Imaging-to-Simulation Framework for Improving Disaster Preparedness of Construction Projects and Neighboring Communities

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Abstract

Unstructured construction sites including incomplete structures and unsecured resources (e.g., materials, equipment, and temporary facilities) are among the most vulnerable environments to windstorms such as hurricanes. Wind-induced cascading damages cause substantial losses, disruption, and considerable schedule delays in construction projects. Moreover, this would negatively affect neighboring buildings and interdependent infrastructures (e.g., electric power transmission or transportation systems), which triggers serious economic losses in our community. Nonetheless, prior works on disaster management mainly focused on post-disaster assessment and reconstruction process of built environments, and thus predicting potential risks associated with expected disasters for proactive preparedness remain largely unknown. This paper presents a new Imaging-to-Simulation framework that can uncover potential risks of wind-induced cascading damages to construction projects and their negative impacts on neighboring communities. The outcomes are expected to benefit our society as it will enhance current windstorm preparedness and mitigation plans, which ultimately promote public safety, property loss reduction, insurance cost reduction, and raise awareness of 'Culture of Preparedness' for disasters.

INTRODUCTION

Dynamic and complex construction sites including incomplete structures and unsecured resources (e.g., materials, equipment, and temporary facilities) are among the most vulnerable environments to windstorms such as hurricanes. Wind-induced damages to construction sites cause substantial losses, disruption, and considerable schedule delays, and thus negatively impact the efficiency of the construction projects. For example, 2012 Hurricane Sandy caused over $185 million worth of damages to the World Trade Center construction site in New York City (Fermino 2013). Moreover, wind-induced cascading damages originated from job sites would negatively affect neighboring interdependent infrastructure systems (e.g., electric power transmission or transportation systems in dense urban environments), triggering serious injuries and casualty as well as economic losses in our community. Failures occurred in construction sites by wind loads can be addressed in the context of (1) primary failures such as structural damages to the as-built environments under construction, and (2) functional failures with limited or non-structural damages (e.g., schedule delay). More importantly, (3) failures outside construction sites also can occur as unsecured materials or temporary facilities can become wind-borne debris and fly outside of the sites and may seriously injure people or directly damage neighboring interdependent infrastructures (e.g., buildings, roads, power pole) as it can trigger cascading damages with serious economic losses in our community. Hence, if construction sites are not well-prepared for extreme wind-related disasters, their cascading impact will influence beyond the construction projects, further affecting our community.

Current technologies for hurricanes forecasting allows time for preparation to reduce their cascading impact on work-in-progress job sites and surrounding communities, which can eventually reduce damages and casualties. However, according to extensive face-to-face and phone interviews recently conducted by the authors, the current practices of major construction companies in the U.S. for securing construction sites from the imminent threat of hurricanes, are mostly limited to: (1) performing general extreme weather action plans by contractors or sub-contractors (e.g., removing materials or bracing equipment), and (2) manually examining the sites by code compliance officers to ensure if appropriate precautionary measures are implemented to secure the job sites. It is also found that construction companies already collect a massive amount of visual data through video recorders and hand-held cameras to document conditions of the sites and surrounding areas before wind hazards (e.g., at the hurricane warning phase). Nonetheless, code compliance officers rely upon human observation for ensuring all precautionary measures taken in large-scale job sites, which are still labor-intensive and challenging for construction documentation. The survey results confirm that the cost and complexity of inspecting and reporting the current state of construction sites are one of the major challenges in establishing adequate preparedness. More importantly, the current practices lack understanding hidden risks of wind-induced cascading damages, which prevents stakeholders from devising proactive risk mitigation strategies to reduce the vulnerability while increasing resilience. In recent decades, hurricane-induced failures could be better understood through advances in structural wind engineering, but it has been mostly limited to post-disaster structural building response, not in the context of vulnerable job sites and the cascading impacts on neighboring communities.

A systematic approach to understand and predict wind-induced cascading damages originated from unstructured construction environments remains to be developed. The gap in achieving such an approach poses a major impediment in reducing or preventing windstorm-induced physical damages and financial losses to construction projects as well as surrounding communities. To this end, by leveraging visual data from both ground and aerial perspectives, a new 'Imaging-to-Simulation' framework is presented as a new reduced-order analysis that couples scalable wind loads to perform multi-physics simulation of multi-body components in construction sites. The primary contribution of this research is the advanced fundamental knowledge on wind responses of unstructured construction environments, which prevent wind hazard events from becoming catastrophic damages to construction projects and neighboring communities. This will enable practitioners to proactively plan precautionary measures to lessen damages. In the following, we first review related prior works, and look into their challenges. Then, each step of the underlying approach is presented with experimental results and findings through case studies.

RELATED WORKS

The structural engineering practice ensures the assessment and design of buildings and other structures to meet the full range of requirements for urban communities to be resilient to extreme wind hazards. Hence, design standards such as ASCE 7 Standard have been developed to strictly enforce buildings and other systems to be structurally robust under extreme wind speeds and generally serviceable under wind loads. In this sense, no major structural damages that may lead to collapse have been reported for large engineered buildings during recent major hurricanes such as 1983 Alicia, 2005 Katrina and 2012 Sandy. Instead, a series of damage survey and analysis including (Cauffman et al. 2006; Xian et al. 2015) have reported that most of damages were found on building envelopes due to local wind effects and wind-borne debris. The wind-borne debris risk assessment has been studied in wind engineering and aerodynamics community such as (Lin and Vanmarcke 2008; Wills et al. 2002) as a problem of describing damages that might be incurred to buildings by wind-borne debris in a certain speed of wind. However, the gap lies in those prior works as they focused mostly on wind-borne debris impacts on the built environments in operation, not their construction phase that is the most vulnerable stage over the life-cycle due to numerous potential wind-borne debris including incomplete structures and unsecured resources and their significant cascading risks to surrounding interconnected civil infrastructure systems.

Similarly, prior works on disaster management mainly focused on post-disaster assessment and reconstruction process of built environments, e.g., post-disaster reconstruction processes and stakeholder networks such as (Opdyke and Javernick-Will 2014; Opdyke et al. 2015); post-hurricane damage assessment using aerial images or light detection and ranging (LIDAR) survey such as (Hatzikyriakou et al. 2016; Xian et al. 2015; Ye et al. 2014). Despite their benefits, these works lack understanding about potential risks of expected wind hazard events to construction projects and surrounding communities, preventing project stakeholders from devising proactive risk preparedness and mitigation strategies. Basically, disaster preparedness efforts require the potential risk assessment as a fundamental prerequisite to efficiently and effectively implement appropriate precautionary measures under given time constraints and organizational resources. Yet there is a dearth of research and practices in construction site windstorm preparedness and their potential impact.

IMAGING-TO-SIMULATION FRAMEWORK

A significant proportion of wind-induced damages to construction projects and surrounding communities is due to inadequate preparedness. This is largely due to the underestimation of potential risks when damages are initiated. To address this challenge, this paper proposes a new

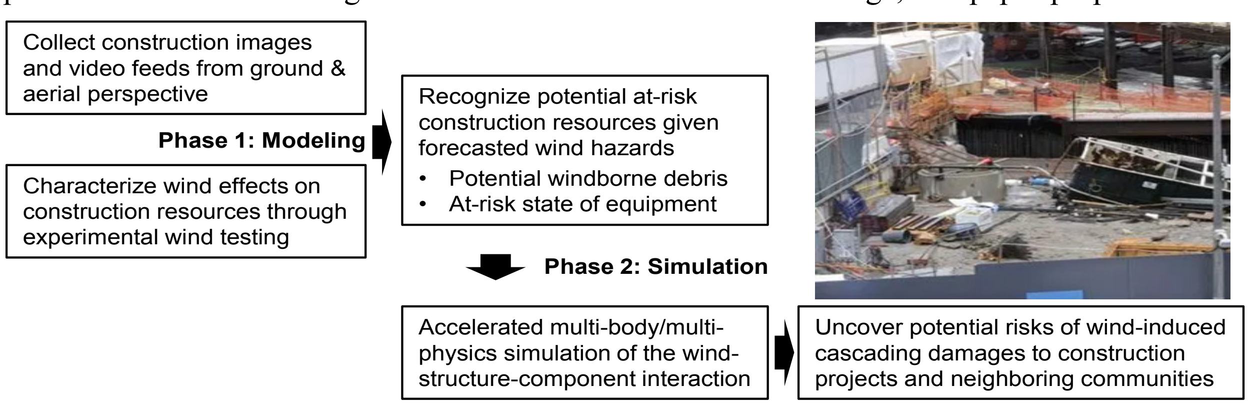


Figure 1. An overview of the data and the tasks for 'Imaging-To-Simulation' framework for disaster preparedness.

framework for understanding potential risks of wind-induced cascading damages from job sites, which support to enhance the resilience of currently vulnerable construction sites as well as surrounding interdependent infrastructures. Figure 1 illustrates the overview. First, vision-based modeling from both ground and aerial perspective is used to characterize the extent to how the as-is construction sites are exposed to extreme wind-related disasters. Then, we leverage the outcomes of the visual recognition as an input for multi-body/multi-physics simulations, which can help rapidly predict and describe a chain reaction of wind-induced cascading damages originated from unstructured construction environments while still maintaining reasonable physical realism. The proposed framework is being demonstrated through case studies conducted on real-world construction projects.

Large-scale 3D visual monitoring on job sites to recognize unsecured construction resources under a given forecasted wind scale. By using the NSF NHERI 12-fan Wall of Wind (WOW) Experimental Facility (EF) (Figure 2), we experimentally estimate the wind effects on typical resources (e.g., construction materials and temporary facilities) associated to job sites. Through careful experimentations, we estimate the wind speeds under which various objects will be displaced or dislodged. In particular, we summarize wind speeds into range categories to reflect types of resources that can be displaced under particular wind speed ranges. The displacement of objects can be due to wind induced (1) uplift (causing vertical lift off), (2) shear (causing lateral displacement), (3) moment (causing overturning), (4) torsion (causing twisting displacement), or (5) a combination of these effects. The modes of various displacements are studied for the resources that are tested. This helps prioritize visual recognition under a given forecasted wind scale, which significantly reduce the computational cost for visual recognition.

Figure 2. Full-scale experimental simulation of hurricanes with a 12-Fan Wall of Wind (WOW) facility (a NSF-supported Natural Hazards Engineering Research Infrastructure (NHERI) Experimental Facility (EF)).

To recognize potential at-risk construction resources and at-risk states of equipment in job sites, we build on both ground images from construction workers and aerial images from

Figure 3. A job site from aerial perspective (Left), potential at-risk construction resources localized in a ground and aerial 3D model (Right).

camera-equipped UAVs (Ham et al. 2016) and the knowledge on potential wind-borne debris through the experimental wind testing. Here, we encode contextual cues obtained from experimental wind testing as a discriminative feature, enabling discriminatively focusing on potential at-risk resources under a given forecasted wind scale. To localize objects in each image frame, we use a sliding window approach. Since the conventional approach is computationally expensive as the classifier functions have to be evaluated over a large set of candidate sub-windows, we build upon an approach of efficient sub-window search (Lampert et al. 2008) to minimize the computational cost. Then, for localizing and mapping the at-risk resources in ground and aerial 3D cyber model, we geo-register ground-based 3D reconstruction to the corresponding aerial 3D models building on (Shan et al. 2014) to address the challenges in 3D modeling caused by large discrepancies in ground (construction worker) to aerial (UAVs) viewing angles.

Multi-body/multi-physics simulation of wind-induced cascading damages to construction projects and surrounding areas. In wind hazard events, even a minor component associated with potential failure such as an unsecured building material in a job site may lead to disastrous consequences, as it may set off a chain reaction of failures by becoming wind-borne debris and hitting neighboring critical infrastructures such as electric power transmission or transportation systems. Hence, simulation of the wind-induced cascading damages requires realistic multi-body and multi-physics consideration, i.e., interaction of multiple bodies (e.g., potential at-risk construction resources) coupled with the modeled wind load (i.e., multi-physics), which can describe the evolving motion of mutually interacting components over time, as opposed to the conventional structural analysis of a single body (e.g., a building) that typically focuses on the mechanical behavior up to the onset of failure.

Given the fact that a hurricane forecast is only accurate with 3 to 5 days prediction, there is a clear time constraint to reasonably predict and evaluate a set of failure scenarios that possibly occurs in construction sites and surrounding areas. Thus, the simulation technique with significant computational efficiency is vital for enabling coordination among stakeholders to proactively devise the preparedness and mitigation measures to minimize cascading impacts. Despite the significance, there is a lack of prior technical solutions for rapid multi-body/multi-physics simulation with reasonable fidelity. The discrete element method (DEM) is widely employed in many engineering disciplines to account for the discrete nature of multi bodies in simulation, but DEM is computationally expensive in general, particularly with required simulation fidelity in typical engineering problems. Hence, the major challenge is confronted by the computational cost to perform the multi-body/multi-physics simulation, which may easily take up to a few weeks even for simple engineering problems.

To address such challenges in computational cost within the limited timeframe, we

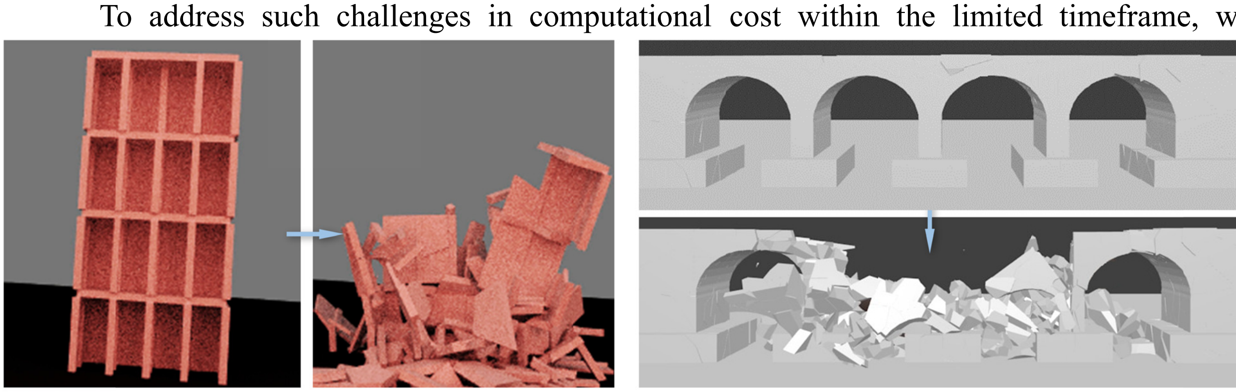
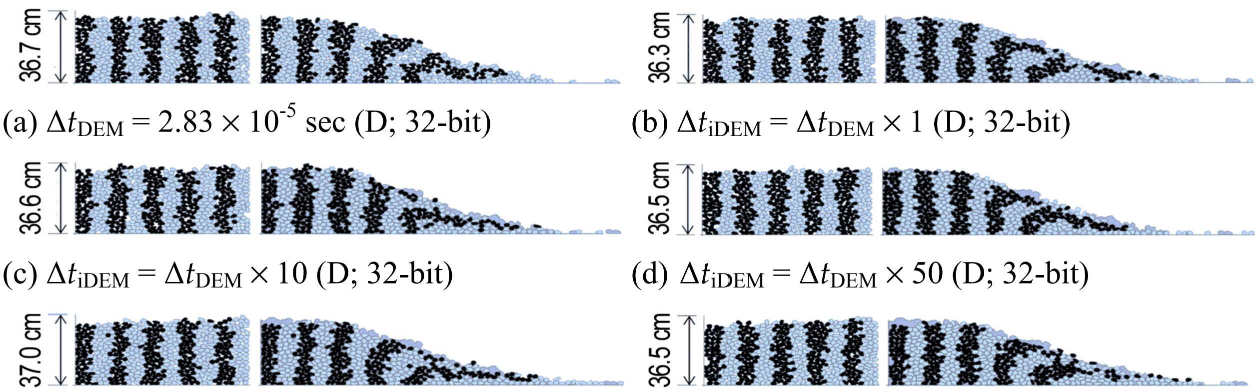


Figure 4. Structural failures through iDEM simulation (e.g., building & bridge).

develop the reduced order DEM, impulse-based Discrete Element Method (iDEM) building upon (Lee and Youssef 2015) that bypass the high computational cost to significantly extend the scale of multi-body simulation while maintaining the simulation fidelity. Figure 4 shows our simulation results of structural failures through impulse-based dynamics to model the realistic discrete bodies' interactions.

As a proof of concept to apply our iDEM to the simulation of wind-induced cascading damage mechanisms and damage predictions associated with potential wind-borne debris in unsecured job sites, we conducted the simulations on particle flows initiated by external controls (to understand physical plausibility rather than being deterministic). Figure 5 and Table 1 present the outcomes with different time step sizes (Δt_{DEM}) to see the performance gains in computational cost and simulation fidelity over the benchmarked DEM simulation.



(a) $\Delta t_{DEM} = 2.83 \times 10^{-5}$ sec (D; 32-bit) (b) $\Delta t_{iDEM} = \Delta t_{DEM} \times 1$ (D; 32-bit)

(c) $\Delta t_{iDEM} = \Delta t_{DEM} \times 10$ (D; 32-bit) (d) $\Delta t_{iDEM} = \Delta t_{DEM} \times 50$ (D; 32-bit)

(e) $\Delta t_{iDEM} = \Delta t_{DEM} \times 100$ (D; 32-bit) (f) $\Delta t_{iDEM} = \Delta t_{DEM} \times 100$ (S; 32-bit)

D: Double-precision arithmetic / S: Single-precision arithmetic

Figure 5. Initial (left) and final (right) configurations from iDEM simulations. The final DEM configuration (a) is shown as the background silhouette image in (b) ~ (f) for comparing the simulation fidelity.

The impulse-based dynamics employ a reduced 1st order dynamics to directly manipulate the velocity ($i = m\Delta v$), compared to the conventional 2nd order dynamics that works on the integration of accelerations as used in the conventional DEM. Hence, significant computational efficiency is demonstrated with almost 2nd orders of magnitude with a greater numerical stability even for a large time step size adopted as shown in Table 1 and Figure 5. The iDEM is formulated to retrieve the 2nd order engineering details (e.g., contact force) with the reasonable

Table 1. Comparison of computing time and speed-up between DEM and iDEM.

	Δt (sec)	*Precision*	*CPU time (sec)*	*Speed-up*
DEM	(a) 2.83×10^{-5}	Double	373	1
iDEM	(b) $\Delta t_{DEM} \times 1$	Double	398	0.94
	(c) $\Delta t_{DEM} \times 10$	Double	43	8.7
	(d) $\Delta t_{DEM} \times 50$	Double	9	41.4
	(e) $\Delta t_{DEM} \times 100$	Double	5.1	73.1
	(f) $\Delta t_{DEM} \times 100$	Single	4.7	79.4

simulation fidelity required for engineering applications that are lost in the impulse-based approach. Therefore, the iDEM significantly enhances the computational efficiency without trading off against the simulation fidelity. As shown, the iDEM simulation rapidly describe a chain reaction of large sale multi-body problems while maintaining reasonable physical realism. Given a time constraint for analysis (e.g., 3 to 5-days forecast for hurricane), this enables to perform more simulations that visualize various failure scenarios. By doing so, we can better characterize and understand the extent to how the as-is construction environments and surrounding areas are vulnerable to expected wind hazard events.

The outcomes of visual sensing and analytics along with the experimental results from the wind-borne debris assessment are leveraged to model the initial conditions of unsecured construction sites for the iDEM simulation. The multi-physics simulation is employed to predict the interactive phenomena between multiple physical models, i.e., the interaction between wind loads and potential at-risk construction resources through the iDEM simulation coupled with a computational fluid dynamics. The wind load is modeled via a fluid velocity field, in which the direction and the magnitude at each grid point are updated every time step. The multi-body iDEM simulation is then followed to apply the computed wind loads to update individual motion of discrete objects and to resolve collisions between the objects in contact.

Ongoing case studies. We have explored each component of the proposed framework. Testing the overall performance under real wind hazards is purely depending on weather conditions. To leverage the concepts introduced above, in collaboration with International Hurricane Research Center, the authors are currently conducting two pilot studies on building projects in Miami, FL under 2016 Hurricane Matthew.

CONCLUSION

To enable project stakeholders to devise proactive preparedness and mitigation strategies for extreme wind-related events, understanding potential risks of wind-induced cascading damages — revealing damage mechanisms to construction projects and surrounding areas — is sorely needed, which is the existing knowledge gap given the increasing number and impacts of disasters. To this end, by leveraging visual data from both ground and aerial perspectives, a new Imaging-to-Simulation framework is presented to uncover potential risks of wind-induced cascading damages to construction projects and neighboring communities. By being able to rapidly estimate and evaluate potential risks of wind-induced cascading damages originated from job sites, the proposed approach can be employed to devise significantly improved windstorm preparedness and mitigation plans based on the most likely scenarios that need to be identified for effective decision-makings. Future works involve exploring each component of the framework and validation on actual job sites under real windstorms situations, which are currently being explored as part of our ongoing research.

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