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Performance-based design of façades for wind-borne debris impacts

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SUMMARY:
Wind-borne debris is one of the major causes of building envelope damage in windstorm events. Past tornadoes and tropical cyclones showed how façades are a vulnerable building component when it comes to wind-borne debris impacts. Standard test requirements for wind-borne debris resistance were developed to improve cladding resilience after Cyclone Tracy in Australia (1974) and Hurricane Andrew in the United States (1992). Current impact test requirements are based on empirical observations and on typical construction types that were analysed after the mentioned extreme wind events. An alternative performance-based design tool is presented, to set a design framework to improve building envelope impact resistance to case-specific wind-borne debris elements. This performance-based design method aims to explore the current code and standard possibility to introduce façade impact test requirements based on engineering analysis. An example focuses on one wind-borne type that is currently not considered for wind-borne debris impact performances of facades, even if such building components are prone to uplift and consequent flight in windstorms. Experimental tests for roofing components failure and flight analyses are validated through the proposed analytical model, through Monte Carlo simulation. Wind-borne debris trajectory analysis is presented, to discuss alternative requirements for impact performances of façades.

Keywords: wind-borne debris, façade impact resistance, performance-based design

1. INTRODUCTION

Building damage from wind-borne debris, particularly to the building envelope, is one of the main causes of extreme wind events' severe damage to the urban environment, according to Minor (1994). It is important to keep in mind that the Joplin tornado, which struck Missouri on May 22, 2011, established the record for the most expensive tornado in American history with damage totaling $3 billion. With 161 fatalities, including 14 at the St. John's Regional Medical Center, the same incident is also the worst tornado event of the new millennium (Kuligowski et al. 2014). According to ASCE 7-22 (2022), the hospital is an essential facility that is meant to aid in recovery, particularly in the aftermath of natural catastrophes. Although most of the hospital's windows were broken, the building's structure was not affected by the storm, but wind-borne debris penetrated the structure. However, the Behavioral Health Unit on the fifth level of this structure included breakage-resistant glass systems, and most of these windows did not break, as noted in the Final Report of the National Institute of Standards and Technology on the Joplin tornado (Kuligowski et al. 2014). Debris elements that were found inside the building which were considered the cause of window breakage were primarily roof gravel (Kuligowski et al. 2014). In extreme wind events, debris can originate from the failure of materials and pieces from source buildings and other man-made structures. Roof gravel, roof tiles, façade elements, antennas, and other urban components such as street signs can be blown away, becoming wind-borne debris that can endanger people and property, hitting surrounding buildings at high speed (ASCE 2014; Butler and Kareem 2012). In this scenario, the building envelope is the first barrier to protect, or at least to mitigate, the effects of extreme wind events on people and property (Minor 2005). Evidence of climate change is now clear and convincing worldwide, and one of the major consequences is the increasing intensity and quantity of extreme weather events (IPCC 2022; Munich RE 2022; Gergis 2019; Sisco et al. 2017). There is an upward trend in natural disasters, in terms of economic losses and people injured or death (Munich RE 2021; Lu et al. 2019; Brody et al. 2008; Eckstein et al. 2021).

At an international level, there is an emerging interest from the International Standard Organization for the introduction of testing requirements to consider wind-borne debris impacts on building envelopes, and Technical Committee 162 “Doors, Windows, and Curtain Walling” formed an ad hoc group between the Working Group 4 (Windows and Doors) and the Working Group 5 (Curtain Walling) in 2021, to set down various levels of resistance of the building envelope when it comes to wind-borne debris impact.

2. PROBLEM STATEMENT, AIMS, AND SCOPE

Based on current knowledge of the aerodynamics of wind-borne debris, wind-induced failures, wind loading, and impact dynamics, a performance-based design framework for wind-borne-debris-resistant façades is proposed. The tool’s generalization will enable designers to consider case-specific building settings for impact-resistant building envelope design. The ASTM standard methods serve as the foundation for the current best practices for impact testing to certify building façade components to withstand impacts from wind-borne debris (ASTM 2019, 2020). Standard “missiles” and impact velocities are used in these standards. Since there is no information concerning the velocity of wind-borne debris in windstorms of different intensities, the impact energies are not based on the aerodynamics of wind-borne debris in local contexts (Kordi 2009). The ASTM standard standards do, however, provide façade designers the freedom to use “other missiles” for the impact testing while still developing ad-hoc wind-borne debris impact tests for their designs, based on engineering assumptions and calculations. The process to create alternative wind-borne debris-resistance test criteria is presented with a specific example using a case study approach.

3. METHODOLOGY

The methods to determine debris failure wind speeds can have a stochastic (e.g., based on fragility analyses), a deterministic approach (e.g., based on fixture strength integrity), or a combination of the two (e.g., failure models). As an example, a fragility analysis is conducted, to determine the probability of impact on the façade for an essential facility. The approach of this research is to utilize and synthesize the existing literature on wind-borne debris impact performances of façades. It uses analysis of failures, debris flight trajectories, and flight speeds. The final goal is to estimate the consequent projectiles and impact energy to be absorbed by a target building envelope in wind events. The current code and design standard requirements that have been identified and adopted as the best practices when it comes to building envelope design in extreme wind-prone areas are analyzed. An extensive review of wind engineering studies regarding wind-borne debris behavior is the basis to formulate the research question that this performance-based design method aims to answer. The current necessity to consider the aerodynamics of wind-borne debris in wind events and specific environments, to provide impact resistance to the building envelopes is underlined through the critical review of the current best practices that are adopted worldwide. Through a probabilistic approach, the research presents a tool for façade designers.

Two main investigation areas are identified for wind-borne debris impact performance definition: the failure mechanism, and the flight assessment, to ultimately have the impact energy on the final target. The failure mechanism considers the "source building", where the wind-borne debris could originate from, and the technical installation of the object, and therefore a probability of failure. The "debris flight" depends on the equations of motions that have been developed in the existing literature (Tachikawa 1983) and on experimental simulations that took to the estimation of the probability function (Kordi et al. 2010), depending on various aerodynamic parameters such as the Tachikawa number (T_a). Through a Monte Carlo simulation, it is possible to estimate the impacts to be conducted on the building envelope of a "target building" (Figure 1).

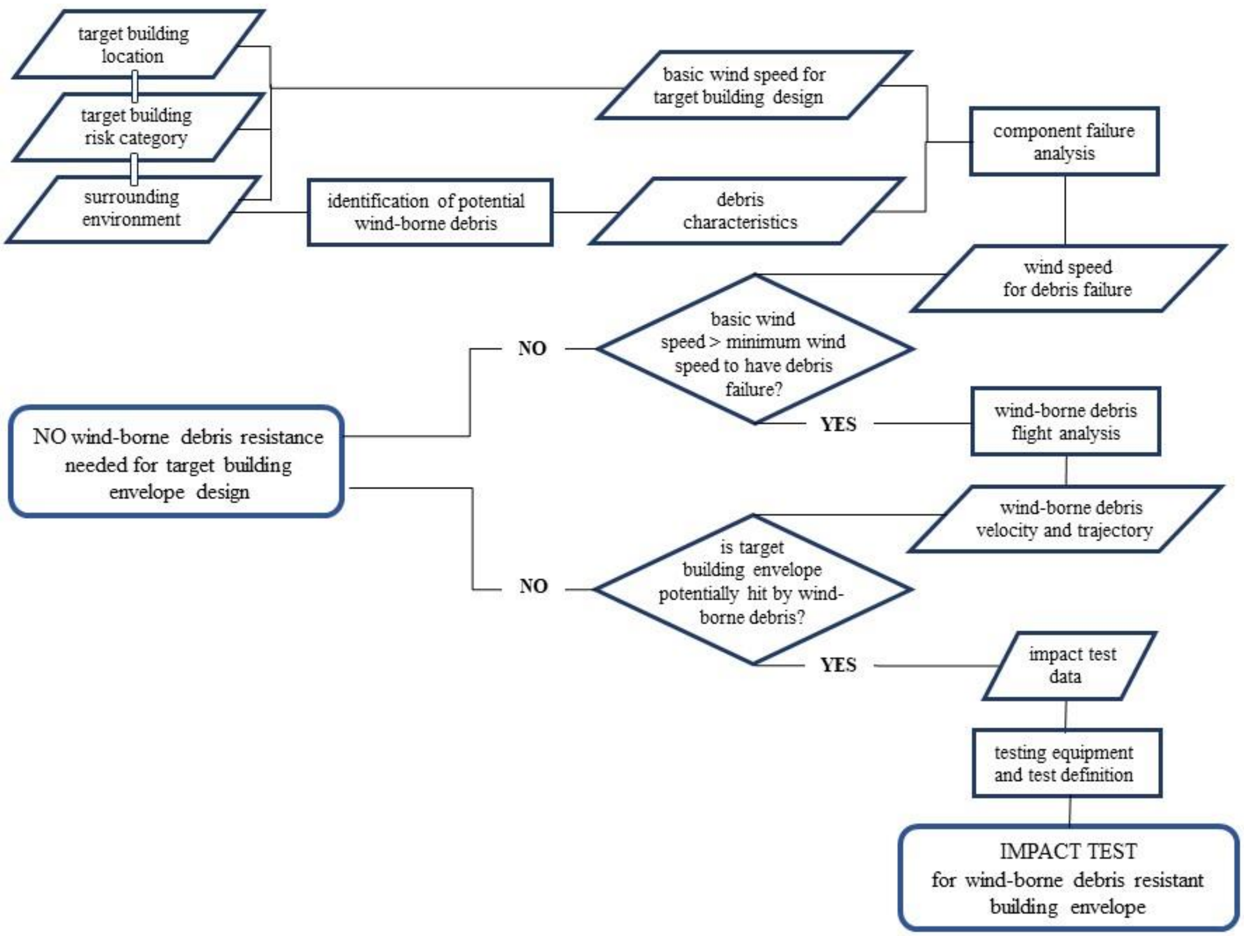

Figure 1. Flowchart of the performance-based design tool.

4. CONCLUSIONS

An alternative design framework for wind-borne debris-impact-resistance of façades is presented. The design method sets a new approach to establishing façade impact testing performance, to provide site-specific wind-borne debris impact resistance of building envelopes, based on building aerodynamics, wind-borne debris trajectory analysis, and risk assessments of the surroundings. This research offers façade designers a solution to relate local wind-borne debris types to specific design performance goals. The impact energies on target façades are, accordingly, evaluated by estimating the trajectory and the velocity of specific debris elements after the failure occurs. The ASTM standard requirements (ASTM 2019, 2020) already give façade designers the chance to go through engineering assumptions to develop ad-hoc wind-borne debris impact tests for their projects, adopting an "other missile" for the impact test. The debris element considered as an example is the concrete low-profile roof tile. From a Monte Carlo simulation, it is found that the direct-to-deck-fixed roof tiles, after the failure occurs on a hip roof with a slope of 36° and a mean roof height of 10 m, can fly for 120 m, reaching an impact speed of 53 m/s. The full paper will present the results of the case study analysis in detail.

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