1-14-2011

Wind Pressure Evaluation for Field and Ridge Tiles

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DOI: 10.25148/etd.FI11040603

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FLORIDA INTERNATIONAL UNIVERSITY

Miami, Florida

WIND PRESSURE EVALUATION FOR FIELD AND RIDGE TILES

A thesis submitted in partial fulfillment of the

requirement for the degree of

MASTER OF SCIENCE

in

CIVIL ENGINEERING

by

Serge Alain Feuze Lekem

2011

To: Dean Amir Mirmiran
College of Engineering and Computing

This thesis, written by Serge Alain Feuze Lekem, and entitled Wind Pressure Evaluation for Field and Ridge Tiles, having been approved in respect to style and intellectual content, is referred to you for judgment.

We have read this thesis and recommend that it be approved.

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Florida International University, 2011

DEDICATION

I dedicate this thesis to my family and to the lady of my heart. Without your support, patience, understanding and most of all love, this work could not have been completed.

ACKNOWLEDGMENTS

I wish to thank my major professor, Dr Girma Tsegaye Bitsuamlak, who guided me with his expertise in order to complete this thesis work, for inspiring me to work towards the Wind Engineering perspective in Civil Engineering. I thank Dr. Arindam Gan Chowdhury and Dr. Nakin Suksawang for their assistance in the completion of my work.

This work would not have been possible without the financial support from Florida Department of Emergency Management (FDEM). The help received from the roofing industry representatives namely Bob Ferrante (Polyfoam Products Inc.), Mike Fulton (O'Hagin Vents), Tim Gabroski (Tim Gabroski Roofing Inc.), Manuel Oyola (Eagle roofing products Florida LLC), Riku Ylipelkonen (Polyfoam Products Inc.), Tom Castellanos (East Coast Metal) throughout the project execution both in terms of sharing their experience, installing the tiles on the roofs and donating raw-materials is greatly appreciated.

Thanks to Amanuel Tecle who was particularly helpful in guiding me toward the various steps of this project. Thanks to all the researchers of the Wall of Wind for their support. I am grateful to my friends; the team that supported me while working on this project particularly Francis, Asmerom, Amelia, and Carlos.

ABSTRACT OF THE THESIS

WIND PRESSURE EVALUATION FOR FIELD AND RIDGE TILES

by

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Florida International University, 2011

Miami, Florida

Professor Girma Bitsuamlak, Major Professor

Wind-induced external and internal pressures on tiles installed on a low-rise building model with gable roof were investigated by using a full-scale wind testing facility generically named Wall of Wind (WoW). Emphasis was given to ridge tile where a failure usually initiates during extreme wind events. Three different profiles field tiles namely high, medium, and low were investigated in combination with two types of ridge tiles namely rounded and three-sided. Effect of weather block on the pressure was examined. The study produced a unique high resolution pressure data in the form of pressure coefficients (C_{pmin} , C_{pmax} and C_{pmean}) for field and ridge tiles. These tests revealed high pressure coefficients for the ridge tile compared to the field tiles including those at the corners. Ridge tiles at the middle of the roof saw slightly lower wind pressure compared to those close to the gable end. Weather blocking of clay tiles while useful preventing water intrusion, increased the wind loads on the field tiles. The case without weather blocking produced significant pressure underneath the field tiles that resulted in lower net pressures.

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LIST OF ABBREVIATIONS

ASCE: American Society of Civil Engineers

AOA: Wind Angle of Attack

CFD: Computational Fluid Dynamics

C_p: Pressure Coefficient

C_{pmax}: Maximum Pressure Coefficient

C_{pmean}: Mean Pressure Coefficient

C_{pmin}: Minimum Pressure Coefficient

DAQ: Data Acquisition System

Deg: Degree

FEM: finite Element Method.

FRSA: Florida Roofing, Sheet Metal and Air Conditioning Contractor Association

HP: High Profile field tile

IHRC: International Hurricane Research Center

LP: Low Profile field tiles

MP: Medium Profile field tile

NHC: National Hurricane Center

NWB: No Weather Block System installed

RMS: Root Mean Square of a series of data

TRI: Tile Roofing Institute

TTU: Texas Tech University

WB: Weather block system installed

WoW: Six-Fan Wall of Wind

1. INTRODUCTION

Hurricanes have often caused extensive economic losses and human fatalities in communities along their paths (Hooke, 2007). On the other hand, over the last 50 years, America's hurricane coasts have experienced significant growth in population and supporting infrastructure, making them more vulnerable to greater losses from hurricanes. These losses have indeed increased from \$1.3B/yr pre-1990 to \$36B/yr post-2000 (Rappaport 2000). With 1,400 (Cutter et al. 2007) fatalities in 2004-05 and losses exceeding \$100B (Lott and Ross 2006) in 2005 alone, hurricanes may be viewed as one of the most challenging stressors on built environment. Among the different pattern of wind-induced damages to buildings, wind damage initiated at roof corners and edges appears to be the single most dominant cause for frequent loss occurrences as reported in FM (1985), IBHS (1999) [1] and [2], IBHS (2009), FEMA (2004) and (2007), Meloy et al. (2007). Reducing the far-reaching impacts of hurricanes on buildings through novel approaches aimed both at reducing the hurricane induced forces (aerodynamic mitigation) and strengthening the infrastructure resistance (structural mitigation) is therefore necessary.

Common building design practices for wind in general and residential homes in particular do not take aerodynamic design parameters into consideration. Their shapes are generally dictated by other architectural and structural requirements. As a result, buildings typically have bluff shapes, as opposed to streamlined-shape, which cause strong wind flow separation resulting in high suctions (negative pressures). Corners at roofs and walls for example are common places where high wind induced pressure

develops and failure usually initiates with a cascading effect to other members. Any breach on the building envelope, in addition to causing water penetration, alters the aerodynamics of the building by adversely affecting the internal pressure that increase wind forces on roofs, doors/windows and other building envelope systems. Moreover, failures caused by strong wind forces in one building will also become a source of wind-borne debris that may produce damages on other buildings in the vicinity.

Significant effort has been made to address these interrelated issues. For example widespread hurricane damage to hip and ridge tiles resulted in the development of an intensive set of guidelines for hip and ridge tile installation, which was adopted into the Florida Building Code and incorporated into the latest edition of the TRI/FRSA Concrete and Clay Roof Tile Installation Manual for Florida. The present code recommendations, such as those shown in Fig. 1, are prescriptive in nature and more research is needed to clearly relate the recommended installation details with magnitude of wind speed and/or wind pressure, roof slope, ridge type etc as wind pressure on ridges vary depending on the shape of the ridge and the roof etc. In recent Wall of Wind workshop conducted at Florida International University both the Miami Dade Building Compliance Office and the National Roofing Contractors Association also identified research on ridge and tile as a priority among roofing-related wind research. (Gascon 2009, Graham 2009).

Figure 1 Hip and Ridge tile nailing detail

Recently a group of researchers at FIU evaluated hip and ridge tile resistance through a detailed experimental and analytical study for clay and concrete tiles with adhesive-set, mortar-set as well as mechanical attachments using static tests on a single clay tile (Mirmiran 2006). Mirmiran et al. (2007) and Huang et al. (2009) further looked into monotonic and cyclic uplift tests for multiple clay tiles (three at a time) as well as dynamic wind simulation test using the 2-fan WoW on a mono slope small roof test specimen that has field clay tiles. The study also developed an analytical finite element model for the mono-slope roof case. Their results showed that the cladding pressure measurements for the tiles on the mono slope have exceeded those provided in ASCE7-2005 for certain wind directions. The external pressure on a tile was also found to be strongly influenced by the surface geometry of the tile (Huang et al., 2009). Their study was however limited to mono-slope roof due to limitation of the wind field size generated by the 2 fan WoW that was available for the study.

The present study looked further into the aerodynamics of the ridge and field tiles installed on gable roofs with three different slopes by using the new 6-fan WoW that can engulf a large scale test specimen in hurricane type of wind flow. Thus the main objective

of the present study is to produce a realistic high resolution wind pressure distribution data on hip and ridge tiles for hip/gable roofs based on full scale testing of various models at the RenaissanceRe 6-fan Wall of Wind facility of Florida International University. This is a necessary step in order to design new tile shape and attachment method that can sustain hurricane type winds thus alleviating the recurring problems at the ridges. The study will be based on the following question:

Hip and ridge tiles of gable and complex roofs are subjected to different magnitude of pressure distribution compared to field tiles: how different?

In order to answer to this question we will conduct the study under the following hypothesis:

Hip and ridge tiles have a pressure distribution different from the one that face field tiles even those close to the corner zones. In gable and complex roof tiles, hip and ridge tiles see higher pressures than field tiles. This study will quantify that difference.

2. LITERATURE REVIEW

The over-all shape of a building is one of the most important factors that affect the magnitude of wind loads (both for the design of MWRFS and C&C). The details at corners are also very critical in determining the MWRFS and C&C design wind loads. Wind performance criteria have been considered in the determination of the overall shape of buildings as well as local details in floor layout and elevation profile for some of the super tall buildings. For example, wind engineers were brought as part of the design team early in the design stage of Burj Khalifa (the tallest building in the world at the moment). Aerodynamically refined shape was developed that literally “confused the wind” (Irwin 2008). Another good example is Taipei 101, the former tallest building, which has received significant input from wind engineers. In the later, the corner modification of the tower as shown in Fig. 2 resulted in 25% reduction of the base moment (Irwin 2006). Chamfers of the order of 10% of the building width, makes 40% reduction in the along-wind response, and 30% reduction in the across-wind response when compared to the rectangular cross-sectional shape without corner cuts (Holmes, 2001).

Figure 2 Taipei 101 floor plans.

Figure 3 Roof ridge and wall failure during hurricane Ike (2008) – picture taken by FIU – IHRC research team.

Residential structures, the subject of the present study, also fall into the category of “bluff bodies” characterized by sharp corners at roofs and walls that causes strong wind flow separation resulting in high suctions (uplift). The severity of vortex-induced uplift observed on roofs for example is well documented by the following researchers (Stathopoulos 1987, Stathopoulos et al. 1990, Kramer and Gerhardt 1989, Gerhardt and Kramer 1992, Mehta and Levitan 1992, Cochran and Cermak 1992, Cochran et. al. 1993, Tieleman et al. 1994, Lin et. al. 1995, Kawai and Nishimura 1996, Lin and Surry 1998, Banks and Meroney 2001 and others). Wide spread roof damages are reported in literature similar to those shown in Fig. 3 at ridge, gable end and wall corners that were observed during recent post damage assessment made by the FIU IHRC (Florida International University- International Hurricane Research Center) research team following hurricane Ike. Team deployed by IHBS (Institute for Home and Business Safety) also reported similar pattern (shown in Fig. 4) of failure from Hurricane Ike (80-90 mph) “Aerial photos taken after Ike showed close to 90 percent of the homes near the coast toward the western part of Bolivar Peninsula had an extensive loss of hip and ridge shingles” (IBHS 2009). Any breach on the building envelope, in addition to causing water penetration, could alter the aerodynamics of the building by adversely affecting the

internal pressure that increase wind forces on roofs and doors/windows. Moreover, failures caused by strong wind forces can become sources of flying debris that can easily damage other buildings.

Figure 4 Damage at gable end (left), hip roof eave and soffit – after IBHS 2009.

There are significant studies carried out by server researchers on evaluation of wind load for design of roof structures, however most of those studies utilized a small scale testing in boundary layer wind tunnels (usually at 1:100 to 1:300), which may not be suitable for producing high resolution pressure measurements at corner details encountered at residential buildings. The details in the corners (such as tile type used, ridge and eave details etc.) need to be duplicated in experimental studies in order to understand the damage initiation process. Thus necessitates a full-scale study similar to the present work that utilized a full-scale hurricane testing facility the Wall of Wind. The Wall of Wind in addition to enabling large scale model testing, it also produces high wind speeds that lacks from the most commonly used low-wind speed wind tunnels. This capability is in agreement with the requirement of dynamic similarity for aerodynamic studies usually referred as Reynolds number similarity. Mismatch in Reynolds number may lead to dampening out of smaller eddies in wind tunnels that are essential to capture realistic aerodynamic pressures around sharp corners and small-size components of buildings such as roof tiles, balconies and roof top equipment. Field data measurements

obtained in natural winds, e.g., at Texas Tech (Levitan and Mehta 1992) and Silsoe (Hoxey and Richards 1993) provide data useful for the validation of both wind tunnel and computational efforts. However, they are primarily useful for validation purposes if carried out in open exposure; they often miss the strong winds near the eye of the storm (Levitan and Mehta 1992; Hoxey and Richards 1993), and depend on uncontrollable natural occurrences. Most mechanical load testing has been limited to components and connections, and has only rarely been concerned with Main Wind Force Resisting System testing. Exceptions are tests by Riley and Sadek (2003), and the Three Little Pigs experiment at the University of Western Ontario where both suction and pressure load driven by wind tunnel data can be applied to an entire two-storey structure through specially designed pressure actuators (Surry et al. 2005).

Previous studies similar to the present study include a study by Robertson et al. (2007) where wind pressure data were collected on the tiled roof of a full-scale test house at Silsoe subjected to natural wind. Their finding indicated that wind loads around the ridge were underestimated by 20% ridges. As described earlier, recently a group of researchers at FIU evaluated hip and ridge tile resistance through a detailed experimental and analytical study for clay and concrete tiles with adhesive-set, mortar-set as well as mechanical attachments using static tests on a single clay tile (Mirmiran 2006). Mirmiran et al. (2007) and Huang et al. (2009a) further looked into monotonic and cyclic uplift tests for multiple clay tiles (three at a time) as well as dynamic wind simulation test using the 2-fan WoW on a mono slope small roof test specimen that has field clay tiles. The study also developed an analytical finite element model for the mono-slope roof case. Their results showed that the cladding pressure measurements for the tiles on the mono

slope have exceeded those provided in ASCE7-2005 for certain wind directions. The external pressure on a tile was also found to be strongly influenced by the surface geometry of the tile (Huang et al., 2009a). Their study was however limited to mono-slope roof due to limitation of the wind field size generated by the 2 fan WoW that was available for the study.

The present study looked further into the aerodynamics of the ridge and field tiles installed on gable roofs with three different slopes by using the new 6-fan WoW. The 6-fan WoW is capable of testing a large low-rise building model. Further, detail aerodynamic illustration that will look into more cases not considered in the present experimental study was carried out by using a numerical approach that employed computational fluid mechanics principles.

3. METHODOLOGY

The present study adopted a full-scale testing methodology using the Wall of Wind testing facility. This chapter will present details of the test specimen used at the Wall of Wind, the instrumentation adopted and measured variables.

3.1 Test-specimen: design, construction and detailing

Gable roofs with floor plan dimensions 11 ft wide and 9 ft long with three different slopes were fabricated (Fig. 2.1). Two bases (i.e. the house without the roof) each having a 2.74 m (9 ft) width x 2.13 m (7 ft) length x 2.13 m (7 ft) height wooden walls and doors were recycled from previous projects. The use of two bases allowed preparation of multiple models ready for test by allowing instrumentation of one model while pursuing the testing on the other model. The overall size of the test building specimen was obtained by conducting a blockage and proximity assessment test in the Wall of Wind following the recommendations on blockage and proximity effect by Bitsuamlak et al. (2009).

Figure 5 Field tiles: high profile (left), medium profile (middle) and low profile (right).

For the field tiles, three different profiles namely high, medium and low (i.e. flat) profiles were considered in the present study as shown in Figs 5 and 6. Three different

ridge tiles namely rounded, three-sided and V-shaped (or two sided) tiles were considered in the present study as shown in Fig 6. Each roof was constructed in accordance with locally prevailing construction methods. The roof envelope was properly covered with underlayment and the tiles were installed by professionals from the roofing industry (see the acknowledgment section).

Figure 6 Filed tile (left column) and ridge tiles (right column).

While the field tiles were nailed to the roof deck, the ridge tiles were attached to the ridge metal channel by using foams (Fig. 7). The Wall of Wind study is purely an aerodynamic study (dealing with shapes, porosity or openings and their interaction with wind), hence for the weather blocking adhesive foams were used instead of mortar due to their ease of application and enabling reuse of the model. It is to be recalled that the Wall of Wind tests in the present study were designed to measure the wind induced pressure not the resistance of the tile attachment, hence the selection of adhesive foams for the current study instead mortar will not affect the aerodynamic data.

Figure 7 Test specimen fabrication

3.2 WoW wind field and blockage characteristics

The test building model was tested in the WoW full scale testing facility at mean wind speed 20.9 m/s (46.7 mph) and turbulence intensity of 22% measured at 3.7 m (12 ft) distance from the fans at eave height i.e. 2.18 m (7.16 ft) from the ground. For more details on the wind flow generation methods see Huang et al. (2009b). Testing larger test specimens within the finite WoW wind field, either to achieve Reynolds number similarity or to assess the performance of full-scale building components under wind, wind-driven rain, and debris impact resistance, may entail blockage issues. The blockage effect discussed in the present study is concerned with the size of the test specimen in relation to the finite size of the wind field generated by the WoW at the inlet. The initial model size of the test building specimen was obtained through a computational blockage and proximity assessment simulation in the Wall of Wind (Bitsuamlak et al. 2009). Following this initial recommendation, an experimental blockage and proximity assessment test were carried out in the WoW for the following three cube sizes: (i) 1.52 m by 1.52 m by 1.52 m (5 ft by 5 ft by 5 ft), (ii) 2.31 m by 2.31 m by 2.31 m (7 ft by 7 ft by 7 ft) , and (iii) 2.72 m by 2.72 m by 2.72 m (9 ft by 9 ft by 9 ft). Based on the experimental result a 7 ft (2.13 m) dimension was chosen for the depth and height of the model. The width of the building was chosen to be 9 ft (2.74 m) so that the test building has a representative rectangular foot print.

3.3 Pressure transducers

SETRA model 265 very low differential pressure transducers (shown in Fig. 8) were used for the measurement of the pressure on field tiles. Each transducer has two ports: a reference pressure port (which is connected to a reference point) and a dynamic

pressure port exposed to the wind flow where it measures the fluctuating pressures. The result produced is a differential pressure which is reported as a voltage ranging from 0 to 5 V. This result is later calibrated and converted in pressure unit (psi). The transducers have a pressure range of ± 1.8 Psi and report at a frequency of 10 Hz and an error of $\pm 1\%$. The reference port of the pressure transducers were interconnected to a pressure manifold using a system of 3/16 in tubing and the pressure manifold connected to a pit located approximately 50 ft away from the test structure.

The dynamic pressure port was connected via a 3/16 in tube to a 1/4 in OD (outside diameter) copper pressure tap which extended from the roof. In order to avoid distortion in the measurement, the total length of the tube extending from the copper tap to the dynamic pressure port was limited to 16 in maximum.

Figure 8 SETRA 265 pressure transducer (left) and Omega PCL- 200 Calibration kit (right)

Calibration of the pressure transducers were carried out to insure the pressure being fed in the pressure port is the same that is reported by the DAQ. Even though the transducers are factory calibrated, they need to be calibrated every time they are used in

order to take into account losses that occur in the wiring system. The calibration took place after the transducers were installed in place and wired. During the calibration process, the dynamic pressure port of the transducer were subjected to different known value of pressure and each time, the output voltage is recorded, then the curve of pressure in function of voltage is drawn and compared to the factory calibration curve (Fig. 9). This was done using the Omega PCL-200 hand held calibration kit shown in Fig. 8.

Figure 9 Sample calibration curve for a SETRA model 265

Figure 10 ScaniValve accessories: The Digital Service Module DSM 3400 (left), 64 channel model ZOC 33/64 PX X1 (middle) and Servo SPC 3000 (right).

The other type pressure measurement instruments used in the present study was ScaniValve pressure scanner (Fig. 10). The device allows the signal delivered to an instrument to be scanned or switched between multiple pressure sensors. The ScaniValve

pressure scanner was used in order to measure the pressure on the ridge tiles. Since it allows the use of small tubes of 2 mm diameter at its ports, it was possible to install rows of seven pressure taps on the ridge tiles in order to have a high resolution of the pressure distribution on those critical tiles. A 64 channel model ZOC 33/64 PX X1 ScaniValve was used in the present study. It is an electronic pressure scanning system which incorporates 64 temperature compensated piezoresistive pressure sensors in a compact self-contained module. Its microprocessor compensates temperature changes and performs engineering units' conversion. It accepts up to 64 pneumatic inputs and converts them into high level electronic signals. Its range is up to 50 psi and its operating temperature is 0 to 60 degrees. The ZOC 33/64 PXX1 was used with various accessories described below and in the schematic shown in Fig 11:

- A Servo Pressure Calibrator SPC 3000. The pressure Calibrator module supplies and measures the precision calibration pressure of the ZOC every time that a measure needs to be done.
- A Solenoid DSMCPM which supplies power to the calibrators and switches system pressures. It also helps purge the system.
- A Pressure Regulator which receives in input dry air and outputs three ranges of pressure: 2psi and 90 psi used as reference by the pressure calibrator, 65 psi used as control pressure by the solenoid.
- A desiccant air dryer model Dayton that takes air from a source (for example an air compressor) and outputs dry air into the pressure regulator.
- The Digital Service Module (DSM 3400). It is an intelligent module designed to interface ZOC electronic pressure scanners to an Ethernet network. The

DSM3400 service module incorporates an embedded PC, eight 16 bit A/D converters, RAM, and flash memory. The DSM microprocessor performs engineering unit conversion and compensates for temperature changes, thereby reducing thermal errors from the ZOC pressure sensors. The microprocessor also control the solenoid valves DSMCPM to perform automatic on-line zero and span calibration. This on-line calibration capability virtually eliminates sensor thermal errors. System accuracy of $\pm 0.08\%$ FS (5 psi and up) is achievable. Pressure data are output in engineering units via Ethernet using TCP/IP protocol or other optional communication interfaces.

Figure 11 Schematic of the air flow in the ScaniValve System.

3.4 Free Stream velocity profile measurement

The measurement of free stream velocity profile was done prior to testing of the test building. For this purpose, a steel frame was built and erected at 9 ft from the edge of the contraction of the 6-fan WoW. A Cobra Probe for the measurement of wind speed

was secured to the frame at 7.16 ft height from the ground (as shown in Fig. 12), corresponding to the eave height of the test building. The wind speed was then recorded during a period of 6 min at a sample rate of 10 Hz with the WoW engines running with quasiperiodic waveform wind profile. The mean wind speed recorded obtained was 49.79 mph and a turbulence intensity of 22%. This value of the mean wind speed will be used to determine the pressure coefficients (C_p) for roofs with less than 9° slope, otherwise, the power law profile will be applied to find the mean wind speed at the middle height of the roof.

Figure 12 Cobra probe set up for velocity field measurement (left) and closeup (right).

3.5 Pressure tap layout

In order to capture external pressure (and internal pressure developing in the space between the field tile and the deck or the ridge tile and the ridge support) distribution on the ridge and field tiles, a total of 88 pressure taps were used on each gable roof. A total of 48 pressure taps were connected to SETRA transducers and 42 pressure taps were connected to the Scanivalve pressure scanner as shown in the tap layout sketch, Fig. 13. Scanivalve that use a 2 mm diameter pressure tubes were used for high spatial resolution pressure measurements on the ridge tiles, which is the main focus

of the present study (Figs 14). The pressure tubes connected to SETRA transducers had a diameter of 8 mm and were installed mostly on the field tiles (Fig. 15). Seven pressure taps were placed in between the ridge tiles and the ridge support, and eight pressure taps between the field tiles and the roof deck to measure pressure (Fig. 13a) that may develop behind the tiles due to the porosity common with discontinuous roof system. The pressure signals from all taps were sampled at a rate of 100 Hz for 180 seconds.

For all cases the ridge tiles were attached to the metal ridge channel using an adhesive and all the field tiles were mechanically attached with two screws to the roof deck.

(a) Pressure taps distribution on the field and ridge tiles (plan view).

(b) Pressure tap distribution on filed tiles (elevation) and (c) Pressure tap distribution along the ridge tile.

Figure 13 Pressure tap distribution (taps on field tiles were connected to Setra pressure transducers and taps on ridge tiles were connected to scanivalve)

Figure 14 Pressure taps installed on ridge tiles, three sided (left) and rounded (right) ridge tiles.

Figure 15 Pressure taps installed on field tiles, three sided (left) and rounded (right) ridge tiles.

The coordinates of each pressure tap installed on a gable roof with high and low profile field tile is shown in Table 1 corresponding to the pressure tap labels shown in Fig. 16 for field tiles and Fig. 18 for ridge tiles. It is to be noted that the rounded ridge

tiles are usually used with high and medium profile field tiles and the three-sided ridge tiles with the low profile (i.e. flat) tiles. Similarly, the coordinates of each pressure tap installed on medium profile field tile is shown in Table 2 corresponding the pressure tap labels shown in Fig. 17 for field tiles and Fig. 18 for ridge tiles.

Rounded ridge tile used with high-profile field tile profile (left) and three-sided ridge tile used with low profile (i.e. flat) field tiles (right)

Figure 16 Pressure tap layout used on gable roofs with high and low field profiles.

Table 1 Pressure tap coordinates used on gable roofs with high and low profile field tiles.

Field tiles																														
1 st ROW	T	X*	Y*	2 nd ROW	Ta	X*	Y*	3 rd Row	Ta	X*	Y*	5 th ROW	Ta	X*	Y*															
	1	7	2		2 nd ROW	12	11.		50	4 th Row	23		23.	110	34	65	16													
	2	7	16			2 nd ROW	13		11.		77		4 th Row	24	23.	129.	35	65	30											
	3	7	30				2 nd ROW	14	11.		95.5			4 th Row	25	30.	2	36	65	50										
	4	7	50					2 nd ROW	15		11.				110	4 th Row	26	30.	16	37	71.	77								
	5	7	77						2 nd ROW		16				11.		129.	4 th Row	27	30.	30	38	71.	95.5						
	6	7	95.5	2 nd ROW	17					19	2				4 th Row		28		30.	50	39	71.	110							
	7	7	110		2 nd ROW	18				19	16		4 th Row				29		35.	77	40	71.	129.							
	8	7	129.			2 nd ROW	19			19	30			4 th Row			30		35.	95.5										
2 nd ROW	9	11.	2				2 nd ROW	20		19	50	2 nd ROW				31	35.		110											
	1	11.	16					2 nd ROW	21	23.	77					2 nd ROW	32	35.	129.											
	1	11.	30	2 nd ROW					22	23.	95.5				2 nd ROW		33	65	2											
Ridge Tiles																														
ROW #1	1	2	62.2		ROW#2	12	8.5	67.2	ROW#4	23	20	63.5	ROW#6	34		54.	68.5													
	2	2	63.5	ROW#2		13	8.5	68.5		ROW#4	24	20		64.7	ROW#6	35	54.	69.7												
	3	2	64.7			ROW#2	14	8.5			69.7	ROW#4		25		20	66	ROW#6	36	69	62.2									
	4	2	66		ROW#3		15	14			62.2			ROW#4		26	20		67.2	ROW#6	37	69	63.5							
	5	2	67.2	ROW#3			16	14			63.5					ROW#4	27		20		68.5	ROW#6	38	69	64.7					
	6	2	68.5			ROW#3	17	14			64.7						ROW#4		28		20		69.7	ROW#6	39	69	66			
	7	2	69.7				ROW#3	18	14		66								ROW#4		29		54.		62.2	ROW#6	40	69	67.2	
ROW # 2	8	8.5	62.2					ROW#3	19	14	67.2		ROW#5								30		54.		63.5		ROW#6	41	69	68.5
	9	8.5	63.5						ROW#3	20	14	68.5			ROW#5						31		54.		64.7			ROW#6	42	69
	10	8.5	64.7							ROW#3	21	14		69.7				ROW#5			32		54.		66				ROW#6	
	11	8.5	66								ROW#3	22		20		62.2				ROW#5	33		54.		67.2					ROW#6

*Coordinates are in inches

Figure 17 Pressure tap layout used on gable roofs with medium profil field tiles

(a) Detail # 1

(a) Detail # 2

Figure 18 Ridge tiles tap layout and numbering

Table 2 Pressure tap coordinates used on a gable roof with a medium profile field tiles

Field tiles															
1 st ROW	Ta	X*	Y*	2 nd ROW	Ta	X*	Y*	3 rd ROW	Ta	X*	Y*	4 th ROW	Ta	X*	Y*
	1	1	2		12	3.5	49.5		23	12	110		34	60	17
	2	1	17		13	3.5	77		24	18	129.		35	65.	31.5
	3	1	31.5		14	3.5	96		25	30.	2		36	60	49.5
	4	1	49.5		15	3.5	110		26	24.	17		37	59.	77
	5	1	77		16	3.5	129.		27	30.	31.5		38	53.	96
	6	1	96		17	18.	2		28	24.	49.5		39	59.	110
	7	1	110		18	12.	17		29	24	77		40	53.	129.
2 nd ROW	8	1	129.	3 rd ROW	19	18.	31.5	4 th ROW	30	30	96	5 th ROW			
	9	3.5	2		20	12.	49.5		31	24	110				
	10	3.5	17		21	12	77		32	30	129.				
	11	3.5	31.5		22	18	96		33	65.	2				
			0							5					
Ridge Tiles															
ROW # 1	1	2	62.2	ROW#3	12	8.5	67.2	ROW # 4	23	20	63.5	ROW # 6	34	54.	68.5
	2	2	63.5		13	8.5	68.5		24	20	64.7		35	54.	69.7
	3	2	64.7		14	8.5	69.7		25	20	66		36	69	62.2
	4	2	66		15	14	62.2		26	20	67.2		37	69	63.5
	5	2	67.2		16	14	63.5		27	20	68.5		38	69	64.7
	6	2	68.5		17	14	64.7		28	20	69.7		39	69	66
	7	2	69.7		18	14	66		29	54.	62.2		40	69	67.2
ROW # 2	8	8.5	62.2	ROW#3	19	14	67.2	ROW # 5	30	54.	63.5	ROW # 6	41	69	68.5
	9	8.5	63.5		20	14	68.5		31	54.	64.7		42	69	69.7
	10	8.5	64.7		21	14	69.7		32	54.	66				
	11	8.5	66		22	20	62.2		33	54.	67.2				

*Coordinates are in inches

4. RESULTS AND DISCUSSIONS

In this chapter the test matrix discussion will be presented followed by details of experimental wind induced pressure measurements and results discussion.

4.1 Experimental test cases and details

Three different sets of gable tile roofs were built with a slope of 7:12; with (i) high profile concrete tiles; (ii) medium profile concrete tiles; and (iii) low profile concrete tiles were tested (Fig. 19). Initially, the roofs were built without weather blocking for the first sets of test and later, the weather blocking was applied for the second sets of tests, in order to find the worst case scenario. It is to be noted that all field tiles were mechanically fastened while ridge tiles were installed using adhesive foam (Polyfoam product) by licensed roofers and in accordance with the specifications of the Florida Roofing, Sheet Metal and Air conditioning Contractors association (FRSA 2005) and the Tile and Roofing Institute (TRI).

Table 3 Wall of Wind test case description

	Case 1: Low profile	Case 2: Medium profile	Case 3: High profile
Field tile attachment	Mechanical/ 2 screws	Mechanical / 2 screws	Mechanical / 2 screws
Ridge tile profile	Three sided	Barrel	Barrel
Ridge tile attachment	Foam	Foam	Foam
Ridge member	Metal Channel	Metal Channel	Metal Channel
Weather blocking	Foam	Foam	Foam

Figure 19 Field tiles: high profile (left), medium profile (middle) and low profile (right).

Each of the gable roofs were tested (Figs. 19, Fig. 20) for five different wind directions ($\alpha = 0^\circ, 30^\circ, 45^\circ, 75^\circ$, and 90° as defined in Fig. 21) for the test cases summarized in Table 3. Each of the three cases was tested prior to applying the weather block (referred hereafter as configuration 1). Once these tests were completed, the weather block was applied and the tests were repeated to assess the effect of the weather blocking (referred hereafter as configuration 2). Both Configurations 1 and 2 were tested using the Wall of Wind as shown in Fig 21. For some test cases, the 50° angle of attack was added based on the recommendation of Levitan et al. (1991) and Mehta et al. (1992) to be the most critical angle resulting in the highest uplift pressures for the eaves, hip and ridge regions of the roof.

A quasiperiodic waveform wind profile that approximated hurricane type of winds as described in Fig. 22 (Huang et al. 2009) was used in the present study. Each test consisted of a 3min long record of the wind pressure at a sample rate of 100 Hz for the pressure transducers and 60 Hz for the ZOC 33/64 PX X1. The sample rate of the ZOC 33/64 PX X1 was chosen at a smaller value due to the extensive length of the tubing between the ZOC and the SERVO.

Figure 20 Test-specimen setup in front of WoW.

Figure 21 Wind angle of attack (α) definition.

Figure 22 Quasiperiodic waveform used for pressure measurement

4.2 Wind induced pressure analysis

Wind induced pressure measurements are usually presented in the form of a pressure coefficient (equation 1). It is a dimensionless variable which describes the relative pressures throughout the air flow and is define as follows.

$$C_{Pi} = \frac{\Delta P_i}{\frac{1}{2}\rho U^2} \quad (1)$$

Where C_{Pi} is the pressure coefficient at the i^{th} measured tap, ΔP_i is the differential pressure at the i^{th} measured tap, ρ is the air density and U is the reference wind velocity usually measured at eave height prior to placing the test specimen in front of the Wall of Wind. Wind pressure measurements are very fluctuating as a typical time history plots in Figs 23 and 24 shows for field and ridge tiles respectively. More time history plots are also given in Appendix A. It is therefore common to use statistical approaches such as mean and RMS (root mean square or standard deviation) to represent the pressure measurements and communicate the results easily. The mean value of the pressure coefficient and the RMS at each individual tap are computed as follows:

$$C_{Pmean} = \frac{\sum_1^N C_{Pi}}{N},$$

$$C_{PRMS} = \sqrt{\frac{\sum_1^N (C_{Pi} - C_{Pmean})^2}{N-1}} \quad (2)$$

The minimum value is given by $C_{Pmin} = \min(C_{Pi})$, where N is the total number of values recorded at each pressure tap. The values of C_{Pmin} , C_{Pmean} and C_{Pmax} were calculated from the pressure time history on field and ridge tiles for each slop and at various angle of attack of the wind on the roof. Typical pressure time histories on field are shown in Fig 23 and time histories for ridge tiles in Fig. 24. Appendix A contains additional pressure time history plots.

Overall, significant peak negative pressures were measured on ridge tiles compared to the field tiles. For example a maximum value of 1800 Pa was measured on the ridge tile compare to a pressure of 1220 Pa measured on a field tile located close to the ridge. Even though such differences exist, other methodologies such as those based on small-scale testing and guide-lines derived from them do not differentiate between the field tiles and ridge tiles near the ridge corner. They prescribe similar pressure values for both. This may lead to underestimation of the design wind load for ridge tiles. High resolution aerodynamic data produced in the present study that accounted for the true geometry of the tiles is expected to alleviate this problem, thus contributing towards loss reductions associated with roof cover failures. Details of field and ridge tile aerodynamics are presented in the following sections.

Figure 23 Typical pressure time history (Pa) on high profile field tiles near the ridge line (AOA 0°) from the wind ward direction (top) and from the leeward side (bottom)

Figure 24 Typical pressure time history (Pa) on rounded ridge tile (AOA 0°) taken from a windward side tap (top) and a leeward side tap (bottom)

4.3 Field tile aerodynamics

In this section both external and internal (pressure that develops between the tile and the sheathing behind the tile) C_{Pmin} , C_{Pmean} and C_{Pmax} obtained for field tiles will be presented. Effect of weather blocking, wind direction, tile profile will be discussed.

Aerodynamics of high profile field tiles

The external C_{Pmin} , C_{Pmean} and C_{Pmax} values on high profile field tiles corresponding to multiple angle of attack are given in Table 4 both for configuration 1 (i.e. with weather block – WB--) and configuration 2 (i.e. without the weather block – NWB --). Plots of the external C_p values are given in Appendix B. While Fig B.1 shows C_p plots for configuration 1 and Fig. B.2 shows for configuration 2. The maximum negative peak value ($C_{pmin} = - 6.49$) was observed at tap # 13 for AOA of 30° for configuration 2 (i.e. when there is no weather block), while the maximum positive peak value ($C_{pmax} = 3.43$) is obtained at tap # 9 for AOA of 45° for the same configuration.

Aerodynamics of medium profile field tiles

Similarly, the external C_{Pmin} , C_{Pmean} and C_{Pmax} value on medium profile field tiles corresponding to multiple angle of attack are given in Table 5, both for configuration 1 (i.e. with weather block – WB--) and configuration 2 (i.e. without the weather block – NWB --). Plots of the external C_p values are given in Appendix B. While Fig B.3 shows C_p plots for configuration 1 and Fig. B.4 shows for configuration 2. The maximum negative peak value ($C_{Pmin} = - 6.10$) was observed at tap # 7 for AOA 0° for WB case while the maximum peak positive peak ($C_{Pmax} = 5.80$) occurred at tap # 22 for 30° AOA for WB case.

Table 4 External C_p values on high profile field tiles for 0° , 30° , 45° , 75° and 90° AOA

HIGH PROFILE: Field tiles												
tap #	0 deg NWB			0 deg WB			30 deg NWB			30 deg WB		
	mean Cp	min Cp	max Cp	mean Cp	min Cp	max Cp	mean Cp	min Cp	max Cp	mean Cp	min Cp	max Cp
1	-1.03	-	0.29	-0.94	-4.82	0.38	-0.29	-2.16	1.07	-0.28	-2.49	1.55
2	-0.99	-	0.07	-0.92	-2.86	0.02	-0.46	-2.08	0.74	-0.47	-2.04	0.65
3	-0.92	-	0.05	-0.95	-2.88	-0.08	-0.51	-2.05	0.65	-0.57	-2.33	0.72
4	-0.87	-	0.11	-0.95	-2.91	-0.11	-0.52	-2.26	0.37	-0.49	-2.03	0.24
5	-0.99	-	0.33	-1.23	-3.45	0.36	-1.31	-3.75	-0.25	-1.69	-4.11	-0.23
6	-1.06	-	2.17	-1.25	-4.73	0.86	-1.13	-5.11	2.23	-1.35	-5.47	1.85
7	-0.81	-	1.92	-0.96	-3.44	1.35	-0.99	-3.61	0.79	-1.11	-3.88	2.55
8	-0.56	-	1.43	-0.59	-3.18	2.50	-0.89	-3.40	0.30	-0.99	-3.49	0.21
9	-0.37	-	1.82	-0.32	-3.23	1.91	0.25	-1.17	2.08	0.41	-1.67	2.44
12	-0.82	-	0.13	-0.88	-2.81	-0.06	-0.01	-1.22	1.37	0.04	-1.30	1.56
13	-0.87	-	0.76	-0.94	-4.07	1.97	-1.23	-4.58	0.06	-1.83	-6.49	1.05
16	-0.69	-	0.33	-0.90	-3.51	0.30	-0.75	-3.48	0.27	-0.79	-4.04	0.46
HIGH PROFILE: field tiles												
Tap #	45 deg NWB			45 deg WB			75 deg NWB			75 deg WB		
	mean Cp	min Cp	max Cp	mean Cp	min Cp	max Cp	mean Cp	min Cp	max Cp	mean Cp	min Cp	max Cp
1	0.22	-1.73	1.95	0.26	-1.91	2.20	0.22	-1.99	2.92	0.48	-1.63	2.67
2	0.09	-1.15	1.51	0.21	-0.86	1.37	0.13	-1.51	1.49	0.26	-1.00	1.73
3	-0.07	-1.32	0.95	0.14	-1.16	1.25	0.09	-1.31	1.53	0.19	-1.12	1.72
4	-0.08	-1.50	0.95	0.11	-1.50	1.07	0.10	-0.83	1.26	0.22	-0.86	1.48
5	-1.13	-2.84	-0.27	-1.57	-4.47	-0.15	-0.24	-1.32	0.29	-0.37	-1.20	0.09
6	-0.93	-3.13	0.39	-1.03	-5.11	1.53	-0.22	-1.61	0.71	-0.40	-1.75	0.43
7	-0.79	-2.57	0.34	-0.93	-3.36	0.39	-0.21	-1.52	0.60	-0.41	-1.89	0.47
8	-0.68	-3.08	0.26	-0.69	-2.63	0.44	-0.20	-1.57	0.47	-0.39	-1.84	0.50
9	0.58	-1.09	3.43	0.64	-1.00	2.77	0.33	-1.50	2.09	0.53	-1.10	2.40
12	0.31	-0.59	1.36	0.41	-0.33	1.85	0.25	-0.48	1.52	0.40	-0.31	1.76
13	-1.12	-5.13	0.26	-1.44	-6.12	1.01	-0.24	-1.74	0.96	-0.39	-1.84	0.68
16	-0.68	-3.17	0.53	-0.62	-2.77	0.39	-0.21	-1.83	0.44	-0.37	-1.69	0.28

Table 5 External Cp values on medium profile field tiles for 0°, 30°, 45°, 50°, 75°, and 90°

AOA

MEDIUM PROFILE: Field Tiles												
Tap #	0 deg NWB			0 deg WB			30 deg			30 deg WB		max
	mean Cp	min Cp	max Cp	mean Cp	min Cp	max Cp	mean Cp	min Cp	max Cp	mean Cp	min Cp	
1	-1.13	-4.89	0.36	-1.21	-4.99	0.23	-0.76	-4.91	1.38	-0.57	-3.30	1.20
2	-0.95	-4.03	0.11	-0.98	-3.14	0.23	-0.76	-4.98	1.27	-0.83	-3.99	0.65
3	-0.89	-3.46	0.06	-0.89	-2.62	-0.07	-0.80	-4.99	1.24	-0.76	-3.58	0.67
4	-0.82	-3.90	-0.06	-0.73	-2.45	-0.11	-0.50	-3.14	0.93	-0.52	-2.25	0.75
5	-1.09	-3.57	-0.05	-1.05	-3.86	-0.04	-1.31	-3.87	-	-1.75	-4.40	-0.47
6	-1.52	-5.61	0.00	-1.67	-5.06	-0.10	-1.58	-5.57	-	-1.43	-4.73	0.02
7	-0.26	-0.59	0.32	-1.79	-6.10	-0.19	-0.10	-0.28	0.15	-1.35	-5.51	0.01
8	-1.19	-5.41	0.09	-1.34	-5.08	-0.04	-1.15	-5.26	0.01	-1.17	-4.22	0.21
9	-0.91	-3.75	1.18	-0.83	-3.61	1.12	0.30	-2.68	2.59	0.35	-1.66	2.07
12	-0.86	-3.12	0.12	-0.82	-2.59	-0.18	-0.47	-2.68	1.82	-0.56	-2.44	0.99
13	-0.97	-2.75	-0.05	-1.02	-3.24	0.06	-1.28	-3.31	-	-1.67	-4.21	-0.51
14	-1.11	-4.01	0.33	-1.16	-3.95	0.45	-1.17	-4.31	0.21	-1.18	-3.89	0.09
15	-1.09	-4.39	0.27	-1.19	-4.46	0.25	-1.14	-4.55	0.20	-1.14	-5.16	0.00
16	-0.63	-3.60	0.94	-0.63	-4.35	0.76	-0.90	-4.27	0.12	-0.97	-4.06	0.35
MEDIUM PROFILE: Field tiles												
Tap #	45 deg NWB			45 deg WB			50 deg NWB			50 deg WB		max
	mean Cp	min Cp	max Cp	mean Cp	min Cp	max Cp	mean Cp	min Cp	max Cp	mean Cp	min Cp	
1	0.51	-2.50	2.16	0.53	-1.41	2.18	0.69	-1.33	2.73	0.56	-0.93	2.07
2	0.27	-2.29	1.91	0.18	-2.46	1.83	0.52	-1.82	2.13	0.26	-2.17	1.87
3	0.22	-3.31	1.50	0.14	-2.24	1.58	0.38	-2.30	1.98	0.17	-2.33	1.66
4	0.05	-2.30	2.08	0.03	-1.45	1.51	0.15	-1.79	1.76	0.12	-1.20	1.57
5	-1.42	-3.90	-0.29	-1.98	-4.98	-0.51	-1.04	-2.90	-0.04	-1.11	-3.28	-0.05
6	-1.48	-5.67	-0.04	-1.40	-5.17	-0.29	-1.08	-4.40	0.12	-0.87	-3.98	0.20
7	-0.14	-0.31	0.09	-1.08	-4.70	0.23	0.07	-0.06	0.26	-0.73	-5.47	0.40
8	-0.81	-3.76	0.40	-0.81	-4.74	0.17	-0.66	-3.02	0.36	-0.62	-4.03	0.24
9	0.76	-0.84	2.78	0.78	-1.79	2.57	0.80	-0.74	2.60	0.72	-1.02	2.59
10	0.56	-1.51	2.42	0.59	-1.35	2.73	0.60	-0.89	2.15	0.52	-1.22	2.27
11	0.45	-1.77	1.89	0.43	-1.44	2.17	0.49	-0.80	2.47	0.40	-1.25	1.71
12	0.28	-2.03	1.88	0.16	-1.80	1.90	0.36	-1.81	1.76	0.27	-1.01	1.67
13	-1.44	-3.46	-0.37	-1.86	-4.91	-0.52	-1.04	-3.02	-0.14	-1.03	-3.27	-0.05
14	-1.11	-4.35	-0.01	-1.16	-3.52	-0.15	-0.81	-2.82	0.07	-0.73	-2.58	0.23
15	-0.92	-3.04	-0.11	-0.98	-4.68	-0.18	-0.71	-2.64	0.04	-0.68	-3.17	0.05
16	-0.70	-3.33	0.19	-0.74	-3.43	0.16	-0.58	-3.02	0.20	-0.56	-2.25	0.20

MEDIUM PROFILE: field Tiles												
tap #	75° NWB			75° WB			90° NWB			90° WB		
	mean	min	Max	mean	min	max	mean	min	max	mean	min	max
	Cp	Cp	Cp	Cp	Cp	Cp	Cp	Cp	Cp	Cp	Cp	Cp
1	0.46	-1.53	2.49	0.39	-1.51	2.88	0.14	-2.01	2.54	-0.04	-2.41	1.79
2	0.39	-0.95	1.94	0.28	-1.08	2.10	0.13	-0.94	1.94	-0.02	-1.47	1.46
3	0.33	-0.52	1.71	0.26	-0.66	1.80	0.06	-1.13	1.28	-0.06	-1.35	1.28
4	0.27	-0.91	1.74	0.19	-1.07	1.65	-0.08	-1.25	1.29	-0.21	-1.81	1.07
5	-0.35	-1.86	0.12	-0.32	-1.26	0.10	-0.40	-2.58	0.12	-0.35	-1.76	0.29
6	-0.42	-2.36	0.28	-0.37	-2.69	0.19	-0.39	-2.10	0.31	-0.36	-1.80	0.27
7	-0.06	-0.17	0.10	-0.40	-4.42	0.33	-0.14	-0.26	-0.04	-0.37	-2.57	0.29
8	-0.44	-3.20	0.34	-0.42	-2.65	0.26	-0.45	-2.48	0.18	-0.40	-2.58	0.26
9	0.69	-0.53	2.83	0.71	-0.42	3.01	0.68	-0.49	3.31	0.61	-0.61	2.93
10	0.46	-0.51	2.01	0.41	-0.82	2.55	0.36	-0.86	2.03	0.27	-0.86	1.92
11	0.40	-0.32	1.70	0.38	-0.42	1.71	0.29	-0.57	1.61	0.27	-0.71	1.61
12	0.37	-0.35	1.58	0.39	-0.30	1.61	0.26	-0.53	1.40	0.25	-0.63	1.41
13	-0.34	-1.23	0.00	-0.33	-1.21	0.04	-0.34	-1.15	0.05	-0.31	-1.08	0.13
14	-0.36	-1.89	0.23	-0.34	-2.25	0.25	-0.35	-1.43	0.32	-0.32	-1.56	0.28
15	-0.39	-1.39	0.22	-0.37	-2.47	0.40	-0.37	-1.62	0.26	-0.34	-1.51	0.26
16	-0.38	-1.79	0.25	-0.38	-1.93	0.23	-0.40	-1.79	0.14	-0.37	-1.78	0.15

Aerodynamics of low profile field tiles

Similarly, the external C_{Pmin} , C_{Pmean} and C_{Pmax} for low profile field tiles corresponding to multiple angle of attack are given in Table 6 both for configuration 1 (i.e. with weather block – WB--) and configuration 2 (i.e. without the weather block – NWB --). Plots of the external C_p values are given in Appendix B. While Fig B.5 shows C_p plots for configuration 1 and Fig. B.6 shows for configuration 2. The maximum peak values are $C_{Pmin} = - 8.76$ at tap # 8 for 30° and $C_{Pmax} = 3.26$ at tap # 1 for 75° both occurring when there is weather block.

Table 6 External Cp values on low profile field tiles for 0°, 30°, 45°, 75°, and 90° AOA

LOW PROFILE: field tiles												
Tap #	0° NWB			0° WB			30° NWB			30° WB		
	mean Cp	min Cp	max Cp	mean Cp	min Cp	Max Cp	mean Cp	min Cp	Max Cp	mean Cp	min Cp	Max Cp
1	-1.24	-7.07	2.29	-1.45	-6.92	2.03	-0.04	-4.48	2.95	-0.40	-6.38	2.33
2	-1.15	-3.94	0.10	-1.16	-4.53	0.02	-1.06	-5.02	0.91	-1.20	-4.46	0.56
3	-0.96	-3.60	0.12	-0.95	-4.48	-0.02	-1.59	-7.28	0.97	-1.71	-7.50	0.93
4	-0.72	-2.56	-0.04	-0.79	-4.17	0.01	-0.77	-4.41	0.66	-0.85	-3.61	0.94
5	-0.95	-3.08	0.10	-1.07	-7.01	0.12	-1.61	-4.38	-0.11	-2.34	-6.50	-0.55
6	-1.19	-5.87	1.40	-1.16	-6.25	0.02	-1.27	-4.97	0.16	-1.28	-7.02	0.36
7	-1.51	-6.00	-0.09	-1.53	-5.95	0.00	-1.39	-6.25	0.02	-1.51	-7.56	0.44
8	-1.08	-6.55	1.79	-1.17	-6.23	2.06	-1.07	-8.76	0.38	-1.09	-7.48	1.13
9	-0.38	-2.36	0.41	-0.39	-2.70	0.36	0.09	-1.59	1.18	0.02	-1.75	0.81
10	-0.90	-3.75	0.39	-0.93	-3.79	0.34	-0.03	-1.37	0.76	-0.08	-2.32	0.86
11	-1.01	-3.46	0.27	-0.94	-3.37	0.30	-0.15	-2.40	0.53	-2.06	-2.44	0.53
12	-0.90	-3.18	0.11	-0.94	-3.35	0.15	-0.36	-2.59	0.55	-0.21	-2.07	1.00
13	-1.10	-4.63	0.01	-1.09	-3.48	0.36	-1.74	-5.64	0.36	-1.43	-5.42	0.33
14	-1.22	-4.29	0.53	-1.12	-4.46	0.31	-1.23	-4.63	-0.13	-1.26	-3.69	-0.10
15	-0.68	-4.01	0.35	-0.68	-3.80	0.40	-0.97	-5.91	0.43	-1.07	-5.37	0.58
16	-0.42	-3.19	0.65	-0.30	-2.84	0.98	-0.84	-3.79	0.55	-0.97	-3.97	0.57

LOW PROFILE: field tiles												
Tap #	45 deg NWB			45 deg WB			75 deg NWB			75 deg WB		
	mean Cp	min Cp	Max Cp	mean Cp	min Cp	Max Cp	mean Cp	min Cp	max Cp	mean Cp	min Cp	max Cp
1	0.49	-2.28	2.81	0.44	-2.38	2.32	0.50	-1.78	2.69	0.56	-2.27	3.26
2	0.38	-2.14	2.07	0.32	-2.26	2.10	0.33	-0.75	2.07	0.40	-0.55	1.97
3	0.13	-3.65	1.85	0.07	-3.72	1.89	0.21	-0.75	1.60	0.26	-0.67	1.69
4	-0.22	-2.44	1.76	-0.16	-2.74	1.60	0.24	-0.74	1.58	0.28	-0.85	1.51
5	-2.09	-5.36	-0.27	-2.53	-7.36	-0.30	-0.35	-1.43	0.09	-0.32	-1.42	0.17
6	-1.31	-5.19	0.20	-1.26	-7.21	0.54	-0.39	-2.83	0.87	-0.36	-3.46	0.47
7	-1.17	-5.53	0.10	-1.12	-5.86	0.07	-0.43	-3.80	0.24	-0.41	-3.13	0.26
8	-0.87	-7.10	1.03	-0.83	-5.55	1.09	-0.41	-4.04	0.69	-0.41	-3.61	1.25
9	0.31	-1.66	1.43	0.27	-2.62	1.58	0.53	-1.77	2.11	0.62	-1.17	2.19
10	0.27	-0.62	1.16	0.26	-0.60	1.35	0.39	-0.68	1.41	0.45	-0.59	1.57
11	0.17	-0.88	1.17	0.18	-0.93	1.09	0.29	-0.63	1.30	0.33	-0.36	1.23
12	0.02	-1.15	0.94	0.09	-1.27	1.16	0.37	-0.27	1.57	0.43	-0.20	1.48
13	-2.04	-6.45	0.07	-1.67	-5.41	-0.09	-0.36	-1.33	0.10	-0.34	-1.17	0.11
14	-1.33	-4.19	-0.05	-1.25	-3.78	-0.12	-0.37	-1.68	0.11	-0.36	-1.39	0.16
15	-0.95	-6.05	-0.01	-0.99	-4.65	0.10	-0.40	-1.49	0.17	-0.39	-1.59	0.23
16	-0.82	-3.86	0.43	-0.85	-4.17	0.37	-0.41	-2.08	0.28	-0.41	-1.85	0.65

	LOW PROFILE: Field Tiles												
	90° NWB			90° WB				90° NWB				90° WB	
Tap	mea	min	max	mean	min	max	Ta	mean	min	max	mean	min	max
#	n Cp	Cp	Cp	Cp	Cp	Cp	p #	Cp	Cp	Cp	Cp	Cp	Cp
1	0.35	-1.55	2.61	0.38	-1.49	3.05	9	0.45	-1.54	2.33	0.64	-1.39	2.65
2	0.15	-1.06	1.55	0.15	-1.25	1.43	10	0.28	-0.94	1.58	0.37	-0.96	1.74
3	-0.01	-1.08	1.17	-0.07	-1.19	1.24	11	0.16	-0.61	1.28	0.22	-0.74	1.28
4	0.04	-1.15	1.00	-0.02	-1.15	1.16	12	0.27	-0.45	1.62	0.32	-0.45	1.75
5	-0.29	-1.45	0.34	-0.39	-1.47	0.16	13	-0.29	-1.20	0.24	-0.39	-1.33	0.04
6	-0.33	-3.08	0.60	-0.41	-5.04	0.89	14	-0.31	-1.79	0.26	-0.39	-1.42	0.06
7	-0.36	-2.79	0.32	-0.43	-3.43	0.21	15	-0.33	-2.01	0.21	-0.41	-1.80	0.25
8	-0.38	-3.36	0.48	-0.45	-6.40	0.37	16	-0.37	-1.98	0.32	-0.45	-2.18	0.23

4.4 Internal pressure underneath field tiles

From the assessment of pressure measurements underneath the high field tile (pressure developing between the field tiles and roof deck), significant positive pressure development was observed in windward side for the case where weather blocking was not applied as shown Fig. 25b . This may have pressure cancellation effect resulting in small net pressure on the field tiles. From Figs 25b, d, f, it was observed that the internal pressure underneath the high profile tiles was higher compared to the internal pressure underneath the medium profile tiles. Similarly, a higher internal pressure underneath the medium profile tiles was compared to the internal pressure underneath the low profile tiles. This is attributed to a larger space behind the high profile tiles compared to medium profile tiles, and a larger space underneath the medium profile tiles compared to low profile tiles.

While comparing NWB case with WB, it was observed that NWB cases provide marginally higher internal pressure than WB cases. The reason for the small difference is attributed for the fact that even for WB case there are significant porosities in

discontinuous roofs such as the ones considered in the present study and the wind will find its way behind the tiles. For example the NWB and WB case for the high profile tiles provided very comparable internal pressure, indicating the weather blocks applied only at corners (ridge, eave and gable end) did not influence the internal pressure that developed underneath field tiles. It is to be noted the weather block could significantly affect the tiles close to the eave of the roof compared to the ones on the roof field.

As mentioned earlier the pressure equalization that develops on external and internal side of the tiles can reduce the net pressure on the tile. However, as opposed to reducing the design pressure (by using the reduced net pressure) it is recommended using the reductions as additional safety factor. This is because during the life time of the roof the space behind the tiles could be clogged with leafs and other dirt on the roof and the internal pressure may not develop all the time.

(a) Tap layout for internal and external pressure measurement

(b) Internal pressure underneath high field tiles NWB, AOA 90 deg

(c) Internal pressure underneath the high field tiles WB, AOA 90 deg

(d) Internal pressure underneath medium field tiles NWB AOA 90 deg

(e) Internal pressure underneath medium field tiles WB AOA 90 deg

(f) Internal pressure underneath the low field tiles NWB AOA 90

(g) Internal pressure underneath the low field tiles WB AOA 90 deg

Figure 25 Internal pressure coefficient (Cpi) plots underneath high, medium, low field tiles with NWB and WB for AOA = 90°.

4.5 Effects of weather blocking on field tile external pressure

Figures 26, 27 and 28 below compare the external pressure coefficients obtained with and without the weather block system. It was observed that the WB resulted in

higher external pressure on high profile tiles compared to medium profile tiles. Similarly, a higher external pressure was observed on medium profile tiles compared to low profile tiles. In fact for low profile tiles, the external mean C_p values were almost equal for NWB and WB cases, suggesting that the blockage system has no influence on the mean external pressure on the low profile tiles. However, for high profile tiles, the external pressure coefficients were higher for weather blocked case. This can be attributed to dissipation of the external pressure due to high porosities associated with high profile tile for the NWB case.

(a) External $C_{p_{mean}}$ plots for 0° AOA on high profile for WB and NWB at taps 1 to 16

(b) External $C_{p_{mean}}$ plots for 75° AOA on high profile for WB and NWB at taps 1 to 16

Figure 26 Comparisons of external C_p values on high profile field tiles

(a) External $C_{p_{mean}}$ plots for 0° AOA on medium profile for WB and NWB at taps 1 to 16

(b) External $C_{p_{mean}}$ plots for 75° AOA on Medium profile for WB and NWB at taps 1 to 16

Figure 27 Comparisons of external C_p values on medium profile field tiles

(a) External $C_{p_{mean}}$ plots for 0° AOA on low profile field tiles for WB and NWB for taps 1 to 16

(b) External $C_{p\text{mean}}$ plots for 75° AOA on low profile field tiles for WB and NWB for taps 1 to 16
 Figure 28 Comparison of external C_p values on low profile field tiles

4.6 Effects of wind direction on field tiles

On low and medium profiles field tiles, the most critical angle of attack of the wind is 45° which generated the highest suction at tap # 5. For the high profile field tiles, 30° angle of attack generated the highest suction at tap #5. Figure 29 below provide comparative plots of C_p values for various wind angles of attack (AOA).

(a) Comparison of external C_p values on low profile for various AOA for taps 1 to 16

(b) Comparisons of external Cp values on medium profile for various AOA for taps 1 to 16

(c) Comparisons external Cp values on High profile for various AOA for taps 1 to 16

Figure 29 Comparisons of external Cp for various AOA

4.7 Effects of field tile shape

Figure 30 below represents plots comparing Cp values for the three different tile shapes used in the present study, namely the high, medium and low profile tiles. It was noticed that for angle of attack smaller than 45°, medium profile tiles usually see a higher suction on the leeward side than other types of tiles, while high profile tiles experience least suction. For all angle of attack, the least suction was observed with high profile tiles. Again this is attributed the high profile shape and associated irregularly somehow dissipating the wind pressure.

(a) External C_{pmean} values for field tiles at 0° AOA for taps 1 to 16

(b) External C_{pmean} values for field tiles at 30° AOA for taps 1 to 16

(c) External C_{pmean} values for field tiles at 45° AOA for taps 1 to 16

(d) External C_{pmean} values for field tiles at 75° AOA for taps 1 to 16

(e) External C_{pmean} values for field tiles at 45° AOA for taps 1 to 16

Figure 30 Comparison of external C_{pmean} values for high, medium and low profile tiles.

4.8 Ridge tile aerodynamics

Two type of ridge tiles were tested: the barrel (used with high and medium profile field tiles following the roofing industry practice.) and the three sided (used with low profile field tiles following the roofing industry practice). The highest suction on ridge tiles were observed on row 1 and 2 located near to the gable end and also on row 4 located on the second ridge tile just after overlap between the first and second tile and where in both cases significant flow separation occurred creating formation high peak pressures. C_{pmin} , C_{pmean} and C_{pmax} were summarized in Tables and plotted in Figures. While the Tables are listed here, the Figures are provided in Appendix C.

Table 7 External Cp values on ridge for medium profile at AOA 0°

MEDIUM PROFILE: Ridge tiles												
0 deg NWB				0 deg WB								
Tap #	mean Cp	max Cp	min Cp		Tap #	mean Cp	max Cp	min Cp				
1	-1.04	-0.21	-2.77		12	-0.98	0.29	-3.40				
2	-1.03	-0.24	-2.69		13	-0.96	0.38	-3.57				
3	-1.05	-0.21	-3.10		14	-0.90	0.46	-3.51				
4	-1.08	-0.24	-3.40		22	-0.67	0.74	-3.67				
5	-1.16	-0.28	-4.48		23	-0.64	0.40	-2.87				
6	-1.25	-0.24	-4.88		24	-0.69	0.32	-3.15				
7	-1.19	-0.22	-4.03		25	-0.64	0.72	-2.64				
8	-0.97	0.04	-3.38		26	-0.70	0.37	-3.14				
9	-0.96	0.15	-3.39		27	-0.72	0.73	-3.21				
10	-0.96	0.31	-3.36		28	-0.73	0.54	-3.91				
11	-0.98	0.35	-3.53									

MEDIUM PROFILE: Ridge tiles												
30 deg NWB				30 deg WB			45 deg NWB			45 deg WB		
tap #	mean Cp	max Cp	min Cp	mean Cp	max Cp	min Cp	mean Cp	max Cp	min Cp	mean Cp	max Cp	min Cp
1	-1.75	-0.50	-4.59	-2.45	-0.69	-5.67	-2.06	-0.59	-4.63	-2.83	-1.01	-8.69
2	-1.83	-0.55	-4.82	-2.54	-0.67	-5.88	-2.23	-0.61	-5.54	-2.99	-0.97	-8.69
3	-2.11	-0.55	-6.12	-3.06	-0.67	-8.48	-2.41	-0.68	-6.92	-2.85	-0.82	-8.69
4	-2.24	-0.58	-6.90	-2.63	-0.59	-7.73	-1.91	-0.51	-9.76	-2.13	-0.71	-6.32
5	-1.60	-0.20	-7.00	-1.76	-0.36	-6.06	-1.30	-0.32	-3.71	-1.44	-0.43	-5.00
6	-0.90	0.33	-4.26	-1.09	-0.05	-3.57	-0.63	0.35	-2.08	-0.75	0.29	-2.35
7	-0.40	0.88	-2.60	-0.44	0.95	-2.53	0.14	1.92	-0.80	0.06	1.43	-0.87
8	-1.32	-0.36	-3.69	-1.33	-0.28	-3.56	-1.26	-0.18	-3.43	-1.41	-0.24	-3.76
9	-1.51	-0.33	-4.35	-1.56	-0.29	-4.76	-1.59	-0.29	-4.32	-1.80	-0.34	-4.83
10	-1.52	-0.34	-5.07	-1.64	-0.22	-5.13	-2.07	-0.39	-5.02	-2.20	-0.57	-5.29
11	-1.41	-0.17	-5.07	-1.58	-0.20	-5.16	-2.07	-0.41	-5.35	-2.16	-0.65	-5.70
12	-1.31	-0.02	-4.41	-1.54	-0.08	-5.06	-2.02	-0.46	-5.59	-2.09	-0.60	-6.13
13	-0.89	0.12	-3.11	-1.02	0.07	-3.62	-1.19	0.22	-4.40	-1.24	-0.03	-3.60
14	-0.39	0.90	-2.41	-0.34	1.17	-2.34	-0.02	1.56	-1.91	-0.10	1.14	-1.59
22	-1.18	-0.27	-4.00	-1.26	-0.15	-3.79	-1.35	-0.09	-4.64	-1.52	-0.21	-4.75
23	-1.23	-0.32	-4.03	-1.29	-0.24	-4.86	-1.38	-0.17	5.73	-1.53	-0.26	-5.41
24	-1.46	-0.29	-4.37	-1.51	-0.29	-4.52	-1.51	0.00	-4.18	-1.71	-0.23	-4.30
25	-1.49	-0.22	-5.00	-1.62	-0.08	-4.63	-1.90	-0.05	-5.01	-2.09	-0.32	-5.21
26	-1.53	-0.20	-4.97	-1.72	-0.30	-4.92	-2.14	-0.40	-5.35	-2.30	-0.65	-6.03
27	-1.13	0.17	-4.20	-1.31	0.07	-4.13	-1.64	-0.31	-5.13	-1.80	-0.30	-4.82
28	-0.35	0.62	-1.82	-0.39	0.62	-2.00	-0.32	1.11	-1.49	-0.43	0.70	-1.55

	MEDIUM PROFILE: Ridge tiles											
	50 deg NWB			50 deg WB			75 deg NWB			75 deg WB		
tap #	mean	max	min	mean	max	min	mean	max	min	mean	max	Min
	Cp	Cp	Cp	Cp	Cp	Cp	Cp	Cp	Cp	Cp	Cp	Cp
1	-1.60	-0.25	-4.43	-1.72	-0.16	-5.43	-0.38	0.01	-1.51	-0.36	-0.01	-1.49
2	-1.64	-0.24	-4.51	-1.70	-0.11	-5.81	-0.45	-0.05	-1.69	-0.40	-0.02	-1.52
3	-1.78	-0.22	-5.79	-1.71	-0.03	-6.26	-0.54	-0.03	-1.74	-0.48	-0.01	-1.49
4	-1.52	-0.20	-6.56	-1.49	-0.08	-4.61	-0.80	-0.13	-2.38	-0.86	-0.11	-2.41
5	-1.11	-0.15	-3.42	-1.14	-0.05	-3.82	-0.87	-0.11	-2.41	-0.92	-0.17	-2.60
6	-0.49	0.49	-1.76	-0.59	0.62	-2.24	-0.33	0.52	-1.27	-0.37	0.66	-1.34
7	0.27	2.05	-0.65	0.20	1.79	-0.66	0.44	1.85	-0.31	0.38	2.01	-0.42
8	-0.99	0.08	-4.18	-0.87	0.11	-3.46	-0.37	0.13	-2.16	-0.31	0.07	-1.28
9	-1.14	-0.09	-3.63	-0.92	-0.01	-3.60	-0.41	0.11	-2.61	-0.33	0.09	-1.44
10	-1.66	-0.24	-4.53	-1.30	0.01	-4.68	-0.50	0.09	-1.96	-0.37	0.13	-1.46
11	-1.78	-0.27	-4.90	-1.54	-0.01	-4.90	-0.97	-0.13	-3.09	-0.77	-0.08	-2.64
12	-1.82	-0.29	-5.38	-1.72	-0.18	-5.88	-1.40	-0.27	-4.74	-1.32	-0.23	-3.96
13	-1.05	0.07	-3.58	-1.04	0.14	-3.83	-0.83	0.31	-3.16	-0.82	0.38	-2.83
14	0.06	1.74	-1.37	0.01	1.22	-1.07	0.22	2.13	-0.89	0.18	1.84	-0.72
22	-0.98	0.18	-4.03	-0.83	0.22	-3.68	-0.36	0.05	-1.71	-0.32	0.07	-1.28
23	-1.06	0.18	-6.09	-0.93	0.30	-5.17	-0.40	0.13	-2.47	-0.35	0.30	-3.09
24	-1.08	0.08	-4.23	-0.92	0.19	-3.94	-0.44	0.30	-3.05	-0.38	0.15	-2.27
25	-1.38	0.01	-4.58	-1.11	0.16	-4.29	-0.63	0.17	-2.46	-0.52	0.17	-1.90
26	-1.80	-0.30	-5.13	-1.68	-0.28	-6.19	-1.15	-0.10	-3.19	-1.07	-0.14	-3.37
27	-1.48	-0.19	-5.00	-1.52	-0.18	-5.57	-1.17	-0.10	-3.59	-1.17	-0.19	-3.52
28	-0.25	1.19	-2.00	-0.30	0.80	-1.33	-0.07	1.11	-0.87	-0.11	1.17	-1.01

	MEDIUM PROFILE: Ridge tiles													
	90 deg NWB			90 deg WB				90 deg NWB			90 deg WB			
Ta	mean	max	min	mean	max	min		mean	man	min	mean	max	min	
p #	Cp	Cp	Cp	Cp	Cp	Cp		p #	Cp	Cp	Cp	Cp	Cp	Cp
1	-0.43	0.06	-1.75	-0.41	0.03	-1.58		12	-1.37	-0.12	-4.95	-1.18	-0.04	-4.59
2	-0.47	0.00	-1.82	-0.45	-0.04	-1.69		13	-0.91	0.10	-3.70	-0.77	0.51	-2.95
3	-0.53	-0.03	-1.73	-0.48	0.04	-1.89		14	0.15	1.70	-1.31	0.13	1.94	-1.46
4	-0.75	-0.08	-2.40	-0.77	-0.06	-2.79		22	-0.35	0.04	-1.29	-0.30	0.13	-1.07
5	-0.90	-0.17	-3.11	-0.90	-0.14	-2.62		23	-0.35	0.25	-2.01	-0.31	0.31	-1.56
6	-0.47	0.32	-1.61	-0.43	0.34	-1.41		24	-0.38	0.18	-1.56	-0.33	0.25	-4.96
7	0.21	1.58	-0.67	0.14	1.41	-0.81		25	-0.57	0.00	-2.53	-0.51	0.01	-2.08
8	-0.34	0.09	-1.63	-0.30	0.15	-1.56		26	-1.14	-0.16	-3.63	-0.99	-0.14	-2.98
9	-0.37	0.13	-1.59	-0.31	0.15	-1.89		27	-1.29	-0.10	-3.69	-1.11	0.12	-3.70
10	-0.41	0.09	-1.90	-0.34	0.16	-1.87		28	-0.10	1.00	-1.25	-0.12	1.35	-0.92
11	-0.75	0.01	-2.80	-0.62	0.06	-2.11								

Barrel ridge tiles with medium profile field tiles

The peak negative pressure coefficient ($C_{pmin} = -9.76$) was observed at tap # 4 for 45° AOA for WB case, while the peak positive value ($C_{pmax} = 1.18$) occurred at tap # 7 at 75° for WB case. Table 7 summarizes the C_p values at critical points on the ridge tile and Figs in Appendix C shows external C_p values plots for the ridge tiles.

Barrel ridge tile with high profile field tile

On high profile tiles, the maximum peak values at the ridge were $C_{pmin} = -5.78$ at tap # 6 for 30° AOA for WB case and $C_{pmax} = 2.36$ at tap # 7 for 90° AOA for NWB case.

Table 8 summarizes the C_p values and the plots are given in Appendix C.

Table 8 External C_p values on barrel ridge tile with high profile field tile for various AOA

tap #	HIGH PROFILE: Ridge tiles											
	0° NWB			0° WB			30° NWB			30° WB		
	mean C_p	max C_p	min C_p	mean C_p	max C_p	min C_p	mean C_p	max C_p	min C_p	mean C_p	max C_p	min C_p
1	-1.88	-	-5.44	-1.21	-0.12	-4.57	-1.54	0.09	-5.39	0.09	0.37	-0.25
2	-1.68	-	-5.43	-1.23	-0.08	-4.71	-1.79	0.13	-5.45	0.09	0.36	-0.27
3	-1.52	-	-4.63	-1.21	-0.22	-4.45	-2.00	0.18	-5.45	0.09	0.33	-0.24
4	-1.52	-	-4.43	-1.20	-0.28	-3.83	-1.85	0.10	-5.45	0.09	0.36	-0.21
5	-1.72	-	-5.36	-1.22	-0.29	-4.13	-1.47	0.34	-5.45	0.09	0.36	-0.18
6	-2.02	-	-5.44	-1.24	-0.30	-5.78	-0.97	0.78	-5.40	0.08	0.35	-0.19
7	-2.13	-	-5.44	-0.20	0.18	-0.77	-0.55	1.18	-4.46	0.09	0.36	-0.17
8	-0.93	0.27	-3.53	-1.07	0.43	-3.12	-0.92	0.07	-3.46	-1.37	-0.18	-4.13
9	-0.79	0.40	-3.79	-1.14	0.37	-3.92	-1.04	0.06	-3.72	-1.68	-0.27	-4.67
10	-0.69	0.57	-3.24	-1.07	0.46	-3.27	-1.12	0.06	-4.74	-1.85	-0.25	-5.34
11	-0.68	0.56	-3.33	-1.10	0.17	-3.19	-1.18	0.04	-4.98	-1.89	-0.29	-5.56
12	-0.72	0.40	-3.27	-1.12	0.06	-3.34	-1.09	0.10	-4.56	-1.62	-0.30	-5.33
13	-0.84	0.29	-3.35	-1.12	0.26	-4.21	-0.79	0.24	-2.94	-1.03	-0.03	-3.31
14	-0.95	0.09	-3.42	-1.07	0.38	-3.52	-0.49	0.59	-2.70	-0.28	0.63	-2.13

		HIGH PROFILE: Ridge tiles											
		45 deg NWB			45 deg WB			75 deg NWB			75 deg WB		
tap	mean	max	min	mean	max	min	mean	max	min	mean	Max	Min	
#	Cp	Cp	Cp	Cp	Cp	Cp	Cp	Cp	Cp	Cp	Cp	Cp	
1	-1.51	0.09	-5.37	0.12	0.47	-0.15	-0.43	0.19	-2.90	-0.37	0.14	-1.58	
2	-1.78	0.11	-5.44	0.12	0.47	-0.12	-0.48	0.38	-3.48	-0.45	0.13	-2.22	
3	-1.84	0.17	-5.44	0.11	0.41	-0.13	-0.54	0.29	-2.51	-0.57	0.07	-2.28	
4	-1.34	0.12	-5.45	0.13	0.43	-0.13	-0.79	0.26	-2.62	-0.96	-0.06	-3.04	
5	-0.96	0.32	-5.36	0.12	0.40	-0.12	-0.64	0.45	-2.96	-0.81	0.25	-2.93	
6	-0.52	1.26	-3.80	0.10	0.39	-0.12	-0.19	1.45	-1.96	-0.37	1.99	-1.65	
7	-0.09	2.72	-2.13	0.11	0.42	-0.15	0.47	3.36	-0.86	0.42	1.79	-0.06	
8	-0.81	0.21	-3.21	-1.06	-0.07	-3.73	-0.35	0.31	-1.79	-0.37	0.10	-1.68	
9	-0.99	0.21	-3.55	-1.26	-0.17	-3.81	-0.37	0.28	-2.35	-0.43	0.06	-2.09	
10	-1.24	0.20	-4.59	-1.80	-0.46	-4.81	-0.47	0.24	-1.97	-0.48	0.04	-1.88	
11	-1.39	0.30	-5.15	-2.06	-0.59	-5.97	-1.10	0.17	-3.56	-1.12	-0.23	-3.25	
12	-1.24	0.20	-4.95	-1.76	-0.47	-4.81	-1.23	0.19	-4.09	-1.34	-0.08	-4.63	
13	-0.78	0.48	-3.63	-0.98	0.08	-2.70	-0.64	0.53	-3.00	-0.79	0.39	-2.65	
14	-0.35	1.02	-2.27	-0.14	0.92	-1.24	0.03	1.56	-2.39	-0.02	1.48	-0.96	

		HIGH PROFILE: Ridge tiles												
		90 deg NWB			90 deg WB				90 deg NWB			90 deg WB		
Tap	mea	max	min	mean	max	min		Ta	mean	max	min	mean	max	min
#	n Cp	Cp	Cp	Cp	Cp	Cp		p #	Cp	Cp	Cp	Cp	Cp	Cp
1	-0.30	0.31	-2.79	-0.38	0.33	-2.94		8	-0.27	0.23	-1.78	-0.32	0.11	-1.54
2	-0.34	0.25	-2.17	-0.44	0.25	-2.77		9	-0.31	0.20	-2.27	-0.37	0.15	-2.35
3	-0.38	0.24	-1.98	-0.48	0.38	-2.99		10	-0.35	0.23	-1.88	-0.38	0.14	-1.79
4	-0.59	0.14	-1.98	-0.83	0.05	-2.80		11	-0.78	0.19	-2.89	-0.93	-0.03	-3.28
5	-0.53	0.31	-1.96	-0.77	-0.02	-2.77		12	-0.99	0.15	-3.79	-1.32	-0.16	-4.47
6	-0.25	0.97	-1.52	-0.39	0.86	-2.23		13	-0.57	0.47	-2.22	-0.79	0.31	-3.02
7	0.23	2.36	-1.12	0.44	1.41	-0.16		14	-0.02	1.46	-1.01	-0.03	1.14	-1.15

Three sided ridge tile with low profile field tile

Three sided ridge tiles were used in combination with low profile field tiles following the roofing industry practice. The highest peaks and mean values were observed on row 1, 2 and 4. A summary of the pressure coefficients obtained at critical points is given in the Table 9 below while the graphs on Appendix C. The maximum

negative peak pressure coefficient ($C_{pmin} = -10.57$) was observed at tap # 2 for 30° AOA with weather block while the positive peak ($C_{pmax} = 1.11$) occurred at tap # 28 for 75° AOA with weather block system.

Table 9 Summary of C_p values on three sided ridge tile with low profile field tile for various AOA

tap #	LOW PROFILE: Ridge tiles											
	0 deg NWB			0 deg WB			30 deg NWB			30 deg WB		
	mean C_p	max C_p	min C_p	mean C_p	max C_p	min C_p	mean C_p	max C_p	min C_p	mean C_p	max C_p	min C_p
1	-1.11	-0.33	-3.53	-1.11	-0.13	-3.81	-2.30	-0.57	-5.57	-2.98	-0.89	-8.41
2	-1.12	-0.26	-3.58	-1.13	-0.10	-3.40	-2.67	-0.78	-6.87	-3.60	-1.07	-10.57
3	-1.12	-0.16	-3.65	-1.16	-0.18	-3.70	-2.51	-0.77	-6.20	-2.63	-0.73	-7.62
4	-1.16	-0.26	-3.65	-1.18	-0.12	-4.19	-2.32	-0.73	-6.25	-2.24	-0.66	-7.14
5	-1.19	-0.29	-3.72	-1.20	-0.17	-4.46	-2.23	-0.65	-6.49	-2.17	-0.63	-6.13
6	-1.21	-0.30	-3.75	-1.27	-0.19	-3.89	-1.46	-0.41	-4.84	-1.36	-0.29	-4.27
7	-1.34	-0.31	-3.58	-1.47	-0.31	-4.26	-1.02	0.05	-3.44	-0.93	0.16	-3.18
8	-1.05	0.08	-4.65	-1.06	0.46	-4.38	-1.51	-0.33	-5.83	-1.35	-0.11	-4.20
9	-1.07	0.08	-4.06	-1.08	0.25	-4.21	-1.78	-0.28	-5.34	-1.78	-0.32	-6.27
10	-1.04	0.21	-3.48	-1.06	0.02	-4.01	-1.72	-0.15	-5.48	-1.78	-0.28	-5.25
11	-1.02	0.47	-3.78	-1.03	0.07	-3.53	-1.42	0.16	-3.97	-1.47	-0.33	-4.83
12	-1.08	0.54	-3.95	-1.07	0.22	-4.27	-1.85	-0.08	-6.19	-2.05	-0.30	-7.11
13	-1.04	0.42	-4.41	-1.04	0.35	-4.36	-1.46	0.06	-4.44	-1.60	-0.15	-4.76
14	-1.00	0.61	-4.18	-1.02	0.17	-5.63	-0.83	0.51	-3.19	-0.82	0.13	-3.55
22	-0.64	0.57	-2.62	-0.66	0.60	-2.69	-1.14	-0.18	-3.71	-1.19	-0.28	-4.31
23	-0.68	0.59	-3.70	-0.70	0.70	-5.11	-1.80	-0.32	-4.80	-1.71	-0.40	-4.31
24	-0.67	0.38	-3.25	-0.70	0.45	-3.27	-1.71	-0.37	-4.49	-1.62	-0.23	-3.95
25	-0.67	0.48	-3.31	-0.69	0.43	-3.49	-1.48	-0.28	-4.14	-1.46	-0.18	-3.52
26	-0.75	0.42	-3.55	-0.78	0.58	-3.26	-2.14	-0.28	-6.37	-2.12	-0.44	-6.43
27	-0.75	0.51	-3.67	-0.79	0.81	-3.79	-1.12	0.06	-3.64	-1.11	0.05	-3.46
28	-0.78	0.45	-3.11	-0.81	0.62	-3.61	-0.63	0.14	-2.71	-0.65	0.21	-2.09

	LOW PROFILE: Ridge tiles											
	45 deg NWB			45 deg WB			75 deg NWB			75 deg WB		
tap #	mean	max	min	mean	max	min	mean	max	min	mean	max	min
	Cp	Cp	Cp	Cp	Cp	Cp	Cp	Cp	Cp	Cp	Cp	Cp
1	-2.88	-0.29	-7.08	-3.32	-0.29	-9.10	-0.34	0.08	-1.42	-0.29	0.16	-1.11
2	-3.36	-0.22	-8.46	-3.78	-0.29	-11.10	-0.38	0.09	-1.25	-0.33	0.10	-1.13
3	-2.45	-0.26	-7.23	-2.42	-0.35	-6.65	-0.42	0.06	-1.28	-0.38	0.07	-1.29
4	-2.08	-0.27	-6.70	-2.03	-0.30	-5.44	-0.56	0.00	-1.71	-0.50	0.03	-1.68
5	-2.20	-0.26	-5.90	-2.22	-0.30	-5.55	-0.91	-0.02	-2.93	-0.78	0.04	-2.73
6	-1.46	-0.12	-3.46	-1.43	-0.20	-3.45	-0.36	0.13	-1.30	-0.26	0.29	-1.28
7	-0.74	0.43	-2.41	-0.70	0.10	-2.33	-0.04	1.02	-0.89	0.03	0.91	-0.82
8	-1.92	-0.11	-6.35	-1.74	-0.08	-5.85	-0.35	0.20	-1.40	-0.30	0.10	-1.40
9	-2.71	-0.17	-6.83	-2.67	-0.24	-7.32	-0.39	0.29	-2.51	-0.31	0.22	-1.54
10	-2.70	-0.16	-6.67	-2.68	-0.25	-7.30	-0.45	0.26	-2.04	-0.35	0.26	-1.62
11	-2.19	-0.19	-5.30	-2.21	-0.30	-5.53	-0.49	0.25	-2.08	-0.35	0.18	-1.76
12	-3.19	-0.38	-5.80	-3.38	-0.36	-6.10	-0.54	0.08	-2.99	-0.38	0.11	-2.39
13	-2.35	-0.46	-6.03	-2.45	-0.38	-6.63	-0.47	0.13	-2.38	-0.34	0.14	-1.65
14	-0.95	0.49	-3.00	-0.96	0.18	-2.90	-0.24	0.98	-1.80	-0.15	0.63	-1.05
22	-1.81	-0.18	-5.35	-1.89	-0.25	-5.69	-0.35	0.12	-1.45	-0.32	0.12	-1.90
23	-3.00	-0.02	-7.75	-2.66	-0.18	-6.92	-0.40	0.28	-1.76	-0.36	0.21	-2.02
24	-2.80	-0.17	-6.70	-2.52	-0.29	-6.31	-0.44	0.20	-1.70	-0.39	0.19	-2.05
25	-2.48	-0.27	-5.91	-2.36	-0.29	-5.58	-0.49	0.26	-2.33	-0.45	0.10	-2.25
26	-3.70	-0.71	-5.44	-3.59	-0.47	-8.01	-0.55	0.03	-3.15	-0.49	0.10	-2.88
27	-1.95	-0.40	-5.00	-1.93	-0.33	-4.86	-0.33	0.22	-1.61	-0.26	0.27	-1.48
28	-1.09	0.00	-3.78	-1.12	0.19	-3.30	-0.34	0.53	-2.24	-0.23	1.11	-1.31

	LOW PROFILE: Ridge tiles													
	90 deg NWB			90 deg WB					90 deg NWB			90 deg WB		
Ta	mean	max	min	mean	max	min		Ta	mean	man	min	mean	max	min
p #	Cp	Cp	Cp	Cp	Cp	Cp		p #	Cp	Cp	Cp	Cp	Cp	Cp
1	-0.29	0.21	-1.41	-0.34	0.13	-1.28		12	-0.64	0.16	-3.96	-0.45	0.06	-3.85
2	-0.30	0.20	-1.36	-0.35	0.06	-1.15		13	-0.61	0.13	-2.49	-0.44	0.13	-2.80
3	-0.35	0.20	-1.39	-0.40	0.07	-1.34		14	-0.39	0.43	-1.94	-0.22	0.49	-1.49
4	-0.45	0.12	-1.70	-0.50	0.04	-1.76		22	-0.42	0.06	-2.03	-0.38	0.10	-1.94
5	-0.55	0.11	-2.37	-0.60	0.05	-2.22		23	-0.46	0.10	-2.14	-0.48	0.14	-2.68
6	-0.27	0.22	-1.33	-0.26	0.24	-1.13		24	-0.50	0.09	-2.11	-0.53	0.12	-2.33
7	-0.15	0.60	-1.06	-0.10	0.64	-0.84		25	-0.55	0.13	-2.79	-0.60	0.06	-2.30
8	-0.43	0.11	-1.74	-0.35	0.05	-1.61		26	-0.61	0.06	-2.94	-0.65	0.05	-3.80
9	-0.47	0.23	-2.67	-0.38	0.33	-1.91		27	-0.43	0.13	-1.84	-0.38	0.29	-1.77
10	-0.50	0.28	-2.27	-0.40	0.23	-2.06		28	-0.47	0.42	-2.61	-0.34	0.50	-1.64
11	-0.57	0.12	-2.38	-0.42	0.10	-2.45								

4.9 Effect of weather blocking on ridge tiles

External $C_{p_{\text{mean}}}$ and $C_{p_{\text{min}}}$ were compared both for NWB and WB cases for various wind angles of attacks (AOA). When used with low profile field tiles, the three sided ridge tiles showed similar peak (negative) pressures with WB compared to NWB or marginally higher (Fig 31). Similar pattern was observed of mean C_p values (Fig. 32). Barrel ridge tiles installed with both high and medium profile tiles showed, similar C_p values for NWB and WB cases as shown in Figs 33 and 34 with medium and high profile field tiles respectively.

Three sided ridge tiles

(b) graphs for $C_{p_{\text{min}}}$ at 75° AOA for WB and NWB on LP for taps 1 to 14
Figure 31 Comparison of external $C_{p_{\text{min}}}$ values for WB and NWB cases on LP field tiles.

(a) $C_{p\text{mean}}$ at 0° AOA for WB and NWB on LP for taps 1 to 14

(c) $C_{p\text{mean}}$ at 75° AOA for WB and NWB on LP for taps 1 to 14

Figure 32 Comparison of external $C_{p\text{mean}}$ values for WB and NWB cases on low profile field tile.

Barrel tiles used with medium profile field tiles

(a) $C_{p\text{min}}$ at 75° AOA for WB and NWB on MP for taps 1 to 14

(c) $C_{p_{mean}}$ at 75° AOA for WB and NWB on MP for taps 1 to 14

Figure 33 Comparison of external $C_{p_{mean}}$ values for WB and NWB cases on medium profile field tiles.

Barrel ridge tiles used with high profile field tiles

(a) $C_{p_{min}}$ at 75° AOA for WB and NWB on HP for taps 1 to 14

(b) $C_{p_{mean}}$ at 75° AOA for WB and NWB on HP for taps 1 to 14

Figure 34 Comparison of external $C_{p_{mean}}$ values for WB and NWB cases on HP field tiles.

4.10 Effect of the wind angle of attack

For the two types of ridge tiles used during the study (barrel and three sided), the most critical angle (the one that produces the highest peak negative pressures and the

highest suction) appears to be at 45°. For all the cases, angle 75° and 90° produce similar values of $C_{p_{mean}}$ and $C_{p_{min}}$. The variations of C_p values for different wind directions are shown in graphs in Figs 35 to 38 for the three sided and barrel ridge tiles.

(a) $C_{p_{mean}}$ at various AOA on LP for taps 1 to 14

(b) $C_{p_{min}}$ at various AOA on LP for taps 1 to 14

(c) C_p at various AOA on LP for taps 29 to 35

Figure 35 Comparison of C_p values for various AOA on three sided ridge with low profile field tile.

(a) $C_{p_{mean}}$ at various AOA on ridge for MP at taps 1 to 14

(b) $C_{p_{min}}$ at various AOA on ridge for MP at taps 1 to 14

(c) Cp at various AOA on ridge for MP at taps 29 to 35

Figure 36 Comparison of Cp values for various AOA on barrel ridge with medium profile field tile.

(a) $C_{p_{mean}}$ at various AOA on ridge for HP at taps 1 to 14

(b) $C_{p_{min}}$ at various AOA on ridge for HP at taps 1 to 14

Figure 37 Comparison of C_p values for various AOA on barrel ridge tile with high field tile.

4.11 Effect of tile shape on the external pressure on ridge

Higher peak negative pressure were observed for three sided ridge tiles used with low profile field tile compared with barrel ridge tiles that were used in combination with medium or high profile field tiles. This implies that the aerodynamics of three sided tiles is less favorable for the wind flow around the tile as shown in Figs 38 and 39. This can be attributed the sharp corners in three-sided compared to rounded barrel tiles (see Fig. 6).

(a) $C_{p_{mean}}$ at 30° AOA on ridge for various profiles at taps 1 to 14

(b) $C_{p_{min}}$ at 30° AOA on ridge for various profile at taps 1 to 14

Figure 38 Comparison of C_p values at 30° AOA on three sided ridge with low profile field tile, and barrel ridge tiles with either medium profile or high profile field tiles.

(a) $C_{p_{mean}}$ at 75° AOA on ridge for various profiles at taps 1 to 14

(b) $C_{p_{min}}$ at 75° AOA on ridge for various profiles at taps 1 to 14

Figure 39 Comparison of C_p values at 75° AOA on three sided ridge with low profile field tile, and barrel ridge tiles with either medium profile or high profile field tiles.

5. CONCLUSION

The present study investigated in detail the aerodynamic characteristics of field and ridge tiles on gable roof through a full-scale testing (Wall of Wind) on a test specimen fabricated following the prevailing construction methods and utilized the actual construction materials.

The study concluded or produced the following:-

- High resolution pressure data in the form of pressure coefficients (maximum, mean and minimum values) was generated by testing actual ridge and field tiles installed on a large scale gable roof. These tests revealed high pressure coefficients for the ridge tile compared to those for the field tiles including the corner tile for the steep slope roof (7:12) considered in the present study. Even though such differences exist, other methodologies such as those based on small-scale testing and guide-lines derived from them do not differentiate between the field tiles and ridge tiles near the ridge corner. They prescribe similar pressure values for both. This may lead to underestimation of the design wind load for ridge tiles. High resolution aerodynamic data produced in the present study that accounted for the true geometry of the tiles is expected to alleviate the underestimations, thus contributing towards loss reductions associated with roof cover failures.
- Weather blocking while useful preventing water intrusion, it increases the external pressure on the field tiles. It was observed that the WB case resulted in a higher external pressure for high profile tiles compared to medium profile tiles. Similarly, a higher external pressure on medium profile tiles was observed

compared to low profile tiles. In fact for low profile tiles, the mean C_p values were equal for the NWB and WB cases, suggesting that the blockage system has no influence on the mean external pressure on the low profile tiles. However, for high profile tiles, the external pressure coefficients are higher on the windward side when there is weather block. This can be attributed to the external pressure dissipation due to high porosities associated with high profile tile for the NWB case.

- The internal pressure underneath the high profile field tiles was higher compared to the internal pressure underneath the medium profile field tiles. Similarly, internal pressure underneath the medium profile tiles was higher than the internal pressure underneath the low profile field tiles. This is attributed to the high space behind the high profile tiles compared to medium profile, and high space underneath the medium profile tiles compared to low profile tiles. While comparing NWB case with WB, it was observed that NWB cases provide marginally higher internal pressure than WB cases. The reason for the small difference is attributed that even for WB cases there are significant porosities in discontinuous roofs such as the ones considered in the present study and the wind found its way behind the tiles. For example, internal pressure underneath the high profile field tile for the NWB and WB case were very similar, indicating the weather blocks applied at corners (ridge, eave and gable end) did not influence the internal pressure that developed underneath field tiles far from the corners. It should be noted, however, the weather block could significantly affect the tiles on the eave of the roof compared to the ones on the roof field.

- The pressure equalization that develops on external and internal side of the tiles can reduce the net pressure on the tile. However, as opposed to applying reduction factor on the design pressure (i.e. by using the reduced net pressure) it is recommended to use it as an additional safety factor. This is because during the life time of the roof the space behind the tiles could be clogged with leaves and other dirt on the roof and the internal pressure may not be available all the time.
- Ridge tiles were shown to face higher suction and thus higher wind loads than field tiles close to the ridge,
- On the ridge tiles, the highest negative peak and mean pressure coefficients are observed near to the gable end and the ridge tiles located at the central region of the ridge line were subjected to lower wind loads.
- Three sided ridge tiles used in combination with low profile field tiles saw higher peak pressure compared to the barrel ridge tiles used with medium or high profile field tiles, implying the aerodynamics of three sided tiles is less favorable.
- The project also helped to foster a very good working collaboration with the local roofing industry. This collaboration will be used in the future as a springboard to continue expanding the high resolution wind pressure data base for different roof slopes, configurations and roof construction material.

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7. APPENDICES

Appendix A:

Pressure time history

(a) Typical Pressure time history for field tiles on high profile roof (AOA =30°)

(b) Typical Pressure time history for field tiles on high profile roof (AOA =75°)

Figure A-1 Typical pressure time history on High Profile field tiles. (a) and (b)

(a) Typical Pressure time history on field tiles for Medium Profile roof (AOA =30°)

(b) Typical Pressure time history on field tiles for Medium Profile roof (AOA =75°)

Figure A-2 Typical pressure time history on Medium Profile field tiles. (a) and (b)

(a) Typical pressure time history on field tiles for low profile roof (AOA =75°)

(b) Typical pressure time history on field tiles for low profile roof (AOA=75°)

Figure C-3 Typical pressure time history on Low Profile field tiles. (a) and (b)

(a) Typical time history for ridge tiles for high profile (AOA = 30°)

(b) Typical time history for ridge tiles profile (AOA = 75°)

Figure C-4 Typical pressure time history on Ridge tiles. (a) and (b)

Appendix B:

External C_p value plots on field tiles at critical locations

The graphs of C_p values at critical points are given in figures B-1 for the case when there is Weather block and figure B-2 when there is no weather block.

(a) C_p values for 0° AOA at field taps 1 to 16 on High Profile WB

(b) C_p values for 30° AOA at field taps 1 to 16 on High Profile WB

(c) Cp values for 45° AOA at field taps 1 to 16 on High Profile WB

(d) Cp values for 75° AOA at field taps 1 to 16 on High Profile WB

(e) Cp values for 90° AOA for taps 1 to 16 on high profile WB

Figure B-1 Graph of Cp values on HP for WB at field taps for various AOA. (a to e)

(a) Cp values for 0° AOA at field taps 1 to 16 on High Profile NWB

(b) Cp values for 30° AOA at field taps 1 to 16 on High Profile NWB

(c) Cp values for 45° AOA at field taps 1 to 16 on High Profile NWB

(d) Cp values for 75° AOA for taps 25 to 40 on high profile NWB

(e) Cp values for 90° AOA for taps 1 to 8 and 33 to 40 on high profile NWB

Figure B-2 Graph of Cp values on HP for NWB at field taps for various AOA. (a to e)

(a) Cp values for 0° AOA for taps 1 to 16 on Medium profile WB

(i)

(ii)

(iii)

(b) Cp values for 30° AOA for taps 1 to 24 on Medium profile WB ((i) to (iii))

(c) Cp values for 45° AOA for taps 1 to 16 on Medium profile WB

(d) Cp values for 50° AOA for taps 1 to 8 and 17 to 24 on Medium profile WB

(e) Cp values for 75° AOA for taps 1 to 16 on Medium profile WB

(f) Cp values for 90° AOA for taps 1 to 8 and 17 to 24 on Medium profile WB

Figure B-3 Graph of Cp values on MP for WB at field taps for various AOA. (a to f)

(a) C_p values for 0° AOA for taps 1 to 16 on Medium profile NWB

(i)

(ii)

(iii)

(b) C_p values for 30° AOA for taps 1 to 24 on Medium profile NWB

(c) Cp values for 45° AOA for taps 1 to 16 on Medium profile NWB

(d) Cp values for 50° AOA for taps 1 to 8 and 17 to 24 on Medium profile NWB

(e) Cp values for 75° AOA for taps 1 to 16 on Medium profile NWB

(f) C_p values for 50° AOA for taps 1 to 8 and 17 to 24 on Medium profile NWB
 Figure B-4 Graph of C_p values on MP for NWB at field taps for various AOA. (a to f)

(a) C_p values for 0° AOA for taps 1 to 16 on Low profile WB

(b) C_p values for 30° AOA for taps 1 to 16 on Low profile WB

(c) Cp values for 45° AOA for taps 1 to 16 on Low profile WB

(d) Cp values for 75° AOA for taps 1 to 8 and 25 to 32 on Low profile WB

(e) Cp values for 90° AOA for taps 1 to 16 on Low profile WB

Figure B-5 Graph of Cp values on LP field taps WB for various AOA. (a to e)

(a) Cp values for 0° AOA for taps 1 to 16 on Low profile NWB

(b) Cp values for 30° AOA for taps 1 to 16 on Low profile NWB

(c) Cp values for 45° AOA for taps 1 to 16 on Low profile NWB

(d) Cp values for 75° AOA for taps 1 to 8 and 25 to 32 on Low profile NWB

(e) Cp values for 90° AOA for taps 1 to 16 on Low profile NWB

Figure B-6 External Cp value plots on LP field taps NWB for various AOA. (a to e)

Appendix C:

External Cp value plots on ridge tiles at critical locations

(a) Cp values for MP on ridge tiles WB at 30° row 1 and 4

(b) Cp values for MP on ridge tiles WB at 45° row 1 and 4

(c) Cp values for MP on ridge tiles WB at 50° row 1 and 4

(d) Cp values for MP on ridge tiles WB at 75° row 2 and 4

(e) Cp values for MP on ridge tiles WB at 90° row 2 and 4

Figure C-1 Graph of Cp values at ridge taps on MP for WB. (a to e)

(a) Cp values for MP on ridge tiles NWB at 30 deg row 1 and 4

(b) Cp values for MP on ridge tiles NWB at 45 deg row 1 and 4

(c) Cp values for MP on ridge tiles NWB at 50 deg row 1 and row 4

(d) Cp values for MP on ridge tiles NWB at 75 deg row 2 and 4

(e) Cp values for MP on ridge tiles NWB at 90 deg rows 2 and 4

Figure C-2 Graph of Cp values at ridge taps on MP for NWB. (a to e)

(a) Cp values for HP on ridge tiles WB at 0° for taps 1 to 14

(b) Cp values for HP on ridge tiles WB at 30° at taps 8 to 28

(c) Cp values for HP on ridge tiles WB at 45° at taps 1 to 14

(d) Cp values for HP on ridge tiles WB at 75° for taps 1 to 14

(e) Cp values for HP on ridge tiles WB at 90° row 2 and 4

Figure C-3 Graph of Cp values at ridge taps on HP for WB. (a to e)

(a) Cp values for HP on ridge tiles NWB at 0° at taps 1 to 14

(b) Cp values for HP on ridge tiles NWB at 30° at tap 1 to 14

(c) Cp values for HP on ridge tiles NWB at 45° at taps 1 to 14

(d) Cp values for HP on ridge tiles NWB at 75° for taps 1 to 14

(e) Cp values for HP on ridge tiles NWB at 90° for taps 1 to 14

Figure C-4 Graph of Cp values at ridge taps on HP for NWB. (a to e)

(a) Cp values for LP on ridge tiles WB at 0° row 2 and 4

(b) Cp values for LP on ridge tiles WB at 30° row 1 and 4

(c) Cp values for LP on ridge tiles WB at 45° row 1 and 4

(d) Cp values for LP on ridge tiles WB at 75° row 1 and 4

(e) Cp values for LP on ridge tiles WB at 90° row 2 and 4

Figure C-5 Graph of Cp values at ridge taps on LP for WB. (a to e)

(a) Cp values for LP on ridge tiles NWB at 0° row 2 and 4

(b) Cp values for LP on ridge tiles NWB at 30° row 1 and 4

(c) Cp values for LP on ridge tiles NWB at 45° row 1 and 4

(d) Cp values for LP on ridge tiles NWB at 75° row 1 and 4

(e) Cp values for LP on ridge tiles NWB at 90° row 2 and 4

Figure C-6 Graph of Cp values at ridge taps on LP for NWB. (a to e)