CWE-8
June 7-11, 2026
London, ON, Canada

A framework for translating hurricane forecasts into real-time cladding damage risk

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SUMMARY

Hurricanes have shown increasing frequency and intensity, posing growing risks to coastal communities and the resilience of the built environment, particularly building envelope systems. This study develops a real-time damage risk assessment framework for building envelope systems that integrates probabilistic hurricane forecasting, multi-demand coupled damage modeling, and surrogate-based real-time evaluation. Site-specific wind speed and direction are derived from National Hurricane Center advisories coupled with a parameterized wind field model, considering the full-range of uncertainty. Envelope damage is quantified through a coupled framework accounting for both drift-induced and pressure-induced damage mechanisms, with uncertainty and interaction effects represented through probabilistic capacity reduction. To enable real-time performance, a Kriging-based metamodel is employed to efficiently map wind intensity to damage statistics. A case study of a building with 8,100 envelope elements subjected to Hurricane Irma demonstrates the framework's capability to provide timely, actionable damage risk information for emergency preparedness and decision-making.

Keywords: *hurricanes, building envelope systems, real-time damage risk assessment, probabilistic wind modeling, metamodeling, emergency decision support*

1. INSTRUCTIONS

Hurricanes have exhibited a clear and concerning trend of increasing frequency and intensity over recent decades, driven by climatic and environmental changes (C2ES, 2025). These evolving hazard characteristics have significantly amplified the vulnerability of coastal communities and the built environment, particularly building envelope systems that serve as the first line of defense against extreme wind and pressure loading. Envelope failures not only result in direct economic loss but can also trigger cascading damage mechanisms, including internal pressurization, water ingress, and loss of functionality, thereby exacerbating risks to life safety and post-event operability.

Current hurricane risk assessment practices for building envelope systems are largely based on offline simulations or post-event damage evaluation, limiting their applicability for real-time emergency preparedness and response. Emergency managers and decision-makers often lack timely, probabilistic information on where damage is most likely to occur as a hurricane approaches and forecast conditions evolve. This gap underscores the need for real-time, uncertainty-aware damage risk assessment frameworks capable of translating evolving hurricane forecasts into actionable damage metrics at the building and component levels.

In response to this need, this study develops a real-time damage risk assessment framework tailored for building envelope systems. The framework is designed to integrate hurricane forecast information, probabilistic wind field modeling, and physics-informed damage modeling into a unified workflow that supports emergency preparedness, response, and operational management.

By explicitly accounting for multiple damage demands, uncertainty propagation, and computational efficiency, the proposed approach aims to advance the state of practice in hurricane risk-informed decision support for the built environment.

2. THE REAL-TIME RISK ASSESSMENT FRAMEWORK

The proposed framework, as shown in Figure 1, consists of four major components: (1) probabilistic hurricane hazard modeling, (2) site-specific wind field characterization, (3) multi-demand coupled damage modeling for building envelope systems, and (4) surrogate-based real-time risk evaluation. These components are integrated to enable continuous updating of damage risk estimates as new forecast information becomes available. At the core of the framework is the ability to rapidly propagate uncertainty from hurricane forecasts through wind field estimation and envelope damage models, producing probabilistic damage metrics that are directly interpretable for emergency decision-making.

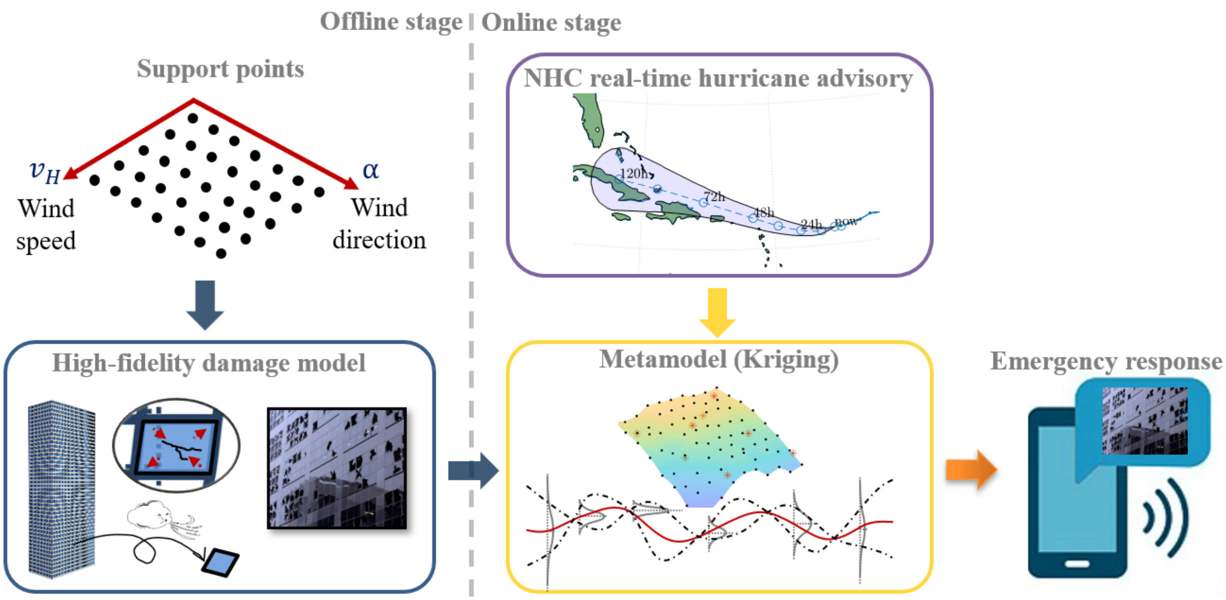

Figure 1. The real time damage risk assessment framework for building envelope systems.

2.1. Probabilistic hurricane hazard and wind field modeling

Site-specific wind conditions, including wind speed and direction, are derived from National Hurricane Center (NHC) advisory data. To capture the inherent uncertainty in hurricane evolution, the framework incorporates stochastic perturbations of hurricane track parameters, including storm position, heading, and intensity. A parameterized hurricane wind field model is then employed to translate these stochastic track realizations into probabilistic wind intensity samples at the site of interest (Jakobsen and Madsen, 2004). This approach enables the generation of ensembles of wind speed–direction pairs that represent plausible local wind conditions as an impending hurricane approaches. These ensembles evolve over time as updated advisories are issued, forming the basis for real-time risk updates.

2.2. Multi-demand coupled damage modeling for envelope systems

Building envelope damage is modeled using a multi-demand framework that simultaneously considers drift-induced and pressure-induced damage mechanisms (Ouyang and Spence, 2020). Drift-induced demands arise from structural deformations under wind excitation, while pressure-induced demands are governed by external and internal wind pressures acting on envelope components. Uncertainties in material properties, component capacities, load effects, and modeling assumptions are explicitly incorporated. Coupling between damage mechanisms is represented through probabilistic capacity reduction, whereby the occurrence of damage in one mechanism reduces the effective resistance of related components to subsequent demands. This formulation captures realistic damage progression and interaction effects commonly observed during hurricane events. The damage model outputs probabilistic damage states for individual envelope elements as well as aggregated damage metrics at the building level.

2.3. Kriging-based metamodeling for real-time implementation

Direct evaluation of the coupled damage model for large ensembles of wind intensity samples can be computationally prohibitive for real-time applications, particularly for buildings with thousands of envelope components. To address this challenge, a Kriging scheme is leveraged to establish an efficient surrogate mapping between wind intensity parameters (wind speed and direction) and envelope damage statistics. The metamodel is trained using a strategically selected set of high-fidelity simulations and validated to ensure accuracy across the range of relevant wind conditions. Once constructed, the surrogate enables near-instantaneous evaluation of damage probabilities, allowing the framework to deliver timely risk updates as hurricane forecasts evolve.

3. RESULTS

The proposed framework is demonstrated through a case study involving a building comprising 8,100 envelope elements subjected to the wind conditions associated with Hurricane Irma. The building geometry, envelope configuration, and component-level damage models are selected to represent a realistic large-scale envelope system exposed to hurricane wind loading. Hurricane Irma is chosen due to its well-documented track, intensity evolution, and widespread damage impacts, providing a representative test case for evaluating the framework's performance under real-world conditions.

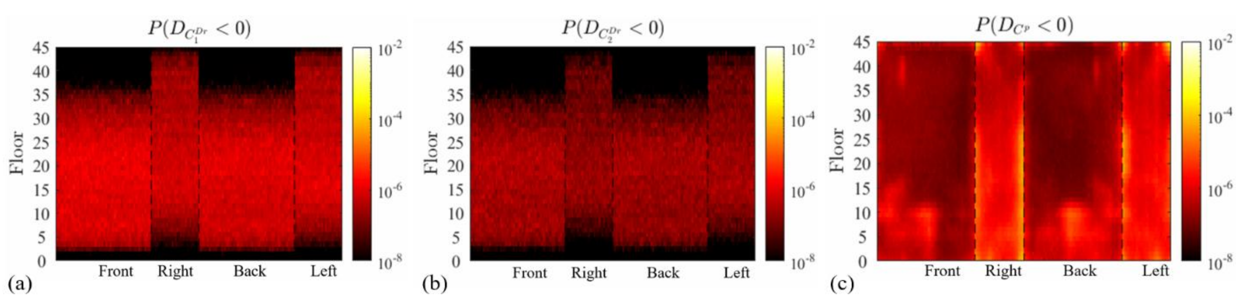

Figure 2. Forecasted damage risks on Sep 06 9:00 am UTC for Hurricane Irma: (a) Hairline crack, (b) Crack, (c) Cladding blowout.

The forecasted damage risks for Hurricane Irma at Sep 06 9:00 am UTC is shown in Figure 2. It is seen the developed framework can provide comprehensive damage risks for the entire cladding system. This information is available for every 6 hours ahead from the current time point to up to

5 days in future. With the aid of the Kriging metamodel, such information can be obtained by regular personal computer with around 1 s, nearly instantaneous. The results highlight the potential of the proposed framework to support risk-informed emergency response strategies, such as targeted inspections, resource allocation, and operational planning. By providing probabilistic, component-level damage information in near real time, the framework enables a proactive approach to managing hurricane-induced risks to building envelope systems.

4. CONCLUSIONS

This study presents a real-time, uncertainty-aware damage risk assessment framework for building envelope systems subjected to hurricane wind hazards. By integrating probabilistic hurricane forecasting, multi-demand coupled damage modeling, and Kriging-based metamodeling, the framework enables timely and computationally efficient evaluation of envelope damage risk as hurricane conditions evolve. The case study application demonstrates the framework's capability to deliver actionable risk information, supporting enhanced emergency preparedness, response, and resilience of coastal communities.

ACKNOWLEDGEMENTS

The research effort was supported in part by the National Science Foundation (NSF), USA under Grant CMMI-1750339 as well as the University of Michigan's Mcubed 3.0 program, USA. This support is gratefully acknowledged.

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