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Distribution of wind-driven rain deposition on low-rise buildings: Direct impinging raindrops versus surface runoff

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ABSTRACT

Wind-driven rain (WDR) effects on various components of a building facade are dependent on the total volume of rainwater deposition. The total volume of WDR deposition at a specific location on the building facade has contributions from both directly impinging raindrops and accumulated surface runoff. The distribution of WDR deposition over the building surface is dependent on the nature of the storm and on the aerodynamic shape of the building. This paper presents an experimental study conducted to investigate the distribution of WDR deposition on the external facade of low-rise buildings. Two parameters that quantify the distribution of direct impinging raindrops and surface runoff rainwater over the building surface—*rain admittance factor* (RAF) and *surface runoff coefficient* (SRC), respectively—were measured separately under simulated WDR conditions. Test-based RAF and SRC datasets were developed for three types of building models (gable, flat, and hip-roof buildings) tested for various wind directions. Test results indicated a higher concentration of direct impinging raindrop deposition on windward vertical surfaces of the building when compared to the horizontal roof components. The test results also demonstrated that the leading edge/corner regions of the buildings received less volume surface runoff rainwater, and the rainwater accumulation increases toward the leeward surfaces. The test-based RAF and SRC data developed in this work may be used for estimation of WDR deposition on façades of low-rise buildings as well as water intrusion through building envelope breaches, openings, and defects.

1. Introduction

Wind-driven rain (WDR) intrusion through building envelope defects and breaches is a major source of damage to building interior components and contents during hurricane landfall. High wind pressure and wind-borne debris can cause major breaches to external building envelope. These breaches along with existing envelope defects and openings (e.g., soffit vents) form pathways for WDR to enter into the building enclosure system and cause damage to building interior components and contents (Bitsuamlak et al., 2009; Chowdhury et al., 2012). Some of the interior building damages caused by WDR intrusion during hurricanes include soaking of roof and wall insulations, weakening of gypsum boards and total collapse of ceilings, rotting of floor systems, and destruction of contents (FEMA, 2005b). In the past, such building damages contributed significantly to the total loss together with subsequent losses due to short and long terms functional disruption of buildings. The extent of building interior damages due to WDR intrusion is dependent on the total volume of WDR ingress through building envelope defects, openings, and breaches. The total volume has contributions from both directly impinging raindrops onto the opening area and accumulated surface runoff rainwater coming from nearby undamaged envelope surface. Currently available models for estimation of the total volume of WDR intrusion through a given opening on a building facade use distribution of WDR deposition on the surface of the building envelope (Dao and Lindt, 2010; Pita et al., 2012). However, the accuracy of such models has been limited due to the scarcity of available field and experimental data on distribution of rainwater deposition over building surfaces. The current study experimentally investigated the distribution of WDR deposition on the façade of low-rise buildings with various roof shapes.

The total volume and mechanism of rainwater deposition on various components of a building façade vary with the exposure to the incident WDR. The wetting pattern caused by impinging raindrops on the building envelope is mainly governed by the interaction of wind, wind-driven raindrops, and aerodynamic shape of the building structure. The rain admittance factor (RAF)

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is a coefficient that quantifies the distribution of impinging raindrops on building envelope as a function of building shape, location on the building façade, and wind direction (Straube and Burnett, 2000). The trajectory of raindrops and their final destination on a building façade is also dependent on the raindrop size, implying the importance of raindrop size distribution in measurements of RAF. Similarly, the volume of surface runoff rainwater at a given location on a building façade is expressed through surface runoff coefficient (SRC) which quantifies the accumulated surface rainwater (total surface rainwater volume leftover from splashing and surface absorption) (Blocken and Carmeliet, 2012). The surface runoff rainwater over the building façade is affected by surface wettability, the absorption capacity of building envelope material, surface roughness, surface tension, gravity, and wind action.

Various field measurements and numerical studies have been conducted to quantify the distribution of WDR deposition on building facades as direct impinging raindrops and surface runoff rainwater. Nore et al. (2007) conducted field measurements of WDR deposition on a low-rise building located in Trondheim, Norway. The study was focused on quantifying the distribution of WDR deposition (direct impinging rain) in relation to wind speed, wind direction, and rain intensity. Detailed measurement dataset including free-field WDR rate, WDR deposition on building façade, wind speed, wind direction, horizontal rain intensity, and building and topographic descriptions were provided for model development and validation purpose. A similar field measurement of WDR deposition as a result of direct impinging raindrops were reported by Blocken and Carmeliet (2005) using the VIELT building of Laboratory of Building Physics at Catholic University of Leuven, Belgium. The field data of impinging WDR deposition were used to develop high-resolution dataset of *WDR coefficients* (analogous of RAF) to be used in estimation of WDR deposition using numerical methods. Van-Mook (2002) measured the rainwater accumulation on the west façade of the main building at the Eindhoven University of Technology (TUE), Netherlands. WDR coefficients were estimated at two locations on the building façade. Results showed wide dispersion of WDR coefficients as a function of reference wind velocity and horizontal rain rate (Van-Mook, 1999, 2002). A more extensive study of WDR deposition on building façade was conducted by Ge and Krpan (2009) on existing five low-rise and three high-rise buildings located in British Columbia, Canada. The study was aimed at improving the adequacy and use of local building WDR exposure data which are used in designing of building envelopes. The field measurement data by Ge and Krpan (2009) suggested that the distribution of WDR coefficients could vary with rain events. The study also indicated that the presence of roof overhang significantly reduced the WDR coefficients on the building façades and the shedding effect of the overhang depends on the wind and rain characteristics (Ge and Krpan, 2007, 2009). Comprehensive review of some early-time field measurements of WDR deposition on building façades are presented by Blocken and Carmeliet (2004); Straube (1998). In general, the field measurements showed that the top and side corners/edges of building walls receive large volume of direct impinging raindrops which is largely attributed to the deflection of raindrops caused by the driving wind action as the consequence of the presence of the building itself. Contrary to field measurements of direct impinging raindrops, measurements of surface runoff rainwater on existing building façade are scarce. Detailed review of surface runoff rainwater measurements on building façade is presented by Blocken and Carmeliet (2012) and Blocken et al. (2013).

In addition to the field measurements, the distributions of direct impinging raindrops and surface runoff WDR deposition on building facades were investigated using numerical and/or computational fluid dynamics (CFD) approach by many researchers including Choi (1993), (1994), Kubilay et al. (2013), Blocken and Carmeliet (2002, 2007), Hangan (1999), Karagiozis et al. (1997) and Van den Brande et al. (2013). Distribution patterns of WDR deposition conforming to the field measurements were reported by these authors using the CFD method. Although the CFD approach produced valuable information on volume and mechanism of WDR deposition on building facades, experimental and field measurement data are scarce to validate the findings based on the numerical analyses.

Therefore, it is the purpose of the current study to develop test-based dataset of RAF and SRC distribution on the facades of commonly available shapes of low-rise buildings. Such database can be used to develop a more accurate method of estimation of WDR deposition on building façade as well as water intrusion through building envelope defects, openings, and breaches. Moreover, understanding of WDR deposition patterns and accumulation mechanisms will facilitate the development of damage mitigation strategies to reduce the building enclosure and interior damages during tropical storms and hurricanes. Section 2 presents the methodology used to develop test-based data of RAF and SRC distributions on the facades of building models. It is accompanied by detailed descriptions of the testing setup, simulation of atmospheric boundary layer (ABL) wind profile and tropical cyclone (TC) WDR using the Florida International University's (FIU) 12-fan *Wall of Wind* (WOW) facility, capable of simulating hurricane wind speeds, instrumentation, and testing protocol for estimating RAF and SRC distribution. Section 3 discusses the test results followed by some important deductions. The conclusions of the study along with summarized major findings are presented in Section 4.

2. Methodology

The test setup to produce test-based RAF and SRC data was carefully designed in order to ensure the realistic representation of test results. Prior to collecting test data, typical hurricane wind and WDR characteristics were simulated in the test setup based on target characteristics obtained from field data collected during hurricanes (Tokay et al., 2008; Yu and Chowdhury, 2009; Yu et al., 2008). A length scale of $\lambda_L = 1{:}4$ and velocity scale of $\lambda_V = 1{:}2$ were used between model and prototype considering the wind flow field dimensions and tropical cyclone WDR simulation at *Wall of Wind*. The following subsections describe the test setup in detail.

2.1. Building models description

Test-based WDR deposition parameters—RAF and SRC—data were developed on facades of building models with three types of roof shapes: gable, flat, and hip. The test buildings were built with double acrylic wall and roof covers attached to an internal wooden framing system. Each building model had a base plan dimensions of $1.52 \times 2.30\ \text{m}^2$ $(5.0 \times 7.5\ \text{ft}^2)$ and eave height of 0.76 m (2.5 ft) assuming the same length scale of 1:4. A 5:12 roof pitch was used for both gable and hip roofs with overhang length of 7.62 cm (3.0 in) on all sides. The length-scale and model building dimensions were selected based on the need to minimize blockage within the flow field (maximum blockage was 9.78% for the gable building). The percentage of blockage was checked against tolerable limits as investigated by Bitsuamlak et al. (2010) and Aly et al. (2011), who reported that up to 16% blockage in an open-jet facility does not necessarily require pressure measurement corrections. The double acrylic wall and roof claddings were designed with grid-format of openings used to mount WDR collecting buckets. Fig. 1 shows the gable building model with opening layout and detailing.