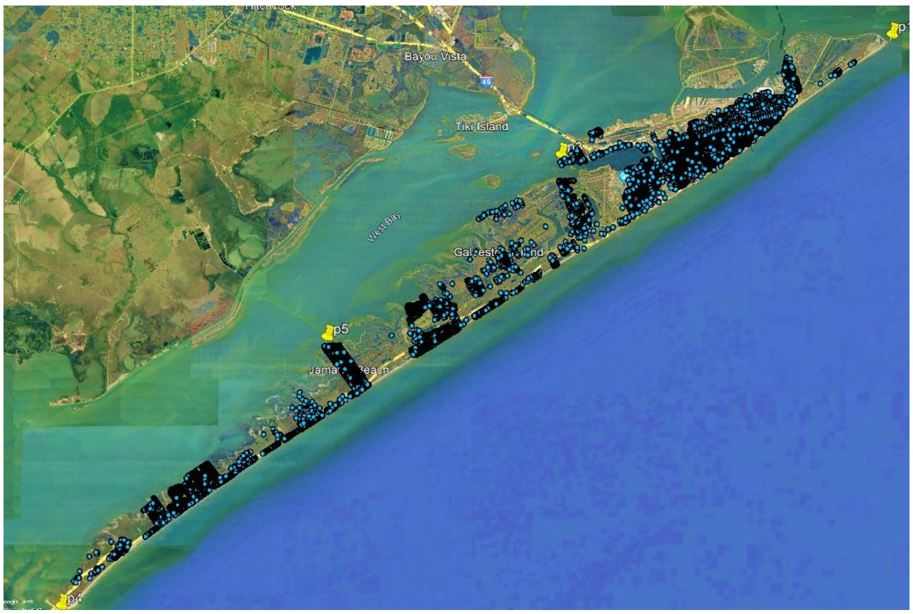

Figure 10. Geospatial visualization of Galveston's building inventory (BI) data mapped over the island.

In addition to mapping the BI, these tools facilitated the visualization of damage assessment outcomes, enabling clear representation of damage state distributions following the simulation of scenario hurricanes HR1 and HR2. The integration of GIS and computational tools ensured efficient management of large datasets and supported spatially explicit analysis critical for community-scale resilience assessments.

The detailed results of the damage simulations, including geospatial distributions of damage states for both hurricane scenarios, are presented in the following section. These visualizations provide valuable insights into the spatial patterns of vulnerability and expected impacts on Galveston's infrastructure under varying hurricane intensities.

3. Damage Assessment Results

A community-scale damage assessment was conducted for Galveston Island under two historical hurricane scenarios—HR1 (1915) and HR2 (1947). The analysis utilized four predefined damage states (DS1 to DS4), consistent with the fragility functions assigned to each building. These damage states range from minor non-structural damage (DS1) to complete structural failure or collapse (DS4), enabling a comprehensive evaluation of potential impacts across the community.

Figure 11 illustrates the spatial distribution of damage states resulting from HR1. The assessment considered the cumulative wind effects along the full path of the hurricane as it traversed the Galveston region. As observed, the concentration of damage is highest in the central areas of the community, corresponding to zones exposed to maximum wind speeds. While a broad portion of buildings experienced minor damage (DS1), the extent of severe damage (DS3 and DS4) was notably localized, reflecting the rapid attenuation of wind intensity with distance from the hurricane's core.

The transition from DS1 to DS4 demonstrates a clear reduction in the spatial footprint of affected buildings, as only structures within proximity to peak wind zones reached higher damage states. Buildings located either too close to the hurricane eye—where wind speeds may momentarily drop—or on the periphery of the storm path predominantly remained within DS1, consistent with typical tropical cyclone behavior.

a) DS1 (0-52%)

b) DS2 (0 – 39%)

c) DS3 (0 – 92%)

d) DS4 (0 – 26%)

Figure 11. Spatial distribution of damage states (DS1–DS4) in Galveston under Scenario Hurricane HR1: (a) DS1 (0–52%), (b) DS2 (0–39%), (c) DS3 (0–92%), (d) DS4 (0–26%)

Further detailing is provided in Figure 12, which focuses on the DS3 distribution for HR1, highlighting areas most susceptible to significant structural damage.

Figure 12. Focused distribution of DS3 damage state in Galveston under Scenario Hurricane HR1.

In contrast, the damage pattern resulting from HR2 exhibited a more symmetric distribution around the hurricane’s path (Figure 13). Due to HR2's lower maximum wind speed compared to HR1, the majority of buildings were subjected to lower hazard intensities, resulting in damage predominantly confined to DS1 and DS2. Notably, no buildings reached DS4 under HR2, and only a small fraction exceeded DS3, reflecting the reduced severity of this scenario.

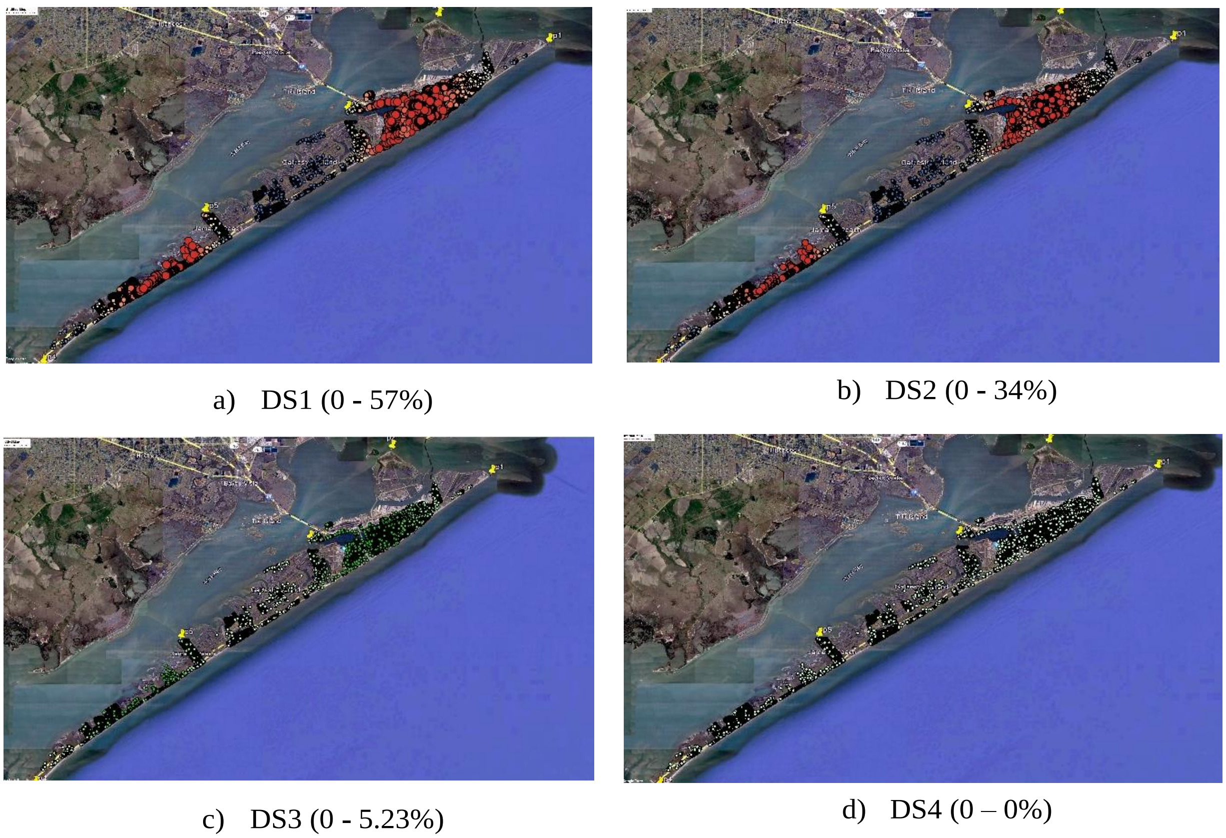

Figure 13. Spatial distribution of damage states (DS1–DS4) in Galveston under Scenario Hurricane HR2: (a) DS1 (0–57%), (b) DS2 (0–34%), (c) DS3 (0–5.23%), (d) DS4 (0%).

These results emphasize the sensitivity of community-level damage outcomes to hurricane intensity and path characteristics. While HR1 induced widespread moderate to severe damage, HR2’s impact was largely limited to minor and moderate damage states. This comparison underscores the importance of scenario-based assessments for understanding the range of potential impacts and informing resilience planning.

4. Discussions and Applications

This study modeled the cumulative effects of each hurricane by simulating multiple stationary wind fields along the full path of the selected scenario hurricanes. The damage status of each building within Galveston Island was determined through the integration of these hazard simulations with building-specific fragility functions, enabling a detailed community-scale assessment.

Community-based hurricane damage assessments, such as the one presented here, provide critical insights for emergency management and disaster preparedness. By identifying areas most susceptible to severe wind-induced damage, these assessments support proactive decision-making, including targeted evacuation planning, resource allocation, and post-disaster response operations. The ability to anticipate high-risk zones allows emergency services to optimize deployment strategies, potentially reducing casualties and expediting recovery efforts.

Moreover, scenario-based modeling serves an important role in validating computational frameworks against empirical data collected after real hurricane events. Validation enhances confidence in predictive models and ensures their applicability in resilience planning. Field data sources that can facilitate this validation process include:

- **Hurricane Response Data** (Office of Cybersecurity, Energy Security, and Emergency Response)
- **NOAA's Post-Storm Reports**
- **FEMA Reconnaissance Reports**
- **Google Street View and Satellite Imagery**

For instance, post-event imagery, such as the Street View documentation of Mexico Beach following Hurricane Michael (October 10, 2018), provides a visual reference for assessing structural damage at specific locations (Figure 14). These tools enable engineers and researchers to qualitatively compare simulated damage patterns with observed outcomes, thereby refining future modeling efforts.

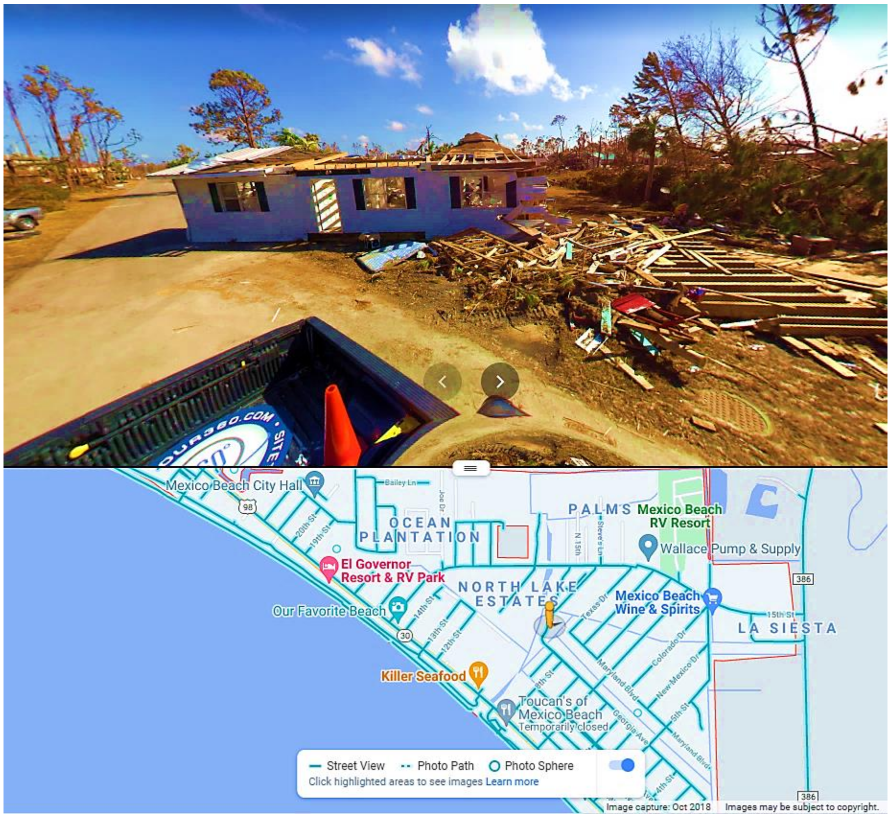

Figure 14. Post-event imagery of Mexico Beach following Hurricane Michael (October 10, 2018) illustrating observed structural damage for validation purposes.

It is important to note that the outcomes of community-level damage assessments are highly sensitive to the characteristics of the selected hurricane scenarios. Variations in wind speed, trajectory, and intensity lead to significant differences in both the extent and spatial distribution of damage. This highlights the necessity of conducting record-to-record sensitivity analyses to capture the full range of potential impacts a community might face under different hurricane conditions.

In summary, the integration of hazard simulation, fragility-based damage assessment, and validation against field data offers a robust framework for advancing community resilience. Such methodologies not only inform immediate disaster response strategies but also contribute to long-term mitigation planning and policy development. While this study provides a robust framework for community-scale hurricane damage assessment, several limitations should be acknowledged. The analysis focuses solely on wind-induced damage, excluding other critical hurricane hazards such as storm surge and coastal flooding, which can significantly impact coastal communities like Galveston Island. Additionally, the fragility functions applied are based on generalized structural typologies and do not capture potential variability in construction quality, maintenance conditions, or retrofitting measures present within the building stock. The study also does not explicitly account for uncertainties in hazard modeling parameters, vulnerability functions, or building inventory data, which could influence the accuracy of damage predictions. Finally, validation was limited to qualitative comparisons due to the lack of detailed historical damage datasets, highlighting the need for more comprehensive post-disaster data collection to enhance future model calibration and validation efforts.

5. Conclusions

The field of community resilience aims to enhance the capacity of communities to withstand, respond to, and recover from natural hazards, including hurricanes, which pose significant risks to coastal regions through both human and economic losses. Damage assessment at the community scale serves as a foundational step in developing effective mitigation strategies, ensuring that critical infrastructure and housing remain functional and that recovery processes are expedited following medium- to large-scale hurricane events.

In this study, a comprehensive damage assessment was performed for Galveston Island using simulated wind fields from two historical hurricane scenarios. The analysis integrated hazard modeling, fragility-based vulnerability assessment, and geospatial community modeling to evaluate structural performance under varying hurricane intensities.

The key conclusions drawn from this research are as follows:

1. Community-scale damage assessment under scenario hurricanes provides essential insights for emergency management and disaster response, enabling identification of high-risk zones and supporting informed decision-making before and after severe wind events.

2. Scenario-based modeling frameworks are valuable tools for validation purposes, allowing comparison between simulated damage outcomes and empirical data collected post-disaster. This enhances the reliability of computational models used in resilience planning.

3. The outcomes of community damage assessments are highly sensitive to the characteristics of the selected hurricane scenario, underscoring the importance of conducting record-to-record sensitivity analyses to capture the full spectrum of potential impacts and to inform robust risk mitigation strategies.

This research demonstrates the critical role of validated, scenario-driven assessments in advancing coastal community resilience and highlights the need for continuous refinement of modeling approaches to address the uncertainties inherent in natural hazard events.

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