Abstract: Most residential buildings use a natural ventilation process by which overheated air inside buildings is vented out and fresh air is pulled in to replace it. Proper ventilation helps maintain a comfortable temperature inside buildings, maintain indoor air quality, increase energy efficiency, and prevent moisture damage. Vents are necessary to prevent heat and moisture buildup and contribute to the longevity of building components. However, the vents are subjected to wind loading and can be the path for water infiltration during hurricane events. Limited research has been performed on water intrusion through various types of vents in residential buildings to relate such water intrusion to the vent mechanism and the differential pressures that the vents are subjected to during hurricanes. The objectives of this research were to perform full-scale holistic testing of vents subjected to simulated hurricane-level wind and wind-driven rain to evaluate such relations and vent performance under hurricane conditions. Two building models incorporating a variety of vents were tested using the wall-of-wind facility. It was found that the extent to which water intrusion increased with higher positive differential pressure across the vent for various angles of attack can be affected significantly by the vent mechanism. DOI: 10.1061/(ASCE)NH.1527-6996.0000039. © 2011 American Society of Civil Engineers.

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Introduction

Most residential buildings use a natural ventilation process that allows air to flow into and out of buildings. Overheated air inside buildings is vented out and fresh air is pulled in to replace it. Attic ventilation is an important aspect of extending the life of the attic and roof structure in residential buildings. Natural ventilation helps prevent moisture from becoming trapped in insulation, structural wood, roof deck, and roofing materials. It also prevents rotting, mildew, drywall damage, peeling paint and warped siding. Vents are necessary to prevent heat and moisture build-up and help maintain a comfortable temperature inside buildings, maintain indoor air quality, and increase energy efficiency. Vents contribute to the longevity of building components by minimizing moisture damage, premature aging and cracking of wood and other roofing materials.

In residential buildings, warmer air is drawn out of the attic space through roof ridge vents; the process is sometimes helped by suction caused by wind flow over the roof ridge vents. Airflow through the soffit vents allows for the replacement of the escaping warmer air through the ridge, roof, and gable vents to maintain a balanced ventilation system. In the absence of wind flow, continuous air flow to facilitate natural ventilation may be maintained through the natural convection action of rising warm air.

However, the vents may be subjected to high wind loading and can be the path for water infiltration during hurricane events. Hurricane winds can drive large amounts of water through vents and the accumulating water soaks insulation, which can lead to mold growth and, in some cases, to the collapse of ceilings (FEMA 2009).

Some research was performed on vents and their performance. Boulard and Baille (1995) presented mathematical models for air exchange rate for roof vents. The wind speed, turbulence intensity, and wind direction were considered as important parameters in their models. They also performed a set of measurements and analyzed test results of air exchange rate through continuous roof vents to validate the models. Some studies related to the performance of ventilation systems were done by utilizing experimental facilities. Breeze (2003) studied the aerodynamic and weather-tightness performance of pitched roof vents by using a new test rig and investigated the correlation between water infiltration and differential pressure. Jiang et al. (2003) studied natural ventilation in buildings with different openings on walls through measurements in a wind tunnel and numerical simulation. Khan et al. (2008) performed a wind tunnel study to observe the airflow around a turbine vent. Grant et al. (2007) performed wind-tunnel testing of a new omnidirectional roof vent that showed promise in improving the performance of membrane roof systems in locations susceptible to high wind.

Kala et al. (2008) investigated the wind pressure on rain screen walls by using a boundary-layer wind-tunnel facility and compared the results with full-scale data conducted by the Technical University of Eindhoven. The main objective of their work was to reduce...
the pressure coefficient on rain screens. After trying various setups, the reduction of pressure coefficients could reach 90% for wind tunnel tests but only 55% for full-scale tests. Although full-scale studies on pressure differentials across building components are more effective, such as rain screens and vents, very limited full-scale experimental research has been performed to date on wind-driven rain intrusion through various vents. Recently, Masters (2006) investigated wind-driven rain intrusion through softifs at full scale.

Some efforts have been made to study the interaction among wind, rain, and buildings using computational fluid dynamics (CFD) simulations (Blocken and Carmeliet 2004). Although a numerical approach did provide a possible route to analyze such interaction, according to Blocken and Carmeliet (2004), the preparation of the numerical model was extremely time-consuming. In addition, the selection of the parameters (e.g., wind speed, turbulence intensity, raindrop size, and building geometries) could be problematic.

Some of the studies mentioned previously focused on pressure differential as the mechanism to move air through vent openings. However, most of these studies were accomplished by either testing vents only (without the building housing the vents) or performing CFD analyses. However, it is also important to investigate at full scale the external pressure distribution on vent surfaces and internal pressures inside the building to estimate the pressure differentials across the vents and their correlation with water intrusion under high winds accompanied by rain. Bitsuamlak et al. (2009) recently employed similar full-scale testing methods to assess the effectiveness of roof secondary water barriers. However, such full-scale studies are rare, and limited research has been performed to date on water-intrusion through various types of vents in residential buildings to correlate such water intrusion to the vent mechanism and the differential pressures that the vents are subjected to during hurricanes. This paper focuses on full-scale holistic testing of vents subjected to simulated hurricane-level wind and wind-driven rain to evaluate such correlation and vent performance under hurricane conditions. Test results are presented showing pressure differentials, water-intrusion amounts through different types of vents, and drag and uplift coefficients for certain roof vents.

**Vent-Testing Methodology**

**Six-Fan Wall-of-Wind (WoW)**

The tests on vents were performed by using the six-fan wall-of-wind (WoW) built by the International Hurricane Research Center (IHRC) at Florida International University (FIU) (Fig. 1). The six-fan WoW hurricane simulator, sponsored by RenaissanceRe Holdings Ltd., is a full-scale wind and wind-driven rain testing apparatus located at FIU’s Engineering Center campus. The WoW is capable of testing low-rise building models fitted with real building components such as roofing materials and vents.

The six-fan WoW system consists of a 2 × 3 array of Chevy 502 big block carburetor engines, each capable of producing 374 kW (502 hp) and turning Airboat Drive Units CH3 2:1 propeller drives, providing a wind stream approximately 4.8 m (16 ft) high by 6.7 m (22 ft) wide. Each engine, driving a pair of counterrotating propellers of approximately 2.3 m (7.6 ft) in diameter, was mounted in a steel frame engine section measuring 2.44 m (8 ft) by 2.44 m (8 ft).

Passive control devices were used to generate reasonable mean wind speed profiles, such as atmospheric boundary layer profiles, for the six-fan WoW (Huang et al. 2009). Application of active controls in the form of quasi-periodic sums of sinusoidal signals to the fan engines, designed on the basis of wind characteristics obtained from analyzing tropical cyclone data collected through the Florida Coastal Monitoring Program (FCMP) (Masters 2004), succeeded in simulating realistic wind turbulence characteristics by improving the longitudinal power spectral densities, turbulence intensities, integral length scales, and gust factors (Huang et al. 2009).

The Saffir-Simpson scale is defined in the Commentary to the ASCE 7-05 Standard (ASCE 2005) in sustained (1 min) speeds over water. According to Simiu et al. (2007), Category 1 hurricanes on the Saffir-Simpson scale correspond to approximately 1.07 × 33.1 m/s = 35.4 m/s (79.2 mph) peak 3 s gust speed at 10 m (33 ft) above open terrain. For the six-fan WoW system, the wind speeds corresponded with Category 1 hurricane conditions when low-frequency signals were applied to obtain desired wind turbulence (Huang et al. 2009). To produce more severe hurricanes, additional research is currently being performed. The goal is to achieve the requisite turbulence generation in the WoW while maintaining higher-level wind speeds.

A plumbing system was designed to produce the impinging rain for the WoW system (Bitsuamlak et al. 2009). To support the plumbing system, a steel frame was placed in front of the six-fan units. A grid of four columns and three rows of Tee Jet spray nozzles, joined together with high pressure hosing, was mounted vertically onto this frame [Fig. 2(a)]. A gasoline-powered pump transferred the water from water tanks through the hosing and into the spray nozzles. The pressurized pump fed the grid and spray nozzles, spraying the water at the specified rate, while the fans produced the wind simultaneously [Fig. 2(b)].

Choi (1993) simulated wind-driven rain movement around a building, that is, the trajectories of raindrops in the vicinity of and as they hit a building facade under the influence of a wind field. The simulation was performed numerically by solving the stochastic equations of motion of the raindrops, in which the forcing term was because of the aerodynamic effect of the wind flow on the drops and the \( k \)-epsilon flow turbulence model was used. Choi’s analysis showed that for small raindrops, the trajectories are strongly affected by the wind flow, and that the effect of the wind flow on the raindrop motion increases with wind speed. Given the high concentration of small and midsize drops in tropical cyclone rainfall (Tokay et al. 2008), this means that it is appropriate to simulate wind-driven rain in the WoW by horizontally placed spray jets, which replicate correctly the nearly horizontal trajectories of typical raindrops in hurricanes.

![Six-fan WoW (image by T.-C. Fu)](image)
Test Specimen and Instrumentation

The experimental setup considered two common residential roof types (gable and hip roofs with a 4:12 slope) mounted at the top of a 2.75 m (9 ft) long × 2.14 m (7 ft) wide building model with an eave height of 2.14 m (7 ft). Before mounting the roof specimens onto the building model, each roof was prepared with 13.6 kg (30 lb) felt paper underlayment, covered with five-tab architectural shingles, and outfitted with the roof and wall vents of interest. For the scope of this study, a 25.4 cm (10 in.) long × 10.2 cm (4 in.) wide × 20.3 cm (8 in.) high gooseneck vent, a 30.5 cm (12 in.) diameter turbine vent, a shingle ridge vent, and 40.6 cm (16 in.) × 15.2 cm (6 in.) ← soffit vents were installed on each of the gable and hip roof building models. Additionally, the building model with gable roof was fitted with a 30.5 cm (12 in.) × 30.5 cm (12 in.) cosh square shape gable end vent. Fig. 3 shows the installation of the roof and soffit vents and the 0 and 90° wind angles of attack (AOA).

A 16-channel Scanivalve Digital Sensor Array DSA 3217/16PX was used to measure the external pressure time histories around the turbine and gooseneck vents during all tests. The DSA module was installed within the attic space of the roof specimens. Eight pressure taps on each of the turbine and gooseneck vents (Fig. 4) were installed by the following: (1) gluing small square tabs made of wood or hard plastic onto the inside walls of the vents at every tap location, (2) drilling a 1.98 mm (5/64 in.) diameter hole at each tap location, and (3) gluing a piece of 1.98 mm (5/64 in.) outside diameter tubing into each tap hole. The tubing length between each pressure tap and the DSA module was no longer than 91 cm (3 ft) to minimize signal distortion. Setra 265 differential pressure transducers were used to measure the internal pressures close to the inside surface of each vent. Similar transducers measured the internal pressures close to the inside surface of each vent. Reference pressure tubing for each transducer was installed in the manner described in Blessing (2007). The Setra 265 pressure transducers were connected to a NI cRIO-9074 module, with NI 9205 32-channel analog voltage inputs. National Instrument Lab View software was used to collect and record the data. All measurements with the Setra transducers and the DSA module were set to a sampling rate of 100 Hz during the testing.

Water-Intrusion Measurement Technique

Wind-driven rain tests were performed on the gable and hip roof models to measure the water intrusion through each vent and quantify the volume of water entering each building model. A piece of plastic sheeting was attached to the inside opening perimeter of each of the gooseneck, turbine, ridge, and gable end vents to contain the water entering the attic space through each vent, and direct the water toward a water-collection container for each vent. The plastic sheeting, secured to the vents with aluminum tape, terminated before reaching each water collection container to allow airflow generated by differential pressure across each vent so that it was not influenced by the presence of the water-collection system. For the gable end, soffit, turbine, and gooseneck vents, aluminum pans [Fig. 5(a)] were used to collect the incoming water. For the ridge vent, a 10.2 cm (4 in.) diameter PVC pipe was cut in half to create a trough that would collect the water after intrusion, and direct it into eight measuring buckets [Fig. 5(b)].

Test Protocol

During this study, the test models were tested at the following five angles of attack (AOA) with respect to the WoW flow field: 0, 15, 45, 75, and 90° AOA (0 and 90° AOA shown in Figs. 3 and 4). A 3-min, quasi-periodic waveform (Huang et al. 2009) was used to
generate the wind (3 s peak gust being 38.3 m/s) for each test needed for pressure measurements. Three-minute baseline pressure data were collected before and after each wind test. Both baseline data sets were used to establish the environmental conditions, and were averaged together and deducted from the test pressure data collected during the WoW run to determine the wind-induced pressures. Coefficients ($C_p$) of mean, maximum, minimum, and root-mean-square (rms) pressures were calculated based on the pressure time histories. The differential pressures coefficients ($\Delta C_p$) were calculated as the differences between the external and internal pressure coefficients. For the gooseneck and turbine vents, each of which had multiple external pressure taps connected to the DSA module through tubing, the external pressures used to obtain the differential pressures were the ones measured at the windward tap experiencing positive external pressure.

For the water-intrusion testing, a water flow rate of 483 mm/h (19 in./h) was used for rain generation in conjunction with winds (3 s peak gust being 38.3 m/s) created by the quasi-periodic engine waveform to drive the raindrops to the test specimen. The water flow rate of 483 mm/h (19 in./h) was used to simulate intense rainfall such that the rain rate was close to 429 mm/h (17 in./h), the highest rain rate given for Miami by Willis et al. (1989). The duration of each wind-driven rain test was 6 min. Water intrusion through each vent was measured after the end of each test. The water-collecting containers were then removed from the building model and weighed on a digital scale. The water was then drained out of the containers, which were wiped dry with a cloth. The dry containers were then weighed and the amount of water intrusion for each vent was calculated.
Differential Pressure Coefficients and Water-Intrusion Test Results and Discussion

Gable Roof Specimen Results

The differential pressure coefficients ($\Delta C_p$) obtained for the vents for the gable roof specimen are plotted in Fig. 6(a) showing different angles of attack. Fig. 6(b) shows the corresponding water-intrusion amounts for the vents. There was no water infiltration through the ridge and soffit vents for the gable roof specimen. However, for the other vents, Figs. 6(a) and 6(b) show good correlation between the water-infiltration amount and the positive $\Delta C_p$ values for each type of vent. In most cases, higher water intrusion was observed for higher positive differential pressure coefficient; however, the vent mechanism also affected the amount of water intrusion for different wind attack angles. For the gooseneck vent comparatively higher water infiltration was noted for 45, 75, and 90° AOA, for which cases the $\Delta C_p$ values show an increasing trend from 0.6 to 0.7. Similarly, the gable end vent had comparatively higher water infiltration for 0, 15, and 45° AOA, for which cases the $\Delta C_p$ values were approximately 0.3 or higher. The water-intrusion amounts and differential pressures for the gable end and gooseneck vents varied with the AOA because both types of the vents had directional frontal openings. The positive differential pressures were high for these two vents as the wind was aimed at the vent frontal openings (i.e., 0° AOA for gable end vent and 90° AOA for gooseneck vent). However, at 0° AOA the amount of water infiltration through the gable end vent was not maximum. This may be attributed to the mechanism of the gable end vent. When the wind-driven rain was perpendicular to the gable end vent surface (0° AOA), the vent louvers could have acted as rain-blockers and blocked some amount of the water from getting into the vent. However, when the wind-driven rain was somewhat inclined (e.g., 15 to 45° AOA) more water could get through the opening under the louvers. Similarly, for the gooseneck vent, inclined wind-driven rain (e.g., 45 to 75° AOA) caused slightly more water intrusion than that for wind-driven rain perpendicular to the frontal opening (90° AOA). This again showed, that in addition to the positive differential pressure, the vent mechanism affected the water-intrusion amount for different AOA. The water infiltration amount through the turbine vent was somewhat independent of AOA for 0 to 90°. Such independence on AOA, consistent with the differential pressure coefficients, which did not show any specific trend either, could be attributed to the omnidirectional opening in the rotating top portion of the turbine vent. For most AOA (45, 75, and 90°) the water intrusion through the turbine vent was much less than that for the gooseneck vent, although the turbine vent was subjected to similar high differential pressures to the gooseneck vent ($0.5 < \Delta C_p < 0.75$). An explanation is that the top portion of the turbine vent was always spinning under wind attack during the tests; the spinning lessened water intrusion through the vent. For the soffit and ridge vents, $\Delta C_p < 0.15$ for most wind attack angles that were tested. The low $\Delta C_p$ values could explain why there was no water intrusion for the soffit and ridge vents during the gable roof tests. This is unusual because soffit-vent water intrusion had been observed during many past hurricanes. For the current tests, the inclination of the soffits (in contrast to horizontal soffits) might have prevented the water infiltration through the soffit vents. Further research is needed in this area to develop methods for reducing water infiltration through soffit vents.

Hip Roof Specimen Results

All the differential pressure coefficients ($\Delta C_p$) for the vents for the hip roof specimen are plotted in Fig. 7(a) for different AOA. Fig. 7(b) shows the corresponding water-intrusion amounts for the vents. There was no water infiltration through the soffit vents for the hip roof specimen. However, for the other vents, Figs. 7(a) and 7(b) show some correlation between the water-infiltration amount and the positive $\Delta C_p$ values for each type of vent. For example, for the gooseneck vent, the highest amount of water infiltration was noted for a 45° AOA, for which case the $\Delta C_p$ value

![Fig. 6. Results for vents on gable roof specimen: (a) differential pressure coefficient; (b) water-intrusion amount](image)

![Fig. 7. Results for vents on hip roof specimen: (a) differential pressure coefficient; (b) water-intrusion amount](image)
was maximum. Similar to the results for the gable roof specimen, the pressure differential and the water-intrusion amount for the turbine vent did not show any specific trend. The continuous spinning of the top portion of the turbine vent during the testing lessened water intrusion, although the turbine vent was subjected to differential pressures similar to those for the gooseneck vent. There was some amount of water infiltration through the ridge vent on the hip roof at 90° AOA, for which case the corresponding $\Delta C_p$ increased abruptly to 0.6. This again shows the increasing chances of water infiltration with increasing differential pressure. All $\Delta C_p$ values were negative for the soffit vents. This could explain why there was no water infiltration through the soffit vents.

**Drag and Lift Coefficients for Turbine and Gooseneck Vents**

Figs. 8 and 9 show sample plots of external pressure coefficients (i.e., mean, maximum, minimum, and rms) measured for the turbine and gooseneck vents for the gable roof specimen. As anticipated, the maximum positive $C_p$ values were obtained at the pressure taps facing the wind direction. For instance, for 0° AOA for the gable roof specimen, turbine vent tap 7 and gooseneck vent tap 13 were the windward taps directly facing the WoW and thus recorded maximum positive pressure coefficients of 3.5 and 4.0, respectively. For the gable roof specimen of 90° AOA, turbine vent tap 5 and gooseneck vent tap 12 were the windward taps directly facing the WoW and thus recorded maximum positive pressure coefficients of 2.0 and 2.2, respectively. As anticipated, mean positive pressures were recorded for the windward taps, and mean negative pressures were recorded for the side and leeward taps. Similar results were obtained for the hip roof specimen. The pressures were integrated over the cross sections of the vents to determine the drag force and the drag force coefficient ($C_D$). The uplift force coefficient ($C_L$) was determined for the gooseneck vent by using the pressure data collected by tap 9 and the projected area of the vent. The drag and uplift force coefficients are plotted in Figs. 10 and 11.

For circular cylinders, the drag coefficient ($C_D$) is a function of the Reynolds number. For the pressure testing performed in the current study, the Reynolds number was calculated as $4.1 \times 10^5$ for the turbine vent. For this Reynolds number value, $C_D \approx 0.35$ (Simiu and Scanlan 1996, p. 158), which compares well with the $C_D$ value for the turbine vent on the hip roof specimen for all AOA and on the gable roof specimen for all AOA except for 45° (Fig. 10). For the gooseneck vent, the maximum $C_D$ values were 1.25 and 0.75 for the gable roof and hip roof specimen, respectively. For the turbine vent, the maximum $C_D$ values were 0.75 and 0.3 for the gable roof and hip roof specimen, respectively. Both the turbine and gooseneck vents could be subjected to higher $C_D$ values and would be more susceptible to shear failure on the gable roof and subsequently could become wind-borne debris. Note that the $C_D$ values may depend in general on the position of the vents on the roof. This dependence will be object of future research.

The uplift force coefficients ($C_L$) for the gooseneck vent are shown in Fig. 11. The $C_L$ values observed for gable and hip roofs were not only different at the peak values, but also the trends of the curves were quite dissimilar. For the hip roof, the gooseneck vent was subjected to uplift forces from all tested wind attack angles. However, for the gable roof, the gooseneck vent was only subjected to uplift forces at 0 and 15° wind attack angles. The highest uplift force was experienced by the gooseneck vent on the hip roof specimen for 15° AOA.

**Fig. 8.** External pressure coefficients for gable roof specimen for 0° AOA: (a) turbine vent; (b) gooseneck vent

**Fig. 9.** External pressure coefficients for gable roof specimen for 90° AOA: (a) turbine vent; (b) gooseneck vent
Summary, Conclusions, and Recommendations

The results showed that the extent to which water intrusion increased with higher positive differential pressure across the vent for various angles of attack can be affected significantly by the vent mechanism. The water-intrusion amounts and the differential pressures for the gable end and gooseneck vents varied with the wind attack angle because both types of vents had directional frontal openings. The positive differential pressures were high for these two vents as the wind was aimed at the vent frontal opening. The volume of water intrusion through the gable end vent for wind-driven rain perpendicular to the vent surface was less than that for slightly oblique angles of attack; however, the differential pressure was higher for the former case. When the wind-driven rain was perpendicular to the gable end vent surface, the vent louvers could act as a rain-blocker and block some amount of the water from getting into the vent; however, when the wind-driven rain was somewhat inclined, more water could get through the opening under the louvers. The water-infiltration amount through the turbine vent was somewhat independent of the wind angles of attack. This could be attributed to the omnidirectional opening in the rotating top portion of the turbine vent. Also, the spinning mechanism of the top portion of the turbine vent could lessen water intrusion even if the vent were subjected to high differential pressure coefficients. The results showed that, in addition to the positive differential pressure, the vent mechanism affected the water-intrusion amount for different wind angles of attack. The inclination of the soffits appears to reduce water infiltration through the soffit vents; however, further research is needed for validation and to determine the effect of soffit inclination on vent functionally and for developing methods for reducing water infiltration through soffit vents.

Future research considering additional angles of attack, various roof slopes, various positions of the vents on the roof, various rainfall rates, and raindrop size distribution is recommended for more definitive inferences on water infiltration through vents. Research is also recommended to develop various mitigation strategies to reduce water intrusion through vents.

The research findings could be used by building code officials, manufacturers, and homeowners to assess the performance and identify potential issues with various vents and develop methods to reduce water intrusion. The research indicated that gooseneck vents may allow substantial water intrusion and should have their frontal openings covered before hurricane events. The rotating top portions of turbine vents could be redesigned to close the openings before windstorms strike. Louvers of gable end vents could be redesigned to reduce wind-driven rain under oblique wind angles of attack. Ridge vents could be protected for wind-driven rain perpendicular to their openings by having a closure mechanism. Active controls could also be designed to close various vents automatically as differential pressure increases with the wind speed and wind angle of attack.

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Notation

The following symbols are used in this paper:

- $C_D$ = drag coefficient;
- $C_L$ = uplift coefficient;
- $C_p$ = pressure coefficient; and
- $\Delta C_p$ = difference between external and internal pressure coefficient.

References


