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An experimental study to assess the effect of soffit louvered vents on wind loads and wind driven rain intrusion on low rise buildings

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ABSTRACT

Wind-driven rain (WDR) intrusion in buildings during hurricanes often leads to significant damage to building interior and contents, causing major losses. Many buildings in hurricane-prone U.S. coastal states are fitted with soffit vents with louvers that are designed to close during high winds and reduce rain intrusion. This paper focuses on the topic of WDR intrusion through soffit vents and, in particular, studies the effects of louvered soffit vents on (i) reduction of water intrusion, and (ii) overall aerodynamic loading of buildings' roofs. A gable and a hip roof building retrofitted with open and closed vents were tested at the Wall of Wind (WOW) experimental facility. WDR intrusion studies were carried out only on the hip roof building, while wind pressure distributions were estimated for the gable and hip roof buildings. Results from the WDR intrusion study indicate a marked reduction in water intrusion for the closed vent roofs. Moreover, the net mean and peak pressure coefficients for the closed vent roofs are reduced in magnitude (less suction) compared to the open vent roofs. Future research is recommended to study the effect of different vent sizes and locations, besides considering other roof types (e.g. mono-slope).

1. Introduction

Wind-driven rain (WDR) intrusion in buildings during a hurricane is a major cause of concern in coastal areas of Florida (Mullens, Hoekstra, Nahmens, & Martinez, 2006). Previous studies have clearly shown the extent of damage to a building's interior caused by mould growth, weakening of gypsum boards and total collapse of ceiling, following rain intrusion during a hurricane (FEMA, 2005). For instance, field measurements carried out by Van-Mook (2002) on a building at Technical University Eindhoven, Netherlands, showed a wide dispersion of WDR coefficients as a function of reference wind velocity and horizontal rain rate. Similarly, Nore, Blocken, Jelle, Thue, and Carmeliet (2007) carried out field measurements on a low rise building in Trondheim, Norway, to assess the WDR deposition on the building façade; the data collected from this study was used for model development and validation. Studies on WDR intrusion were carried out through field measurements by Ge and Krpan (2009) on five existing low-rise and three high-rise buildings in British Columbia, Canada to improve the existing WDR intrusion guidelines available for building designers. Their studies showed that the WDR coefficients could vary significantly with rain events. Furthermore, roof overhangs were found to reduce WDR coefficients on the building facades in some cases (Ge and Krpan, 2007, 2009). Besides field measurements, WDR intrusion has also been simulated in wind tunnels. For instance, studies at the University of Florida (UF) by Salzano, Masters, and Katsaros (2010) showed that 'water barrier' and 'drainage installation' methods used in wood buildings with windows could prevent water intrusion in buildings during a hurricane. Similarly, studies by Lopez (2011) were carried out at the UF on the performance of a residential window in static wind load and time varying wind load conditions. Their studies showed that WDR intrusion through static air pressure differential across the window was sufficiently accurate. Besides physical modelling, WDR simulation using Computational Fluid Dynamics has been carried out by various researchers (Choi, 1993; Hangan, 1999; Blocken and Carmeliet, 2007). There are many studies on WDR focussed on the rain size distribution (e.g. Friedrich, Higgins, Masters, & Lopez, 2013), although more recent studies have successfully developed a method of estimating target WDR rate as a function of test wind speed based on

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target rain size distribution and rain rates (Baheru, Chowdhury, Bitsuamlak, Masters, & Tokay, 2014). Most studies have focused on water intrusion through windows and other fenestration. However, limited information is available on the effect of soffit louvered vents on WDR intrusion, when exposed to wind and rain in an Atmospheric Boundary Layer (ABL) flow, and therefore further research is needed in this direction.

Besides water intrusion, hurricane winds exceeding 100 miles per hour (44.7 m/s) have greatly affected coastal areas of USA, resulting in damage of buildings and property worth millions of dollars (Boughton et al., 2011). The roof of a building is generally vulnerable to wind induced structural damage, due to high suctions causing roof lift-off (Kumar and Stathopoulos, 2000). Buildings that are lower than 18 m high are considered low-rise buildings as per ASCE 7, 2010, and these buildings have different roof forms, such as hip, gable and mono-slope roofs. Attic vents are generally used to ventilate the attic space in low-rise buildings (TenWolde and Rose, 1999). Previous studies on the performance of vents in hurricane conditions carried out at the Wall of Wind (WOW) experimental facility at Florida International University (FIU) showed that water intrusion in the building was affected by the vent mechanism (Chowdhury, Bitsuamlak, Fu, & Kawade, 2011). However, as the wind enters the building through these openings, there can be an increase in internal pressure, resulting in higher roof uplift forces. For instance, Irwin and Sifton, 1998 carried out extensive studies on the effect of wind induced internal pressures due to wall openings of various sizes. Various studies also suggest that besides the size of the openings, compartmentalisation of a building can greatly influence the internal pressure coefficient (Holmes, 1979; Saathoff and Liu, 1983; Vickery, 1986). Roof vents can help ventilate buildings, but these openings can lead to high internal pressure that may damage the building envelope and its interior (Tecle, Bitsuamlak, & Chowdhury, 2012). There is a gradual increase in the use of soffit louvered vents (Platts, 2002, U.S. Patent No. 6,484,459) in the state of Florida that have the capability of automatically closing in the event of high wind speeds (> 10 m/s) in order to prevent air and water intrusion, while remaining open at all other times. Most standards such as ASCE 7–10 do not provide design guidelines for the safe design of roofs with such soffit louvered vents. This explains the need to carry out further research on the effect of these soffit louvered vents in altering damage patterns to the building roof, besides preventing WDR intrusion into the building.

This paper presents a set of experimental results from tests carried out at the Wall of Wind (WOW) experimental facility on two low-rise buildings fitted with soffit louvered vents. The main objectives are to assess the WDR intrusion into the soffits, as well as to estimate the mean and peak pressure coefficients on the external and internal surfaces of the hip and gable roofs. Two different cases were considered for both hip and gable roof buildings; soffit vents without louvers and soffit vents with louvers. The wind directions varied from 0° to 90° for the gable roof building, while for the hip roof building, the wind directions varied from 0° to 45°. Furthermore, detailed tests on WDR intrusion into the hip roof building at 0° and 45° was also carried out. WDR intrusion studies were carried out only on the hip roof building, while wind pressure distributions were estimated for the hip and gable roof buildings. Section 2 of this paper presents the WOW experimental set up, while the various building configurations are discussed in Section 3. Sections 4 and 5 describe the WDR test procedure and the pressure measurements. Section 6 presents Results and discussion, while Conclusions form part of Section 7.

2. Wall of Wind Experimental Set up

The Wall of Wind (WOW) is a state-of-the-art large scale wind engineering experimental facility at FIU, USA (Aly, Chowdhury, & Bitsuamlak, 2011). The facility consists of 12 large 700 horsepower electric motor fans placed in two rows as shown in Fig. 1(a). The flow field is 6.1 m wide, 4.3 m high, and consists of blocks representing roughness elements (Fig. 1(b)) which allows the development of an ABL over a length of 9.75 m downstream of the contraction zone. The WOW is capable of generating wind speeds exceeding 150 mph (67.05 m/s), which is equivalent to a category 5 hurricane in the Saffir-Simpson scale (Aly et al., 2011).

The velocity and turbulence intensities were measured using Cobra probes (Turbulent flow instrumentation, 2008) located at various heights above the WOW floor, as shown in Fig. 2. The eave height of both buildings used in this study was 1.27 m, and the mean velocity at this height (V_{eave}) was 25.67 m/s. Although wind speeds of 67.05 m/s can be achieved in the WOW, the purpose of the study was not to test the buildings at such high speeds. The key objectives of this study were to assess the effect of louvered soffit vents on the WDR intrusion and wind loads on the building roof. Since the vents automatically close at wind speeds exceeding 10 m/s, a wind speed of 25.67 m/s at the building eave height was sufficient for this to be achieved, thereby disallowing air and water entry into the building. Fig. 2(a) and (b) show the normalized mean wind speed and turbulence intensity profiles, where h_{ref} = 1.83 m (10.97 m full scale) and V_{ref} = 28.5mps. ESDU, 2001 has been the source for estimating full scale parameters. Fig. 2(c) presents the turbulence power spectra at the model roof height, compared to the corresponding full scale spectra. The comparison confirms that the high frequency turbulence is captured adequately in the measurements, while the low frequency part is deficient because of the large scale of the model and the limited size of the test section with respect to the large eddies that form in full scale. This deficiency is analytically compensated through the adopted method for peak analysis, as discussed in the following paragraph.

The length scale in the present study is 1:6, and the velocity scale was 1:1. The length scale of turbulence in the WOW is approximately 0.4 m. Although accurate simulation requires matching of Reynolds number between model and prototype, Kind and Wardlaw (1982) have shown that a larger mismatch has minimal effect on the accuracy of the measurements. A Partial Turbulence Simulation (PTS) technique was used in determining the peak pressure coefficients (Mooneghi, Irwin, & Chowdhury, 2016). According to Mooneghi et al. (2016); the PTS technique focusses on obtaining a good match of the high frequency part of the spectrum, while the missing low frequency part of the spectrum is included in the post-test analysis through a quasi-steady approach. The various cases investigated for this study are described further.

3. Building configurations tested in WOW

Four different Cases for various wind directions (θ) were tested in the WOW. A hip roof and gable roof building were used, which have an eave height of 1.27 m and square plan of 1.63 m × 1.63 m at model scale. Both buildings had roof slope of 4:12. The various building configurations (Fig. 3) tested in the WOW include:

1. Gable roof building – vent without louver (θ = 0°, 15°, 30°, 45°, 60°, 75°, 90°),
2. Gable roof building – vent with louver (θ = 0°, 15°, 30°, 45°, 60°, 75°, 90°)
3. Hip roof building – vent without louver (θ = 0°, 15°, 30°, 45°)
4. Hip roof building – vent with louver (θ = 0°, 15°, 30°, 45°)

The front view of the gable roof building (Fig. 3(a)) and the inside of the gable roof (Fig. 3(b)), as well as the front view of the hip roof building (Fig. 3(c)) and the interior of the hip roof (Fig. 3(d)) are shown. The soffit vents were located on the corners of the buildings as shown in Fig. 3(e). The ranges of wind directions for each building are shown in Fig. 3(f), while the soffit vent is shown in Fig. 3(g). As mentioned earlier, the ‘vents with louvers’ have the capability to automatically close during the event of high wind speeds (> 10 m/s),