Wind Loading on Ridge, Hip and Perimeter Roof Tiles: A Full-Scale Experimental Study

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Abstract

Full-scale experiments were conducted to investigate wind loading on roof tiles in hip, ridge, and perimeter locations, identified from past storms as main points of damage initiation. The objectives were to: (i) provide test-based data on wind-induced loads for tiles, and (ii) evaluate characteristics of near-surface flows to assess tile loading models. The experiments included pressure measurements on the external surface and in the cavity underneath the tiles, and wind speed measurements near tile surfaces. The highest net uplift pressure (computed as external pressure minus the cavity pressure) was observed on the gable end ridge tiles. Except for a few non-critical cases, due to effects of pressure equalization net uplift was lower than external surface uplift. Mean wind speeds at tile surfaces were recorded that were up to 55% higher than the mean wind speed at mid-roof height in the approach flow. Two alternative models that use wind speeds near the tile surface to determine net design wind loads on tiles were investigated. The results showed that the models can underestimate wind loading. However, when used with appropriate parameters, the models can produce results comparable to those obtained using ASCE's external pressure coefficients in conjunction with pressure adjustment factors.

Keywords: Roof tiles; Full-scale experiments; Near-surface wind flow; Pressure measurement; Pressure adjustment factor; Wall of Wind.

1 Introduction

Damage to roof covering is historically recognized as a leading building performance problem during high wind events. In hurricanes, rainwater entering a building through damaged roofs can cause major damage to interior finishes and contents (Baheru et al. (2014a); FEMA (2009)). Permeable roof coverings are mostly made of roofing elements attached to an underlying support system and overlapping each other with interlocking patterns. The interlocking between individual roofing elements is important for load sharing, that is, for better distributing extreme loading. The interlocking enhances roof uplift resistance, but can at the same time increase susceptibility to progressive failure. When a single tile flies off, it not only exposes the roof deck to wind loads while initiating progressive failure; it can also become a flying debris impacting other structures downwind. The term “permeable” refers herein to permeability to wind flow.

Post-storm reports have indicated that ridges, hips, and roof edges on tiled roofs are frequently where tile damage and progressive failure is initiated, especially when the tiles lack efficient mechanical anchors (FEMA 2005d; Meloy et al. 2007; RICOWI 2006). Such failure has been observed even in hurricanes with speeds well below the design wind speed (FEMA 2009; Baheru et al. (2014b)), and might be attributed not only to poor construction practices but also to the inadequacy of code and standard provisions on design wind loads for hip, ridge and eave regions and/or on tile attachment methods for these roof regions.

This paper presents results of experimental investigations performed to understand and quantify the characteristics of wind loading on roof tiles in regions of damage initiation (i.e. on hip, ridge, and eave/perimeter tiles). Tests on a low-rise small building model fitted with full-scale roof tiles were performed in the Wall of Wind (WOW) open jet facility at Florida International University (FIU). Full-scale testing is needed to: (i) better replicate the details of roofing systems, (ii) perform tests under high wind speeds to observe potential failure; (iii) and avoid effects of Reynolds number violation that occur in scaled model testing. Such effects include the weakening of local vorticity at edges and corners, resulting in typically weaker local pressures than those at full scale (Simiu 2011), and the distortion of mechanisms

of pressure equalization due to wind flow through the very small openings between the roofing tiles. Moreover, full-scale testing captures the response of roofing systems to realistic wind loading, which is not the case for conventional product evaluation testing that uses uniform static pressures. Habte et al. (2015) showed that full-scale testing can capture wind-induced vibration effects that can lead to different types of failure modes than those typically observed in static pressure testing. Limitations and disadvantages of full-scale testing are: (1) higher costs, (2) blockage constraints that can limit test models sizes, and (3) the difficulty of applying flow measurement devices such as Particle Image Velocimetry (PIV) due the open-jet nature and large test section size of the facility.

Details and backgrounds of the specific objectives of this experimental investigation are provided in the following subsections. Although vibration effects on roof tiles are not within the scope of this study, it is noted that the vibration of roof tiles for prolonged periods of time can make them loose and undermine their anchorage strength, particularly in the case of mechanically attached roof tiles (Baheru et al. 2014b).

1.1 Evaluation of wind loading on hip, ridge and perimeter tiles

Although many experimental results on wind pressure coefficients and the failure mechanisms of roof tiles are available in literature, most of them are focused on field tiles (Geurts (2000); Hazelwood (1981); Huang et al. (2009); Kramer and Gerhardt (1983); Okada et al. (2009); Robertson et al. (2007)). The availability of test-based data on roof tiles including eave, ridge, and hip roof regions is very limited. Hip, ridge and perimeter tiles are more prone to wind damage because they experience high wind loads as they lie in wind flow separation and conical vortex regions that create highly negative, localized external pressures (i.e., uplift pressures or suctions). Field tiles may also be affected by conical vortices; however, in general the strength of those vortices, and thus the magnitude of negative pressure induced by them, decreases away from the roof corners and edges. Kawair and Nishimura (2003) carried out field measurements to assess the uplift forces on hip roof tiles in natural wind and observed that net uplift pressures depended on whether the under-tile cavity spaces were ventilated. Moreover, perimeter tiles often overlap the edge of the roof substructure and are thus not protected against positive pressurization of

81 their under-tile cavity spaces (Hazelwood 1980), which could result in increased net pressures on those
82 tiles. Full scale tests have been performed to study the effect of roof pitch and tile profiles on the
83 distribution of pressure coefficients on external and underneath surfaces of ridge and field tiles on a gable
84 roof; their results showed that considerably higher pressures occurred on the gable-end ridge and corner
85 tiles, and that the use of high profile field tiles increases the net pressures on ridge tiles (Tecle et al.
86 2013). Using a multi-scale experimental study, Li et al (2014) compared wind uplift on bare roof decks to
87 roofs with high-profile tiles, and observed significant differences. Li et al (2014) also conducted a
88 vulnerability study which showed that using net wind uplift loading on tiles, rather than external surface
89 pressures only (i.e. assuming tile underneath cavity pressure to be zero), may significantly affect the
90 estimated probability of roof tile damage. Detailed information on typical loading patterns experienced by
91 gable and hip roofs can be found in much previous research (e.g., Meecham et al. 1991, Holmes 1994 and
92 Ahmad et al 2002).

93 Wind loading on roofs with permeable roof cover elements (such as tiles and shingles) depends on
94 several factors, including external roof profile, roof covering elements' geometric details, and roof
95 porosity. Some codes and standards address the design of such systems by applying pressure equalization
96 factors (e.g., the Netherland code, NEN EN 1991-1-4/NA (1991) and Australian Standard for wind loads,
97 AS1170.2 (2011)), or by using data from experiments on roofs with permeable covers (for example
98 German wind code, DEUTSCHE NORM (2002)). However, in the American Society of Civil Engineer's
99 Minimum Design Load for Buildings and Other Structures (ASCE 7, 2010) there are no provisions on the
100 effects of pressure equalization on wind pressures experienced by air permeable roofing elements (see
101 Chapter 30, Section 30.1.5 of the ASCE 7-10). Hence, the primary objective of this paper was to provide
102 data on net wind-induced loading for hip, ridge, and eave/perimeter tiles. Such data can be used to
103 improve aerodynamic load provisions in building codes and standards, and to validate wind load models.

1.2 Evaluation of near-surface local flows for hip, ridge and perimeter tiles

Wind loading on permeable roof coverings is influenced by the characteristics of the wind flow near the roof surface (Peterka et al. 1997). Besides affecting wind loading, other important aspects of surface flow velocity are its influence on rain penetration or snow accumulation, and on ventilation and the dispersion of fumes from heating systems (Barnard and Driviere 1994).

The net wind pressure acting on a roof tile element is the algebraic sum of the external pressure on the tile's top surface and the internal pressure in the underneath cavity of the tile. If a tile element is situated in an entirely separated flow region, the external pressure depends mainly on the building flow field, but if the tile element is located in an attached flow region, the external pressure is also influenced by the tile elements' local flow field. For brevity, the wind flow approaching the building (undisturbed by the building) and the wind flow near the tile surface are henceforth referred to as "approach flow" and "surface flow" respectively. The under-tile internal pressure is determined by the external pressure, the space between the roof deck and tile, and roof permeability (Kramer and Gerhardt 1983, Robertson et al. 2007).

In the absence of comprehensive net wind loading data on roof tiles, loading models which make use of surface flow wind speeds to estimate net wind loading on porous roofing elements have been in use. Hence, another objective of the current experimental investigation was to measure local surface flow wind speeds at selected hip, ridge and perimeter tiles in an effort to (i) investigate the characteristics of near tile surface flows in relation to the approaching wind flow, and (ii) analyze roof surface flow-based alternatives for estimating net design pressures on hip, ridge and roof perimeter tiles. This will assist in developing new wind loading models or calibrating existing models which use surface flow wind speed to estimate net wind loading data on roof tiles.

2 Experimental Setup and Testing Protocol

A two-phase full-scale experimental investigation was conducted using the 12-fan Wall of Wind (WOW) facility at FIU. In the first phase, aerodynamic wind pressure measurement tests were performed on

selected hip, ridge, and eave/perimeter tiles for different wind directions. In the second phase, local roof surface wind speed measurement tests were conducted. Pressure and wind speed measurement tests were conducted separately in order to avoid any effects the wind speed measurement equipment might impose on the wind pressure experienced by the roof tiles.

2.1 Roof models for testing

The roof models had the shape of a half-cut hip roof (with a pitch of 4:12 or 18.4 degrees) to represent edges and corners of both hip and gable roofs (Figure 1). The plan dimensions of the roof models were 4 m x 3 m with 0.30 m overhang on the gable-end side and 0.60 m overhang on the remaining three sides. The model represented a portion of a low-rise residential roof, and was placed on a wood frame base with height of 2 m. The experiments were conducted on only one model; however, it should be noted that for the same terrain conditions, insignificant deviation in uplift pressure at the upwind roof corner and edge regions is expected as the roof plan dimensions change (this was shown by several researchers including Lin et al. (1995) and Kopp et al. (2005)). Nevertheless, effects of roof height on pressures might exist and this warrants further investigation.

The roof deck was made of 19 mm thick plywood sheathing with a hot mop base sheet installed over its surface. High profile concrete tiles were installed on the base sheet with standard accessory tile pieces used for the hip and ridge conditions. A mechanical method of tile attachment was used. The installation of tiles was performed according to the Florida Building Code (FBC 2010) requirements (Fig. 1c and 1d). The eave tiles were attached to the substrate with hurricane clips as specified in RAS118/119 (FBC 2010). A metal panel enclosure was used to fill out the openings between the first course eave tiles and the roof deck.

Figure 1. Tiled-roof light-frame test building model representing portions of: (a) Gable roof, (b) Hip Roof, (c) cross-section detail of field tile installation, and (d) cross-section detail of ridge tiles installation RAS118/119 (FBC 2010)

The experiments were performed in the 12-fan Wall of Wind (WOW) facility at FIU. The WOW facility can generate up to a 67 m/s (Category 5 hurricane wind speed on the Saffir Simpson scale). The test section is 6 m wide and 4.25 m high which allows aerodynamic testing of full-scale models of portions of small low-rise buildings. Figure 2a and 2b show the profiles of the mean wind speed and turbulence intensity, respectively. Figure 2c shows the wind speed spectra by comparing the Kaimal spectrum, the atmospheric boundary layer (ABL) full turbulence spectrum as simulated in a boundary layer wind tunnel by Fu (2013), and the WOW partial turbulence spectrum at the mean roof height for suburban terrain. These WOW profiles and spectrum were generated using a set of triangular-shape spires and floor roughness elements.

Figure 2. Simulation of atmospheric boundary layer in the Wall of Wind (a) Wind speed profile (b) Turbulence intensity profile, and (c) Wind Spectrum at mid-roof height (Asghari Mooneghi et al. 2014)

The tests were performed with a partial turbulence simulation in which the turbulence intensity was lower than that for the atmospheric boundary layer (ABL) flow containing the full spectrum of turbulence. This is mainly due to the fact that low frequency turbulence cannot be simulated fully when using full or large scale models due to the limited size of the wind testing facilities, and only the high frequency end of the turbulence spectrum is simulated (Fig 2c). Simulation of the high frequency fluctuations has been noted by a number of researchers as necessary for correct simulation of local flow aerodynamics (Kopp and Banks (2012); Banks (2011); Irwin (2009); Richards et al. (2007); Tieleman (2003); Suresh Kumar and Stathopoulos (1998)). In this paper, the partial turbulence simulation method proposed by Asghari Mooneghi (2014) and Asghari Mooneghi et al. (2016) was used for data analysis. The method accounts for the missing low frequency turbulence for tests performed in a flow with partial turbulence simulation. Details of the partial turbulence simulation methodology and its validation using Silsoe and Texas Tech field measurements are available in Asghari Mooneghi et al. (2016).

2.2 Aerodynamic pressure tests on hip, ridge, and eave/perimeter tiles

Pressure measurement tests were conducted on a total of 12 tiles (3 hip, 3 ridge, 2 gable end and 4 eave/perimeter tiles). The numbering of the tiles instrumented with pressure sensors, and the wind directions tested are shown in Figure 3. Tiles “H”, “R”, and “E” were barrel/ridge tiles, while the “T” tiles were Capistrano type high-profile tiles. Depending on their locations on the roof, the instrumented tiles were divided into hip roof and gable roof tiles. Tiles H1, H2, H3, T1, T2, T3, T4, R2 and R3 were used to

represent wind loading on hip roof tiles (the hip roof side is outlined by the “dash-dash” line in Figure 3), while tiles R1, R2, E1 and E2 represented wind loading on gable roof tiles (the gable roof side is outlined by the “dash-dot” line in Figure 3). Each tile was instrumented with 20 pressure taps to measure the pressure at the external surface, and 2 pressure taps to measure the underside pressure in the space between the tiles and the roof deck (Figure 4). The use of a limited number of pressure taps in the under-tile cavity space was justified since no significant spatial pressure gradients were observed in the underside of tiles in experiments performed by Li et al (2014). The locations of the instrumented tiles were carefully selected in such a way that they captured the expected maximum loads on the hip, ridge, and eave tiles, and that they be representative of tiles in the flow separation and vortex generation regions. The aerodynamic pressure measurement tests were performed at a mid-roof-height mean wind speed of 28.1 m/s (‘approach flow’ wind speed).

A 512 channel Scanivalve Corporation pressure scanning system was used for pressure measurements. Pressure data were acquired at a sampling frequency of 512 Hz for a period of two minutes (the adequacy of the testing duration in representing an hour of wind in the field is discussed in Appendix). A transfer function was used to correct for tubing effects (Irwin et al. 1979), and the pressure data were passed through a low-pass filter of 150 Hz frequency. A Cobra Probe was installed at the building mean-roof height and upstream of the building model to record the wind speed of the approach flow.

Figure 3. Tile numbering and test wind directions.

Figure 4. Pressure taps layout (a) Hip/ridge tile with installed pressure taps (b) Numbering of pressure taps

2.3 Measurement of wind flow near hip, ridge, and eave/perimeter tiles' surfaces

Wind velocity near a solid surface tends towards zero, and the value at any given distance above the surface depends on the local boundary layer profile. Peterka et al. (1997) and Cochran et al. (1999) used a location 25 mm above a roof surface to measure local wind velocities on roof shingles. For this study, it was decided to measure the surface flow velocity at the same 25 mm above the tile surfaces. The tile centers (defined as intersection of (i) the mid-line of the tile length, and (ii) the mid-line of the tile width)

were selected as representative points for the velocity measurements. Besides the turbulence of the approaching flow, additional turbulence (termed as ‘signature’ turbulence) is generated near the tile surface flow due to the building shape and tile profiles. Hence, it is difficult to correctly predict the direction of wind flow near a tile’s surface. To overcome this issue, multi-hole cobra probes were used for wind speed measurements which were capable of measuring static pressure and wind speeds coming from all the x-, y- and z-directions (within a 45 degree cone) for estimating the resultant wind vector. For every wind direction tested, the probes’ holes were aligned to face the direction of the approach flow. However, in some cases the actual direction of wind flow near a tile’s surface was outside the range covered by the probe and those cases were eliminated from the analyses.

Figure 5a shows the cobra probes installed above the surface of the tiles, and the selected locations are indicated in Figure 5b. For each of the wind directions shown in Figure 5b, the velocities of the approach flow and the near tile surface flow were measured simultaneously. The wind velocity measurement tests were conducted for a period of 2 minutes at a 100 Hz sampling rate.

Figure 5. (a) Cobra probes installed 25 mm above the roof tiles, (b) Locations of cobra probes

3 Results and Discussions

3.1 Pressure measurement results

In this section the results from the pressure measurement experiments are presented. The mean pressure coefficients at any location were obtained as:

$$C_{p\ mean} = \frac{P_{mean}}{\frac{1}{2}\rho V_{mean}^2} \quad (1)$$

where P_{mean} is the mean pressure, ρ is air density and V_{mean} is the mean wind speed measured at the building mean-roof height. All pressures were measured relative to a reference static pressure outside the WOW's open jet flow field. The peak pressure coefficients were obtained as:

$$C_{p\ peak} = \frac{P_{peak}}{\frac{1}{2}\rho V_{3sec}^2} \quad (2)$$

where P_{peak} is the peak pressure, and V_{3sec} is the peak 3-s gust at the reference height. The 3 sec gust was used in estimating peak pressure coefficients in order to provide direct comparison with the values specified in the ASCE 7-10. As was mentioned earlier, for full scale testing the ability to simulate the low frequency end of the turbulence spectrum (and a large enough turbulence integral scale) in wind tunnel is usually compromised by the limited size of the facility. In order to calculate the peak pressure, P_{peak} the “Partial Turbulence Simulation (PTS)” method was used (Asghari Mooneghi 2014, Asghari Mooneghi et al. 2016). In this method, the turbulence is divided into two distinct statistical processes, one at high frequencies which can be simulated correctly in the wind tunnel, and one at low frequencies which can be treated in a quasi-steady manner. The joint probability of load from these two processes is derived, with one part coming from the WOW data and the remainder from the assumed Gaussian behavior of the missing low frequency component. For the evaluation of these estimated values, the peak value with 79% probability of not being exceeded in one hour of wind with full turbulence spectrum was used. A summary of the PTS method and the parameters used is provided in the Appendix.

The instantaneous external pressure coefficient C_{pext} for each tile was calculated by area averaging of the 20 instantaneous pressures obtained at the external pressure taps evenly distributed across the tile surface (see Figure 4). The instantaneous internal pressure coefficient C_{pi} for each tile was similarly obtained using the two internal pressure taps for each tile. The net time-series pressure coefficient for each tile was computed from instantaneous area-averaged external and cavity pressures as:

$$C_{pnet}(t) = C_{pext}(t) - C_{pi}(t) \quad (3)$$

Pressures are normal to the surface of a tile, so net uplift force for an individual tap can be estimated as net pressure for that tap multiplied by the projected horizontal ‘tributary area’ for the tap. Total net uplift force time history for a tile can then be obtained by summing up the instantaneous net uplift forces for all taps on the tile. The total peak net uplift force can be used for the design of the tile and its fixings. If required, the area-averaged peak net uplift force coefficient can be also obtained by dividing the total peak net uplift force on a tile by the projected horizontal area of the entire tile and the 3-s gust dynamic pressure ($\frac{1}{2} \rho V_{3sec}^2$). This procedure accounts for the different orientations of the pressure taps on a tile while estimating total peak net uplift force or area-averaged peak net uplift force coefficient.

The pressure equalization factor, r is defined as the ratio of the net peak pressure coefficient to the external peak pressure coefficient (Geurts 2000), and is expressed as:

$$r = \frac{C_{pnet,peak}}{C_{pext,peak}} \quad (4)$$

The pressure equalization factor was first introduced in the Netherlands building code NEN 6702 (1993).

In most cases pressure equalization helps to reduce the net pressure on air permeable roofing elements (i.e., $r < 1$), such as roof tiles, as the cavity pressure acts in a direction opposite to the external surface pressure. However, in some cases it was found that net pressure escalation occurs instead of pressure equalization ($r > 1$). For this reason in the current paper r is termed as *pressure adjustment factor* as opposed to pressure equalization factor.

For design of a tile and its connections to the roof deck, it is important to consider the highest net uplift pressure coefficients for all wind directions, based on the highest external uplift pressure coefficients for all directions. Pressure adjustment factors, the values of which are presented in this paper, can be used in conjunction with the external peak pressure coefficients for tiles to obtain the net peak pressure coefficients. In the absence of test-based external pressure coefficients for ridge, hip and perimeter roof tiles, pressure adjustment factors can be used in conjunction with external peak pressure

coefficients based on code provisions for Component and Claddings (C&C) to obtain the net peak pressures needed for the design of tiles and local mechanical attachments using nails or foam adhesives. This approach improves upon the assumption that peak pressure coefficients on tiled roofs are the same as those specified in codes or standards on the basis of wind tunnel tests on scaled building models that do not simulate the geometric details of roof tiles on the roof deck. For example, in the absence of test based aerodynamic data on tiled or shingled roofs, the Florida Public Hurricane Loss Model (Florida Office of Insurance Regulation 2005, p. 55, 2005) uses roof external pressure coefficients specified in code provisions and assumes 'zero' cavity internal pressure when estimating wind loading on roof coverings. Pressure adjustment factors, as presented in the following sections, can account for the effects of cavity internal pressure on net uplift on tiles. As the current study will show, the near surface flow wind speed based models, when used with appropriate parameters, can also produce results comparable to those obtained using pressure adjustment factors in conjunction with ASCE's external pressure coefficients.

3.1.1 Pressure measurement results on hip roof

In this section the results from the pressure measurement experiments for the hip roof model are presented for hip, ridge and perimeter roof tiles. It is recalled that negative net pressure and negative external pressure correspond to uplift pressure (i.e., suction).

3.1.1.1 Hip tiles (H1, H2, and H3)

Figure 6 shows the mean and peak external and net pressure coefficients on hip tiles for different wind directions. It can be seen that positive mean pressures were observed on the hip tiles when the wind directions were almost parallel to their hip-line. The highest suctions for H1, H2 and H3 roof tiles occurred at 210-degree wind direction. The maximum mean and peak negative external pressure coefficients recorded were -0.9 and -2.3 respectively on tile H1 at wind direction 210 degrees. The results show that the most critical external suction pressure on hip roofs occurs when the wind direction is normal to their hip-line. The cavity pressure had a worsening effect on the uplift load as the net pressure was larger than the external pressure alone (i.e. pressure adjustment factor, r was greater than one) when

the wind direction was nearly parallel to the hip-line (closest wind direction tested was 120 degree). The front end of H1 was covered with mortar while the joints of H2 and H3 were open, hence positive internal cavity pressures of higher magnitude were observed on H2 and H3. For tiles H2 and H3 (not having mortar to close the overlapping joints) the peak net pressure coefficient was about -0.6 as compared to the peak external pressure coefficient of -0.3 for 120 degree wind direction. On the other hand the cavity pressure alleviated the net uplift when the wind direction was normal to the hip-line. For example, for 210 degree wind direction tile H1's peak net pressure coefficient was about -2.0 as compared to the peak external pressure coefficient of -2.3. This is due to the pressure equalization effect (pressure adjustment factor r being 0.87) between the exterior and underneath surfaces of roof tiles. The maximum peak net uplift (in magnitude) for H2 and H3 (corresponding to 210 degree) were also alleviated due to the pressure equalization effects.

Figure 6. External and net $C_{p,mean}$ and $C_{p,peak}$ on the hip tiles on the hip roof

3.1.1.2 Ridge tiles (R2 and R3)

Figure 7 shows the mean and peak external and net pressure coefficients on the ridge tiles for different wind directions. Tile R2 experienced higher suctions than R3 for all the wind directions tested. In contrast to the hip tiles, the highest suctions were observed on ridge tiles when the wind directions were parallel to

either of the hip lines i.e. around 135 degree and 225 degree. Pressure equalization effects produced lower net $C_{p_{mean}}$ and $C_{p_{peak}}$ values than the external pressure coefficients and the effects of pressure equalization were more significant at R3 (pressure adjustment factor $r \approx 0.84$ for 90 and 270 degrees for R3; $r \approx 0.96$ for 135 and 225 degrees for R2).

Figure 7. External and net $C_{p_{mean}}$ and $C_{p_{peak}}$ on the ridge tiles on the hip roof

3.1.1.3 Eave/Perimeter tiles (T1, T2, T3, and T4)

Figure 8 shows the mean and peak external and net pressure coefficients on the tiles located on the perimeter/eaves of the hip roof for different wind directions. Eave tiles T1 and T2 were subjected to negative mean external pressure for all wind directions while positive pressure coefficients were measured on eave tile T4 for wind directions 120 degrees to 240 degrees and on eave tile T3 for wind directions of 120 degree to 180 degree. The worst mean and peak negative external pressure coefficient recorded were $C_{p_{mean}} = -0.58$ and $C_{p_{peak}} = -1.47$ for tile T1 at wind direction 210 degrees. The under-tile cavity pressures were observed to amplify net uplift on the upwind perimeter tiles (i.e. at around 90 degrees for tiles T1 and T2, and at around 180 degrees for tile T4). For instance, eave tile T4 had an increase of around 40% in the peak net uplift co-efficient when the wind direction was normal to the eave (180 degree). But, pressure equalization reduced the effect of the worst external $C_{p_{mean}}$ and $C_{p_{peak}}$ values

recorded on the eave tiles. For tile T1, the net pressure coefficients were $C_{p_{mean}} = -0.38$ and $C_{p_{peak}} = -1.11$, corresponding to 34% and 24% reductions, respectively, with respect to the external pressure coefficients.

Figure 8. External and net $C_{p_{mean}}$ and $C_{p_{peak}}$ on the perimeter tiles on the hip roof

3.1.1.4 Pressure equalization effect

Figure 9a shows the pressure adjustment factor r plotted for three selected tiles, H1, R2 and T1 for which the highest external pressure coefficients were observed in each tile group. The results show that the pressure adjustment factor highly depends on the roof zone and also the wind direction with respect to the tile joint; similar conclusions were reached by Geurts (2000). Note that the high values of pressure adjustment factors r , shown in Figure 9a, were observed during low uplift pressures. For instance, r value of up to 2.0 was observed on tile H1 at wind direction of 135 deg, but the peak external and net pressures were only -0.14 and -0.28, respectively; thus these high r values are not of interest from a design perspective.

As stated earlier, for design purposes, it is important to consider the highest net uplift pressure coefficients for all directions based on the highest external uplift pressure coefficients for all directions (e.g., values given in the codes for Component and Claddings, C&C). Figure 9b shows the ratios $\max(C_{p_{net}})/\max(C_{p_{ext}})$ (i.e., the highest (largest in magnitude, representing the worst suction) net uplift coefficients to the highest external uplift coefficients) for each tile on the hip roof. It can be seen in Figure

9b that for most roof locations, pressure equalization occurs (i.e., $r < 1$) between the external and underneath pressures, leading to reductions in the highest wind load. Though for tile T3 the r value is higher than 1, the magnitude of the highest pressure was small and not important for design purposes. The highest peak external and net uplift pressure coefficients observed on all hip-roof tiles, for all wind direction considered, were -2.28 and -2.0, respectively, and the pressure adjustment factor was 0.87. However, pressure adjustment factors, if used along with external peak pressure coefficients based on code provisions to obtain the net peak pressure coefficients, should consider the location of the tiles on the roof.

Figure 9 a. Pressure adjustment factor r , b. Pressure adjustment factor r on the hip roof tiles for wind direction producing highest external $C_{p_{peak}}$

3.1.2 Pressure measurement results on gable roof

In this section the results from the pressure measurement experiments for the gable roof side are presented.

3.1.2.1 Ridge tiles (R1 and R2)

Figure 10 shows the mean and peak external and net pressure coefficients on ridge tiles for various wind directions. Note that the peak uplift pressure coefficients for the ridge tile R2 for the gable roof case were much higher in magnitude compared to those for tile R2 tested as part of the hip roof (see Sec. 3.1.1.). At wind direction zero degree, wind flow separation starts directly at tile R1, which causes high suction on its surface. For tile R1 the mean external suction pressure was higher than for ridge tile R2 for

all wind directions, with the largest values occurring at wind directions of 60 degrees and 300 degrees. The results also demonstrate that for all wind directions, the internal pressure helped in alleviating the external suction pressure. This was because the opening of R1 was filled with mortar and the joint between R1 and R2 was not facing the oncoming wind (see Figures 1 and 3), which precluded the development of positive tile cavity pressure to escalate the net pressure. Similar findings were reported in the past based on pressure measurements on field tiles (Kawair and Nishimura 2003; Li et al 2014).

Figure 10. External and net $C_{p_{mean}}$ and $C_{p_{peak}}$ on the ridge tiles on the gable roof

3.1.2.2 Edge tiles (E1 and E2)

Figure 11 shows the mean and peak external and net pressure coefficients on the edge tiles as functions of wind directions. The edge tiles were curved tiles at the gable end of the roof (see Figure 12). High external pressure variations were observed, i.e., at some wind directions the top external side of the tiles experienced positive pressures while the front external side experienced suction. This had a reduction effect on the external uplift pressure over the entire tile surface. Figure 12 demonstrates this using instantaneous external pressure distribution on tile E2 for wind direction 45 degrees (Note that instantaneous pressure distributions vary widely throughout the duration of pressure recording, and the distribution shown in Figure 12 was selected as a typical representation of the observed instantaneous

pressure distributions). For instance, on tile E2, at wind direction of 45 degrees, a mean suction coefficient of -0.7 was recorded at one of the external pressure taps, but the averaged external mean uplift on the tile was almost zero. As a result, the net uplift was mostly dependent on the internal cavity pressure which was positive as the tile joint was exposed to the oncoming wind for wind direction of 45 degrees. This resulted in a very high pressure adjustment factor for tile E2 (see Figure 13a.). Tile E2 experienced significantly higher uplift pressure than tile E1 and the highest net suction occurred between 300 and 360 degrees wind direction, which are the directions critical for design.

Figure 11. External and net $C_{p,mean}$ and $C_{p,peak}$ on the edge tiles on the gable roof

Figure 12. Contour plot of typical instantaneous external C_p distribution on tile E2, wind direction 45 deg

3.1.2.3 Pressure equalization effect

Figure 13a shows the pressure adjustment factor r plotted for two selected tiles, R1 and E2, for which the highest external pressure coefficients were observed in each tile group. As in Figure 9, the results showed that the pressure adjustment factor depends on the roof zone and the wind direction with respect to the tile joint. The dependence of r on wind direction was more significant on the gable end tiles. As for the hip-roof, the high values of pressure adjustment factors r shown in Figure 13 were observed during low uplift pressures, thus having little significance for design. Figure 13b shows, for all directions, the ratios of highest peak net uplift coefficients to the external uplift coefficients for each tile in the gable roof. It can be seen that for the most unfavorable wind directions pressure equalization leads to reductions

in the uplift load. The highest peak external and net uplift pressure coefficients observed on all gable-roof tiles, for all wind direction considered, were -2.61 and -2.37 respectively, and the pressure adjustment factor was 0.91.

Figure 13. a. Pressure adjustment factor r . b. Pressure adjustment factor r on the gable roof tiles for wind direction producing highest external $C_{p_{peak}}$

Table 1 shows the summary of the results for pressure adjustment factors, r , observed in both the hip and gable roof models. The roof model is divided into roof zones in accordance with the specifications of the ASCE 7-10 (Components and Cladding, Figure 30.4-2B, pp. 337). Note that each value of r reported in Table 1 for a roof zone, represents, the ratio of the highest $C_{p_{net}}$ to highest $C_{p_{ext}}$ for all wind directions and roof tiles in that roof zone. It can be seen than pressure adjustment factors of slightly higher magnitude were experienced in the gable roof tiles when compared to the hip roof tiles.

Table 1. Summary of pressure adjustment factors, r

Roof Zone	Roof Type	
	Hip Roof	Gable Roof
Zone 2	0.88	0.92
Zone 3	0.87	0.91

3.2 Tile surface wind flow measurement results

This section provides results of near tile surface wind speed measurements. Two alternatives for determining design wind loads on hip, ridge and perimeter tiles besides direct net uplift pressure measurements (as discussed in Section 3.1) are also studied.

The instantaneous resultant surface flow wind speed, V_s and resultant approach flow wind speeds, $V_{a,h}$ are calculated using Equation (5).

$$V = \sqrt{U_x^2 + U_y^2 + U_z^2} \quad (5)$$

where V is resultant surface or approach flow wind speed, and U_x , U_y and U_z are instantaneous wind velocities recorded in the cobra probes' local x-, y- and z-directions. Note that the reference approach flow wind speeds, $V_{a,h}$ were measured at mean-roof height h , and upwind of the test model in a wind flow region undisturbed by the presence of the test model.

Figure 14 shows ratios of mean roof surface flow wind speed to mean approach flow speed, $\bar{V}_s/\bar{V}_{a,h}$ (denoted hence-forth as *roof speed factor* for brevity) versus wind directions for all the cobra probes used (see Figure 5 for definitions of probe locations and wind direction). A general increase in surface flow wind speed was observed with increasing uplift pressure. The highest mean surface flow was recorded by CP-2 (which is installed on R1), and was around 55% higher than the approach flow. In a small-scale wind tunnel study conducted by Cochran et al. (1999) on roof shingles, mean surface flows of up to 60% higher than the mean approach flow (measured at model eave height) were recorded. Probe CP-1, which

was installed at the corner gable-end experienced mean roof speed factors of less than one for most wind directions. In contrast, at the probes installed at the roof ridge, i.e. CP-2 and CP-3, wind speeds higher than the approach flow were recorded for all the wind directions tested. The surface flow speed at CP-2 was higher than at CP-3 when wind approached from the gable end, but the reverse was true when the wind approached from the hip-roof end. For the probes installed at the hip tiles, i.e. CP-4 and CP-5, the mean roof speed factor was less than one only when the wind direction was nearly parallel to the hip-line. When the wind flows up the hip-line its speed was observed to decrease which might be due to roof surface roughness and drag caused by the steps of the tile overlaps. Fluctuations of surface flows were observed to increase as the measurement location moved further away from the upwind side.

Figure 14. Ratio of mean surface flow to the approach flow at different wind directions

In the following sections, discussions of different tile loading models which use surface flow speeds to evaluate design pressures are provided, and their applicability to ridge, hip and perimeter tiles is also assessed.

3.2.1 Roof Tile Loading Model – Florida Building Code

In the Florida Building Code (FBC 2010, Equation 16.33) and International Building Code (IBC 2012, Equation 16-34) the design wind load on rigid roof tiles is defined in terms of aerodynamic uplift moment acting to raise the tile's leading edge, M_a , as shown in Equation (6)

$$M_a = q_h C_L b L L_a (1 - GC_p) \quad (6)$$

where q_h represents 3-sec gust dynamic pressure at a reference height h (i.e. $q_h = 1/2 \rho V_{h,3sec}^2$, where ρ is air density and $V_{h,3sec}$ represents the 3-sec gust wind speed at height h), C_L represents tile lift coefficient (C_L taken as 0.2 for concrete and clay tiles, or it is evaluated according to TAS108 (FBC 2010)), b and L are the tile width and tile length respectively, L_a denotes the moment arm from the axis of rotation to the point of uplift on the roof tile, and GC_p represents roof external pressure coefficient for each applicable roof zone as determined from Chapter 30 of ASCE 7. In Equation (6), peak (design) uplift pressure is calculated as $C_L q_h (1 - GC_p)$, where C_L is the lift coefficient (or tile net area-averaged uplift pressure coefficient), and the term $q_h (1 - GC_p)$ is used to calculate the dynamic pressure of the surface flow (which can be heavily influenced by building induced turbulence). This representation of near tile surface flow dynamic pressure was first formulated by Hazelwood (1980) under the assumption that the total pressure in the approach flow is equal to the total pressure at the tile surface (i.e. using the Bernoulli's equation as shown in Equation (7a)), which leads to the equations for dynamic pressure of the surface flow (Eq. 7b, Eq. 7c).

$$P_a + \frac{1}{2} \rho V_{a,h}^2 = P_s + \frac{1}{2} \rho V_s^2 \quad (7a)$$

$$\frac{1}{2} \rho V_{a,h}^2 (1 - GC_p) = \frac{1}{2} \rho V_s^2 \quad (7b)$$

$$q_h (1 - GC_p) = q_s \quad (7c)$$

In Equation (7), P_a and P_s denote static pressure of the approach flow and surface flow respectively. The Bernoulli's equation is only valid in inviscid flows, and it was used in Hazelwood (1980) because at that time it was not possible to conduct an experimental program to measure velocities of surface flows. Hence, to evaluate the adequacy of using Bernoulli's equation on hip, ridge, and roof perimeter tiles, dynamic pressures computed from direct surface flow wind speed measurements, q_s , were compared to those estimated using the Bernoulli's equation (i.e. estimated as $q_h (1 - GC_p)$). Values of peak external pressure coefficients presented in Section 3.1 were used as GC_p . Figure 15 shows the result of those

comparisons for all the cobra-probes measurements. Bernoulli's equation produced conservative results, and the highest ratio of measured to predicted surface flow dynamic pressures was 0.89. Similar observations were also reported by Barnard and Driviere (1994) in a wind-tunnel investigations (using 1:100 scaled models) of wind velocities over pitched roofs.

Figure 15. Ratios of measured surface flows to those estimated using Bernoulli's equation

3.2.2 Roof Tile Loading Model Based on Method Applied for Shingle Loading (Peterka et al. 1997)

Roof tiles and roof shingles are categorized as porous roofing materials, and have similar wind loading mechanisms. Hence, an alternative method of estimating wind loads on hip, ridge, and roof perimeter tiles could be using the peak speed-up factor approach as used for roof shingles (Peterka et al. 1997). In the model developed by Peterka et al. (1997), the peak design pressure $D\hat{P}$ is computed as the product of mean dynamic pressure of the approach flow ($1/2\rho\bar{V}_{a,h}^2$), mean net-differential pressure coefficient (DC_p) which depends on shingle shape or thickness, and ratio of the squares of peak surface flow speed to mean approach flow speed ($\hat{V}_s^2 / \bar{V}_{a,h}^2$) as shown in equation (8). Note that this wind loading model uses the “quasi-steady” assumption, i.e. it assumes the loading mechanism for wind to be the same for short and long duration gusts and that it varies with the square of the wind speed only. Peterka et al. (1997) also evaluated an upper bound value of 2.5 for $\hat{V}_s / \bar{V}_{a,h}$ in one story buildings with shingled roofs, which was later confirmed to be conservative by Cochran et al. (1999).

$$D\hat{P} = \frac{1}{2} \rho \bar{V}_{a,h}^2 * \left(\frac{\hat{V}_s}{\bar{V}_{a,h}} \right)^2 * \overline{DC_p} \quad (8)$$

It should be noted that the upper bound value of 2.5 is deemed appropriate for single story shingle roofs, and an estimation of an upper bound value for tile roofs is necessary if equation (8) is to be employed. Hence, values of $\hat{V}_s / \bar{V}_{a,h}$ for the WOW model were evaluated and are shown in Figure 16 as functions of the ratios of mean surface flow to mean approach flow ($\bar{V}_s / \bar{V}_{a,h}$). Since the WOW testing was conducted in a partially simulated turbulence wind flow, the ratio of peak surface flow gust to mean approach flow velocity would be smaller compared to a wind flow with fully simulated turbulence. In order to account for the missing frequencies, $\hat{V}_s / \bar{V}_{a,h}$ was multiplied by factor of 1.88, which is a factor used to convert the denominator from a 0.18 sec gust to a mean 3600 sec wind speed. Note that the 0.18 sec gust is an estimate of the maximum duration gust simulated in the WOW, based on the extent of the turbulence spectrum shown in Figure 2 (see Appendix). It can be seen in Figure 16 that $\hat{V}_s / \bar{V}_{a,h}$ values can reach up to 3.20, which is higher than the upper bounding value of 2.5 used in roof shingles. The highest peak speed-up factor was recorded on CP-2, which was installed on R1. Note that this speed-up factor might depend on tile profile, and the value reported here is for high profile hip, ridge and perimeter tiles only.

Figure 16. $\hat{V}_s / \bar{V}_{a,h}$ for hip, ridge and perimeter tiles

3.2.3 Comparison of the Roof Tile Loading Models

The main difference between the estimation models shown in equation (6) and equation (8) is the way in which the near surface flow dynamic pressures are evaluated. For the building model considered in this study, when equation (6) is used, the dynamic pressure of the near surface flow is computed as $q_h(1 - GC_p)$ based on Hazelwood (1980). Using $GC_p = -2.61$ (i.e. the highest value of peak $C_{p\ ext}$ recorded, which was on tile R1, for the gable roof model at wind direction of 60 deg), the dynamic pressure of the near surface flow is equal to $3.61 * q_h = 3.61 * (\frac{1}{2} \rho \hat{V}_{a,h}^2)$, where $\hat{V}_{a,h}$ is the 3 sec gust speed of the approaching wind. If instead equation (8), with $\hat{V}_s / \bar{V}_{a,h}$ value of 3.20 is used, the dynamic pressure of the near surface flow will be equal to $10.24 * (\frac{1}{2} \rho \bar{V}_{a,h}^2)$, or $10.24 / 1.74^2 * (\frac{1}{2} \rho \hat{V}_{a,h}^2) = 3.39 * (\frac{1}{2} \rho \hat{V}_{a,h}^2)$ which is close to the value obtained using Hazelwood's approach. Note that 1.74 is a factor used to convert the wind speed from a mean hourly to a 3 sec gust.

The work by Hazelwood (1980) was related to the uplift forces on field tiles that were in a region with attached/reattached flow. However, most damages to roof tiles in windstorms had occurred to gable end ridge tiles, hip tiles, and perimeter tiles located in regions subjected to separated flows and corner vortices (Li et al. 2014). The current study focused of these types of tiles. The dynamic pressure of the near surface flow as estimated above using Hazelwood's approach (equations 7a to 7c) in conjunction with the

measured peak $C_{p\ ext}$ showed good agreement with that based on Peterka et al.'s quasi-steady assumptions (equation 8). Also, as noted earlier Bernoulli's equation produced conservative results when comparing with surface flow dynamic pressures using cobra-probes measurements. These suggest that the model using Bernoulli's principle (using equations 7a-c) may also be applied for tiles under flow patterns other than attached/reattached flows. However, this needs further investigation.

Comparison of design pressures estimated using the r factors provided in Table 1, to those calculated using the wind loading models described in sections 3.2.1 and 3.2.2 were also conducted. Recall that both coefficients C_L and $D\bar{C}_p$ represent differential pressures normalized by the wind speed near the surface of the roofing element, hence for the purpose of this comparison, C_L and $D\bar{C}_p$ were assumed to be identical. Both coefficients are determined in controlled testing chambers using uniform wind flows, and the FBC recommends C_L value of 0.2 for concrete and clay tiles. For the WOW model, lift coefficients, $C_{L,wow}$ were calculated for the tiles instrumented with a cobra probe, at different wind directions using equation (9),

$$C_{L,wow} = \frac{\bar{P}_{net}}{\frac{1}{2}\rho\bar{V}_s^2} \quad (9)$$

where $\bar{P}_{net}$ denotes mean net pressure, and $\bar{V}_s$ represents mean surface flow near the tile elements. The average of all the evaluated $C_{L,wow}$ was equal to 0.62, and has been used in the comparison process. Table 2 shows comparisons of design pressures (as functions of $^{1/2}\rho\bar{V}_{a,h}^2$) evaluated using (i) pressure coefficients from the ASCE 7-10 and pressure adjustment factors, r (i.e. from Table 1), (ii) FBC (2010) tile loading method, using $C_L = 0.2$, and $C_L = 0.62$, and (iii) roof shingle loading model (with speed up factor of 3.20), using $D\bar{C}_p = 0.2$ and $D\bar{C}_p = 0.62$. The results show that using a C_L or $D\bar{C}_p$ of 0.2 produces very low estimates of the design pressure, however when a C_L or $D\bar{C}_p$ value of 0.62 is used, the estimates of design pressure tend to closely match those computed using the r factor. Although the highest design pressure is of utmost importance, the FBC loading model provides more design flexibility when compared with the shingle loading model. When used with appropriate values of C_L or $D\bar{C}_p$, and speed up

factors (in the case of the roof shingle loading model), both models can produce good estimates of the net design pressure.

Table 2. Comparisons of Uplift Design Pressure Coefficients

Roof Type	Roof Zones (ASCE GC_p values)	Uplift Design Pressure Coefficients (normalized by $^{1/2}\rho\hat{V}_{a,h}^2$)				
		GC_p multiplied by r factors	C_L (1- GC_p (based on FBC loading model and ASCE based GC_p values))		$D\bar{C}_p$ (3.39 ²) (based on method applied for shingle loading, Peterka et. al., 1997, but using speed up factor of 3.20)	
			$C_L = 0.2$ (FBC)	$C_L = 0.62$ (WOW)	$D\bar{C}_p = 0.2$ (FBC)	$D\bar{C}_p = 0.62$ (WOW)
Gable Roof	Zone 2 ($GC_p = -1.7$)	-1.56	-0.54	-1.67	-0.68	-2.20
	Zone 3 ($GC_p = -2.6$)	-2.37	-0.72	-2.23	-0.68	-2.20
Hip Roof	Zone 2 ($GC_p = -1.7$)	-1.49	-0.54	-1.67	-0.68	-2.20
	Zone 3 ($GC_p = -2.6$)	-2.26	-0.72	-2.23	-0.68	-2.20

4 Observations and Conclusions

This paper presented results of full-scale experimental studies on roof tiles located in the critical regions on the roof i.e. hip, ridge and eave/perimeter. Experiments were performed in the 12-fan WOW facility at FIU. The experiments included pressure measurements on the external surface and underneath cavity of the tiles, and surface flow wind speed measurements near the tile surfaces. The following points summarize the major observations and conclusions drawn from this work:

- On the hip roof the highest uplift was recorded for the tile on the hip line nearest to the roof corner, ($Cp_{net} = -2.0$ and $Cp_{ext} = -2.28$). The results also showed that the most critical external suction pressure on hip tiles occurs when the wind direction is normal to their hip-line. In contrast to hip tiles, in the ridge tiles the highest suctions were observed when the wind directions were parallel to either

of the hip lines, i.e. around 150 degree and 210 degree. Relatively lower suction was recorded on the perimeter tiles.

- On the gable roof, the overall highest peak uplift pressure coefficients of about $C_{p_{net}} = -2.37$ and $C_{p_{ext}} = -2.61$ were measured on ridge tiles near the gable end. The highest suctions were experienced at wind directions around 60 degrees and 300 degrees. The gable end perimeter tiles experienced high pressure variations on their external surfaces.
- The effect of pressures in the tile cavity (the space between the roof deck and tile) on net uplift pressure was highly dependent on the tile location and wind direction with respect to the tile joint. In most tiles, pressure equalization occurs between the external and underneath pressures, leading to reductions in the wind load. In most cases, for the critical wind directions which produced the highest external suctions, tile cavity pressures had an alleviating effect, and the pressure adjustment factors mostly ranged between 0.87 and 0.92. However, this was not the case for eave tiles for wind direction normal to the eave, in which case positive cavity pressure increased the net pressure. Hence, the results demonstrate that proposing any pressure adjustment factor for codes and standards should consider the location of the tiles on the roof. Values of pressure adjustment factors for the edge and corner regions of sloped gable and hip roof are also provided.
- Comparisons of tile surface flow speeds to approach flow speed showed that tile-surface speed-ups of up to 55% higher than the approach flow can occur on ridge tiles. A general increase in mean roof speed factor was also observed with increasing net and external uplift pressures.
- Alternative models for determining wind loading on hip, ridge and perimeter tiles, which use near tile surface wind speed were also investigated. Comparisons of measured surface flow velocities to those estimated using Bernoulli's equation showed that Bernoulli's equation produces conservative estimates of surface wind flows. In contrast to roof shingles whose upper bound value for ratio of peak surface flow to mean approach flows is 2.5 (Peterka et al. 1997), values of up to 3.20 were observed in the case of hip, ridge and perimeter tiles.

- Comparison of uplift design pressure coefficients computed using (i) the pressure adjustment factors (Table 1) in conjunction with ASCE's external pressure coefficients, (ii) the FBC tile loading model, Equation (6) (FBC 2010, Equation 16.33), and (iii) the roof shingle loading model as applied to tiled roofs, Equation (8) (Peterka et al. 1997), was conducted. Using a lift coefficient, C_L of 0.2 (as recommended by the FBC) in conjunction with ASCE based GC_p values, and using $D\bar{C}_p = 0.2$ in conjunction with a speed up factor of 3.20, produced unconservative results using methods (ii) and (iii), respectively. However, when C_L or $D\bar{C}_p$ of 0.62 and speed up factor of 3.20 (both values computed from the WOW measurements) were used, the values obtained with methods (ii) and (iii) compared well with those obtained using method (i). This shows that the FBC tile loading model can produce unconservative wind loading on tiled roofs' most vulnerable regions (i.e. eave, ridge and perimeter tiles - which are the regions where failures were mostly noted in the past hurricanes such as Hurricane Wilma). It also shows that the ASCE's external pressure coefficients can be used in conjunction with r factors to produce realistic *net* loading for tiled roofs' most vulnerable regions (edges, ridges, corners).

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Appendix: Partial Turbulence Simulation (PTS) for Predicting Peak Pressure Coefficients

Summary of the Theory

In this paper a method called "Partial Turbulence Simulation (PTS)" is used to estimate peak pressure coefficients, and determine the equivalent full-spectrum gust duration of the mean WOW wind speed. In

this method, the turbulence is divided into two distinct statistical processes, one at high frequencies which is simulated in wind tunnel, and one at the missing low frequencies (but can be treated in a quasi-steady manner). It can be shown (Asghari et al, 2015) that in a partially simulated turbulence spectrum with turbulence intensity I_{uH} the intensity of the missing low frequency I_{uL} is:

$$I_{uL} = \sqrt{I_u^2 - I_{uH}^2} \quad (A1)$$

where I_u is the full-spectrum longitudinal turbulence intensity.

Although in reality there is not any sharp dividing line between the low and high frequency turbulences, it can be theoretically shown that Eq. (A2) can be used for approximately calculating an equivalent cut-off frequency, n_c , between the simulated high frequency and the missing low-frequency turbulence.

$$n_c = 0.0716 \frac{U}{xL_u} \left(\frac{I_u}{I_{uH}} \right)^3 \quad (A2)$$

where the xL_u and U are the full spectrum values of longitudinal integral scale and the mean velocity respectively. This means that in a partial turbulence simulation, turbulence fluctuations at frequencies above n_c can be simulated, while those below n_c need to be accounted for by other means.

Method for predicting peak pressure coefficients

In the PTS method for predicting peaks the sample period is divided into subintervals of sufficient duration so that they can be treated as independent events. The probability that the peak pressure coefficient will not exceed a given value in a subinterval can be measured and fitted by a Fisher Tippet Type I distribution. The probability distribution of wind turbulence in a generic boundary layer (i.e. one free from local aerodynamic effects of upwind structures) is approximated as Gaussian. To calculate the expected peak pressure coefficients ($\hat{C}_p$), the joint probability of load from the two processes (high frequency and low frequency) is derived, with one part coming from the WOW data and the remainder from the assumed Gaussian behaviour of the missing low frequency component. It can be shown that the probability that a given value of $\hat{C}_p$ will be exceeded in a particular subinterval in the full turbulence can be obtained from the following equation:

$$G\left(\frac{\hat{C}_p}{b}\right) = \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}\xi^2} \left[1 - \exp \left\{ -\exp \left\{ -ab \left(\frac{\hat{C}_p}{b} \frac{1}{(1 + I_{uL}\xi^2)} - 1 \right) \right\} \right\} \right] d\xi \quad (A3)$$

where $\xi \equiv \frac{u_L}{U}$ in which U is the mean flow velocity and u_L is the part of the fluctuating velocity contributed by the low frequency end of the spectrum. The parameters a and b can be measured from

time histories of pressures in partial simulations. Then, given the turbulence intensity of the low frequency fluctuations, I_{uL} the probability of exceeding a given value of $\hat{C}_p/b$ in a single subinterval can be computed by numerical integration using Eq. (A3).

If the full sample period is one hour in which we have N subintervals then the highest pressure coefficient will have probability $1/N$ of being exceeded. So, if our subintervals on the model are scaled up to be $t_{gust,p}$ seconds at full scale, then we need to determine the value of $\hat{C}_p/b$ that has $t_{gust,p}/3600$ probability of being exceeded in one hour. The cut-off frequency as calculated from Eq. (A2) can be used to estimate the equivalent gust-duration at full scale using: $t_{gust,p} = 0.45/n_c$.

Note that the probability G in the way calculated above gives the peak pressure coefficients with 37% probability of not being exceeded in the hour of wind. To convert it to other probability values like P_{tar} , the following equation can be used:

$$G = 1 - P_{tar}^{1/N} \quad (A4)$$

Scaling parameters

The speed scaling was set as the ratio of the mean speed in PTS to the full-scale gust due to missing low frequency turbulences which can be estimated using the peak factor of 3.4 used in ASCE 7 for background turbulence:

$$\hat{U}_{LP} = U_p (1 + 3.4 I_{uL}) \quad (A5)$$

Having the length scale as $\frac{b_p}{b_m}$ and speed scaling as $\frac{U_m}{\hat{U}_{LP}}$, the frequency scale comes from $\frac{n_m}{n_p} = \frac{U_m}{U_p} \frac{b_p}{b_m}$. So the time scale will be $\frac{t_m}{t_p} = \frac{n_p}{n_m}$. The subscripts m and p denote the model and prototype respectively.

It should be noted that the number of subintervals used in calculating the ?? and ?? parameters in the Fisher Tippet Type I distribution should be limited by the requirement that no correlation should exist between events in adjacent subintervals. To calculate the maximum number of subintervals first the gust-duration at model scale is calculated from $t_{gust,m} = t_{gust,p} \times \frac{t_m}{t_p}$. The maximum number of subintervals can then be calculated from $\frac{\text{Test duration in PTS}}{t_{gust,m}}$.

Calculation for the current problem

In the WOW experiments the high frequency fluctuations (I_{uH}), longitudinal integral length scale (xL_u), and mean wind speed (U_m) were 7.7%, 0.6 m, and 28.1 m/s respectively, and testing was conducted for a testing duration (t_d) of 120 sec. For a corresponding flow with full-spectrum turbulence, I_u and xL_u were estimated from ESDU as 31% and 25 m respectively. Hence:

$$\text{Intensity of the missing low-frequency fluctuations, } I_{uL} = \sqrt{I_u^2 - I_{uH}^2} = 30\%$$

684 Equivalent full-scale gust due to the missing fluctuations, $\hat{U}_{LP} = U_p(1 + 3.4I_{uL}) = 56.86 \text{ m/s}$

685 Velocity scaling, $\frac{U_m}{U_p} = \frac{28.1}{56.86} = 0.49$

686 Frequency scaling is: $\frac{n_m}{n_p} = \frac{U_m b_p}{U_p b_m} = 0.49$

687 Time scale is: $\frac{t_m}{t_p} = \frac{n_p}{n_m} = 2.02$

688 Cut-off frequency: $n_c = 0.0716 \frac{U}{L_u^x} \left(\frac{L_u}{L_{uH}} \right)^3 = 5.26 \text{ Hz}$

689 Equivalent gust-duration at full scale: $t_{gust,p} = \frac{0.45}{5.26} = 0.09 \text{ sec} \rightarrow t_{gust,m} = 0.18 \text{ sec}$

690 Maximum number of sub intervals without correlation between events in adjacent subintervals,

$$N_{si,max} = \frac{t_m}{t_p} \times \frac{t_d}{t_{gust,m}} = 692$$

691 Using number of subintervals, $N_{si} = 500$, targeted probability for 60 min full spectrum, G ;

$$G = \frac{t_d}{N_{si}} \times \frac{t_m}{t_p} \times \frac{1}{3600} = 0.000033$$

692 $G_{79\%} = 1 - 0.79^{0.000033} = 0.0000076$ (for 79% probability of not being exceeded in the hour of wind)

693 The required testing duration corresponding to a full scale duration of 3600 sec is,

$$t_{dr_{3600 \text{ sec}}} = 3600 \times \left(\frac{U}{\bar{x}_{Lu}} \right)_{field} \times \left(\frac{x_{Lu}}{U} \right)_{wow} = 86.51 \text{ sec} < 120 \text{ sec}$$

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