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EFFECT OF SPOILERS TO PRESSURE DISTRIBUTION ON BUILDING ROOF SURFACES

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Abstract: The effect of spoilers placed on the critical regions of 15° sloped gable roof of a building model on the pressure distributions was experimentally investigated in this study. The values of mean and peak pressure coefficients on the roof of the model placed in simulated atmospheric boundary layer were obtained for a variety of roof-to-spoiler apertures and wind directions. Flow separated from the leading edge of the roof attached on the windward side of the roof and re-separated from the roof ridge. The largest negative pressures on the roof surfaces occurred in the separated flow regions. Spoiler elements placed along the roof edges and roof ridge displayed noteworthy effects in the decreasing of suction loads on roof surfaces. Spoilers located with 1 mm aperture on the roof model decreased the suction loads on those regions up to 50%. It was seen that the spoilers can easily be used to reduce critical suction loads on the roofs as a new novel technique.
Keywords: Spoiler, Gable roof, Surface pressure, Wind direction

BİNA ÇATI YÜZEYLERİ ÜZERİNDEKİ BASINÇ DAĞILIMINA SPOİLERLERİN ETKİSİ

Özet: Bu çalışmada, 15° eğimli beşik çatılı bir bina modelinin çatısı üzerinde emme etkisinin kritik olduğu bölgelere yerleştirilen spoiler benzeri akış yönlendirici elemanların çatı yüzey basınç dağılımları üzerindeki etkileri deneysel olarak incelenmiştir. Rüzgar tüneli test bölgesinde oluşturulan atmosferik sınır tabaka içine yerleştirilmiş bina modelinin çatısı üzerinde, farklı çatı-spoiler açıklıkları ve rüzgar doğrultuları için ortalama ve pik yüzey basıncı ölçümleri yapılmıştır. Çatı ön kenarından ayrılan akış, rüzgar tarafındaki çatı yüzeyinde tutunmuş ve çatı sırtından itibaren tekrar ayrılmıştır. Çatı yüzeyleri üzerindeki en kritik negatif basınçlar ayrılmış akış bölgelerinde oluşmuştur. Çatı kenarı ve çatı sırtı boyunca yerleştirilmiş spoiler benzeri elemanların çatı yüzeylerindeki emme yüklerini azaltmada önemli bir etkiye sahip olduğu görülmüştür. Çatı yüzeylerinde basıncın negatif pik değerler aldığı kritik bölgelere yerleştirilen 1 mm açıklığa sahip spoiler benzeri elemanlar, bu bölgelerde meydana gelen emme yükünü %50 ye varan bir oranda azaltmıştır. Spoiler benzeri elemanların çatı üzerindeki kritik emme yüklerini azaltmada yeni bir teknik olarak kullanılabileceği görülmüştür.
Anahtar Kelimeler: Spoiler, Beşik çatı, Yüzey basıncı, Rüzgar doğrultusu

NOMENCLATURE

Cp	Pressure coefficient [$\Delta P / (\rho U_o^2/2)$]
Cport	Mean pressure coefficient
Cprms	RMS pressure coefficient
Cpmax	Maximum pressure coefficient
Cpmin	Minimum pressure coefficient
H	Model height [m]
L	Model length [m]
ΔP	Difference between the surface pressure and the atmospheric pressure [N/m^2]
P	Pressure [N/m^2]
P_o	Atmospheric pressure [N/m^2]
Re	Reynolds number [U_oH/υ]
U_o	Free stream velocity [m/s]
u	Velocity components in x direction [m/s]
$\sqrt{\overline{u^2}}$	Turbulent velocity in x direction [m/s]
v	Velocity components in y direction [m/s]
W	Model width [m]
x	Horizontal coordinate
y	Vertical coordinate
δ	Boundary layer thickness [m]
α	Roof slope [°]
θ	Wind angle [°]
υ	Kinematic viscosity [m^2/s]
ρ	Density of air [kg/m^3]
n	Power

INTRODUCTION

The roofs of buildings such as houses and factories which are structured horizontally are built in different geometries with traditional kinds. The events related to the roof aerodynamics such as the dynamic loads on buildings and on their roofs, the vibrations originating from vortex shedding and the collapse or moving of roofs are caused from the changing atmospheric condition. The loading effects of the natural wind on buildings are rather complicated in interactive process between the wind flow and the various components of the building. Damage to buildings results from aerodynamic wind pressure that develop as air flow over and around the building. According to a damage investigation, most wind damage to houses is restricted to the envelope of buildings, in particular to the roof sheathing. For this reason, it is very important to understand sufficiently the wind effects on low-rise buildings, and in particular, on roof sheathing. Wind tunnel experimentation plays an important role in the evaluating of design roof wind loads. Wind tunnel studies concerning the determination of wind loads on low rise building roofs began in the middle of 1960s and have become widespread now days with the development of simulation techniques. Due to the increasing investigations in the experimental and numerical methods, more detail information about flow fields on buildings has been obtained. Studies related to the understanding of flow field around 3D obstacles have aimed the determination of the influence of inlet flow characteristics on pressure distributions. An experimental study to investigate flow field around a cube mounted surface for laminar and turbulent flow conditions was conducted by Castro and Robin (1977). Sockel and Taucher (1981) investigated wind effects on prismatic building models with flat roofs immersed turbulent boundary layer in wind tunnel. They measured mean velocity, turbulence and surface pressure in the reverse flow regions to found a relation between velocity and pressure data. Kind (1988) displayed that the most critical suction values were mostly same for low, middle and high building configurations and occurred on the small regions of roof edges. Saathoff and Melbourne (1989) examined the peak pressures on the roofs and noted that increment in flow turbulence has increased peak values of pressure distribution. Ginger and Letchford (1992) measured local and area-averaged pressures on the 1:100 scaled roof model in the wind tunnel and found that critical mean and minimum suctions occurred in the shear layer. Kawai and Nishimura (1996) evaluated wind loads on a flat roof for the uniform and turbulent flow conditions and they concluded that the most critical suction occurred on the windward roof corners for oblique wind direction because of conical vortex. Kumar and Stathopoulos (1998) performed pressure measurements on low rise building models immersed in an atmospheric boundary layer for different terrain types and obtained wind pressure spectra. They noted that wind spectra was effected from terrain condition. Studies concerning the investigation of flow fields around the buildings have focused on the pressure measurements. A literature review related to the wind pressures on low rise building was presented by Uematsu and Isyumov (1999). Ginger *et al.* (2000) determined the mean and peak pressure distribution on the roof of a typical low rise building with 1:50 scaled wind tunnel study. They found that the most critical wind loads occurred near the leading edge of the roof because of the flow separation on the windward side of the roof.

Studies on the effect of parapet on the roofs are generally experimental in the literature. An experimental study for the evaluation of wind loads on the low-rise building roofs with parapets was performed by Stathopoulos (1982). Wind effects on flat roofs with and without parapets for open country and urban terrain conditions were investigated by Stathopoulos and Baskaran (1987). They measured local and area-averaged pressures on roofs by taking building and parapet height as geometric parameters for various wind direction and concluded that parapets generally decreased critical suctions on the roof edges but increased on the middle roof surfaces. Kareem and Lu (1992) obtained mean and fluctuating pressure distribution on a square cross section building roof. They used parapet walls with two different heights for the rural and urban terrain conditions and concluded that parapets affected mean and peak pressure distribution on the roof. Kopp *et al.* (2005) examined the effects of the parapets on the wind-induced loads on the roof corners of low-rise buildings with pressure measurements. They found that the parapets altered the suction loads on the roof by changing the location of the corner vortex relative to the roof. Mans *et al.* (2005) carried out a set of pressure measurements on parapet surfaces to analyze the effect of parapets on wind-induced loads on low-rise buildings. They noted that the worst structural load coefficients over all wind angles were approximately constant with the same ratio of the parapet and building heights because of opposing trends of the pressures on the interior and exterior parapet surfaces. Karimpour and Kaye (2013) investigated parapet height role on the roof gravel blow-off rate for low rise buildings with a new experimental technique.

Parapets are very effective in reducing the magnitude of local suctions near the leading edges on building roofs. This feature is related to the fact that parapets lift up the separated shear layer in normal winds. Reducing of wind induced loads is necessary for the design of the roofs and the knowledge of the effects of architectural details on these loads is also of interest. It is also important to control both the location and magnitude of these loads. This study has suggested a new alternative technique to the parapets to reduce critical suction loads on the roofs. In the present study, the effect of spoiler elements placed on the critical regions of gabled roof of a building model has been investigated with the pressure measurements.

EXPERIMENTAL STUDY

The experiments were carried out in a low speed, open circuit wind tunnel at the Karadeniz Technical University. The wind tunnel had a working section of 457 mm wide, 457 mm high and 2450 mm long. The combination of barrier, vortex generators and roughness elements at the entrance to the test section was used to simulate atmospheric boundary layer (power-law exponent, n=0.2) over a city suburb. Model was constructed to a geometric scale of 1:65. A turbulent boundary layer of 150 mm thickness was obtained at the free stream velocity of 15 m/s, giving a Reynolds number based on building height of Re=65000. Figure 1 indicates a schematic diagram of the wind tunnel test-section and the measurement system. δ and H represent the boundary layer thickness and characteristic height of model, respectively. The ratio of boundary layer thickness to model height (δ/H) is 2.3. The mean and fluctuating surface pressure measurements were conducted with a measurement chain system consisting of the components of signal conditional module, Setra 239 pressure transducer, A/D converter, package and computer. The output of the pressure transducer was fed through a signal conditioning unit before being digitized and recorded. The signals from the transducer were sampled at a rate of 1000 samples per second for a period of 16 s and data were low-pass filtered at 300 Hz. The mean and fluctuating velocity measurements at the reference boundary layer were performed with TSI IFA 100 constant-temperature anemometer and TSI model 1211 hot-film probe.

A gabled roof model with slope of 15° with the distribution of measurement taps on its surfaces are shown in Figure 2. The model made of plexiglas was H=65mm height, L=202 mm length and W=106 mm width. The model was placed at a distance of 4H from the reference boundary layer. As stated by Oliveira and Younis (2000), this distance must be at least 3H because reference boundary layer must not be affected from existence of model. To measure pressure distributions on the roof, 82 pressure taps of 15 mm long pieces with 1.6 mm external diameter and 1 mm internal diameter stainless-steal tubing were inserted into the holes drilled in the plexiglas. Corner, edge and ridge regions of the building roofs are more exposed to the critical suction effects because of the flow separation. Hence, the pressure taps were intensified on these critical parts of the roof for this study. The model was rotated from 0° to 360° wind angle (θ) with 15° increment in clockwise direction to conduct measurements over the entire roof. Symmetry was invoked to reduce the number of measurements. Spoilers aiming to decrease suction loads on the roof surfaces were 10 mm width and 1 mm thickness and were parallel placed on both sides of the roof ridge and edges of the model. Surface pressure measurements were conducted for apertures of 1, 3 and 5 mm between roof surfaces and spoilers. Measurements were performed at the spacing of 15° wind angle along the mid-axis of the model. A scanning valve was used to supply linkage from pressure taps to pressure transducer. All pressure taps were connected to the scanning valve using the vinyl tubing of 60 cm lengths and 1 mm inside diameter. The pressure difference between the local surface pressure (P) and the static pressure (Po) was divided by the reference dynamic pressure at a equivalent height to give pressure coefficient Cp expressed as $Cp=(P-Po)/0.5\rho Uo^2$, where Uo was the free-stream velocity and ρ was the air density. Ambient temperature and atmospheric pressure were continuously recorded during the experiments to identify changes in the air density. The blockage ratio defined as the ratio of the projected model area to the cross-sectional area of test section was about 7.3%. Kirrane and Steward (1978) noted that ground-mounted models were less susceptible to blockage effect and

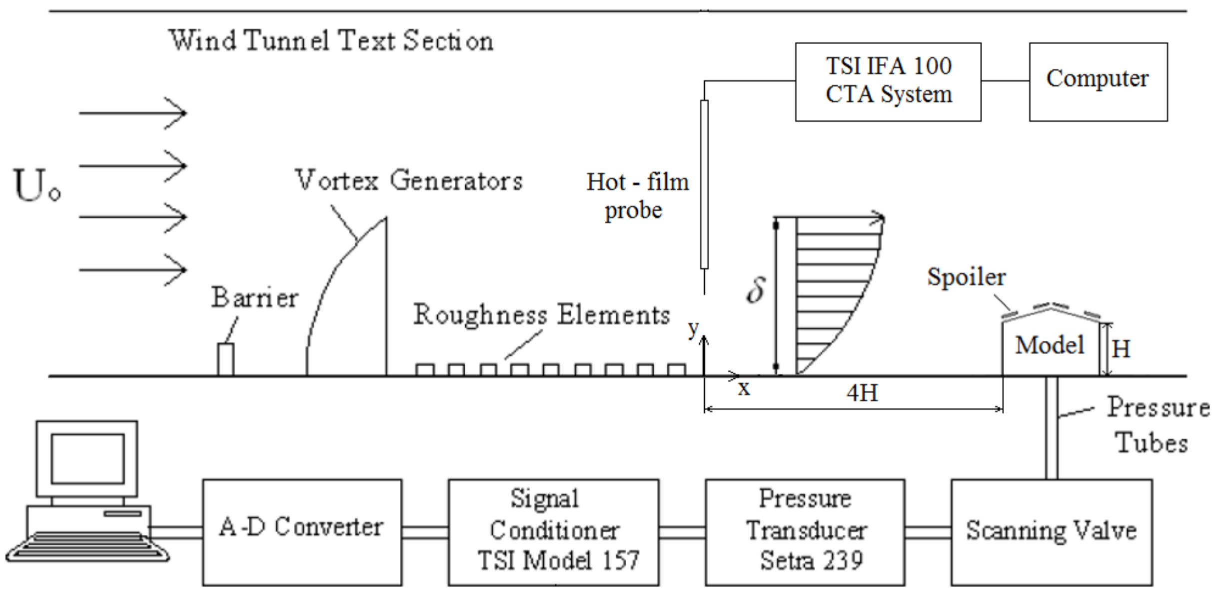
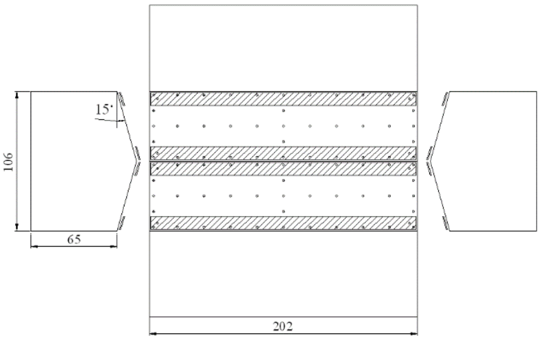
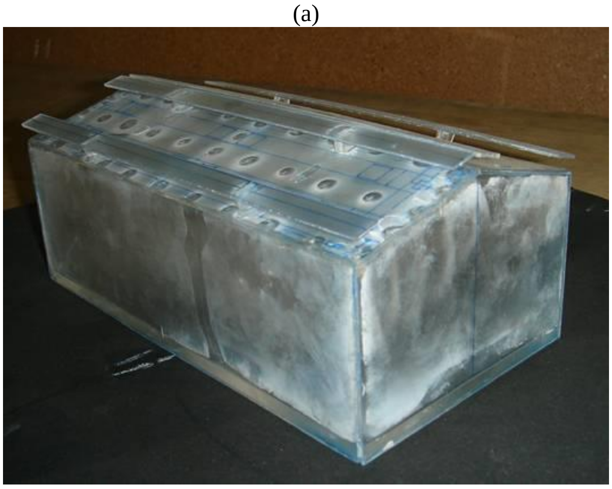


Figure 1. Wind tunnel test section and pressure measurement system

10% blockage might be acceptable without correction. But some other researchers regarded 5% as the safe limit for blockage (Cook, 1990). Correction for the effect of the wind tunnel blockage was made in this study. A semi-empirical model derived by Maskell (1965) was used for the blockage correction. Correction equation was based on correction of the dynamics pressure increment around the model by using momentum balance within a control volume. It was seen that pressure distributions on the roof surfaces were not affected from blockage correction. A method presented by Kline and McClintock (1953) was used for the calculating uncertainty in experimental results. The uncertainties in the measurements of the axial mean velocity and axial turbulence velocity were found to be less than ±2.07% and ±4%, respectively. Mean and fluctuating pressures have a corresponding calculated uncertainty of ±3.06% and ±4.6%, respectively. The experimental results were reliable within these uncertainty ranges.



(a)



(b)

Figure 2. Gabled roof building model (a) Schematic of the model (b) Picture of the model

RESULTS AND DISCUSSION

The mean velocity and turbulence intensity profiles of the stream wise velocity components measured at the reference boundary layer are shown in Figure 3. It was seen that the mean velocity profile in the reference boundary layer agreed well with the power law of n=0.2 and the turbulence intensity near the wall reaches up to 11%.

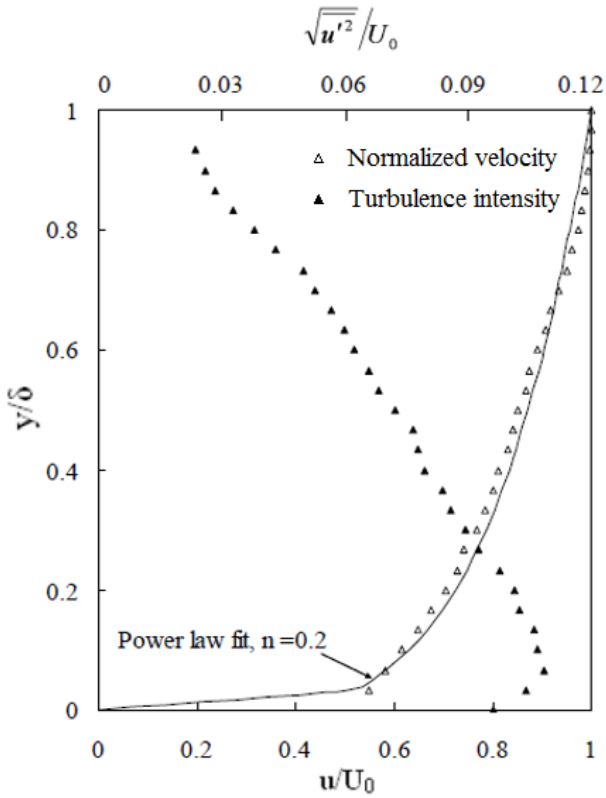


Figure 3. Profiles of mean velocity and turbulence intensity

The resulting data consisted of maximum, minimum, mean and root-mean-square values of pressure coefficients which were normalized by the mean dynamic velocity pressure of the free stream. The variations of the mean and the minimum pressure coefficients measured along the roof mid-axis for the roof-to-spoiler apertures of 1, 3 and 5 mm are presented together with those obtained from non-spoiler configuration in Figure 4a and b. Negative pressure fields occurred on the roof because of flow separated from the leading edge of the roof. The flow separating from the leading edge of the roof attached on the windward side of the roof and then re-separated from the roof ridge. The largest negative pressures occurred in the separation flow regions were progressively reduced in magnitude in the reattachment regions. The mean pressure distribution along the mid-axis of gable roof was also compared with the measurements of Easom (2000) in Figure 4a. There was a good accordance between the mean pressure distributions. As can be shown in Figure 4a, the spoilers decreased the suction on the roof ridge about 16% for 5 mm spacing and 27% for 3 mm spacing, without making any effect on the windward edge of the roof. For the spacing of 1 mm, the spoilers caused a reducing effect on both the roof edge and the roof ridge up to 50%. This reduction was because of the fact that spoilers tend to prevent flow separation on the roof surfaces. Similar findings are shown for minimum pressure coefficients in Figure 4b. Minimum values of fluctuating pressures denoting the magnitude of suction effect were smaller than the mean values around 25%. To reduce suction effects on roofs various parapet configurations located near

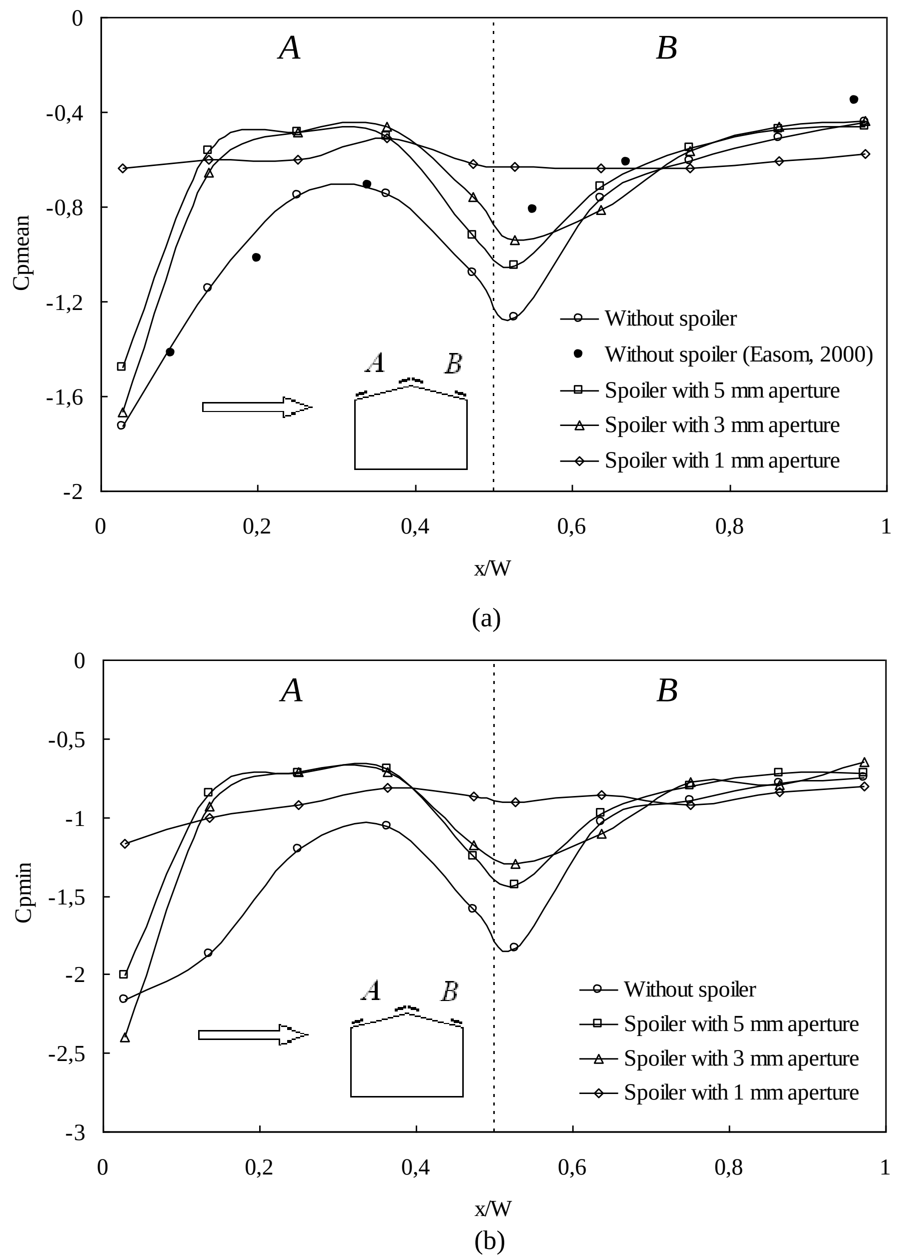


Figure 4. Variation of pressure coefficients along the roof mid-axis for different spoiler apertures (a) mean (b) minimum

the roof edges were used in the literature. Sockel and Taucher (1981) pointed that parapet height having % 2 of the building height attenuated suction effects at the rate of 50%. These results showed that the spoilers were an alternative solution to the parapets to reduce suction effects on the building roofs.

Figure 5a and b illustrate the variation of pressure coefficient with the wind direction at the critical tap 1 on the roof corner for the roof with 1 mm spoiler aperture and without spoilers, respectively. While the most critical minimum pressure coefficient occurred between the wind directions 75° and 90° as -1.52 for the roof with spoiler (Figure 5a), it was about -2.71 at the wind direction of 75° for the roof without spoiler (Figure 5b). It was seen that the 1 mm spoiler aperture decreased minimum peak pressures about 44%. Wind angles causing critical suction effects also increased rms values.

Figure 6a and b show the variation of pressure coefficient with the wind directions at the critical tap 2 on the roof ridge corner for the roof with 1 mm spoiler aperture and without spoilers, respectively. The largest minimum peak pressure coefficient was -1.9 for 345°wind direction on the roof with spoiler (Figure 6a) and the most critical minimum pressure coefficients obtained as -2.60 and -3.07 for the wind directions of 45° and 315° on the roof without spoilers (Figure 6b). It was noted that spoiler elements with 1 mm aperture attenuated the minimum peak pressures on the roof ridge corner up to 38%. There was a symmetrical behavior for the pressures measured on the roof ridge corner with respect to the wind angle.

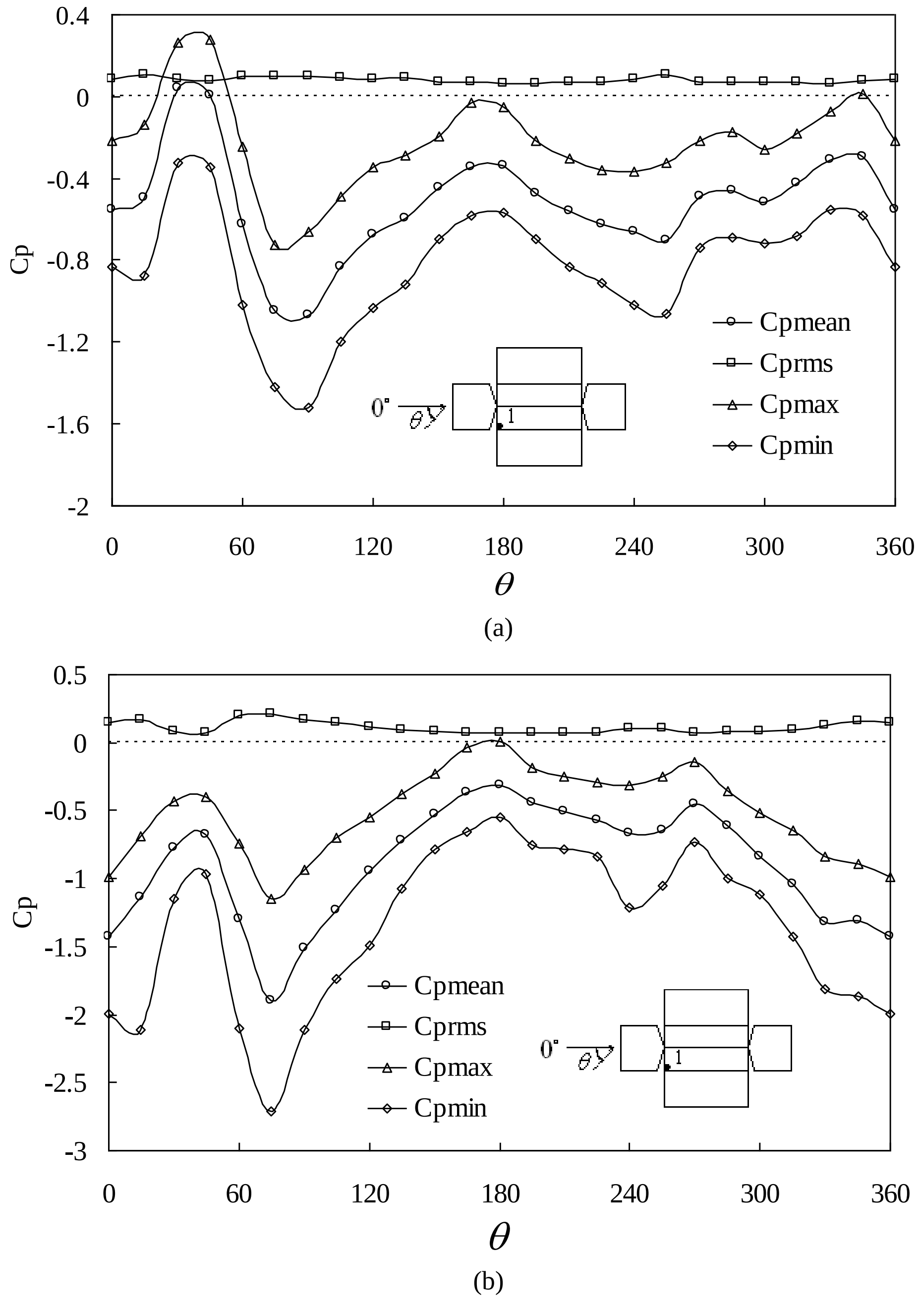


Figure 5. Distribution of the local pressure coefficients with wind direction on the 15° sloped roof corner (a) roof with 1 mm spoiler aperture (b) roof without spoiler

Figures 7 displays the variation of local mean and minimum pressure coefficients on roof surfaces as contour at the wind direction of 0° for the roof with 1 mm spoiler aperture and without spoilers, respectively. Only the negative values were observed on the roof surfaces which represented suctions or pressures exerted in an outward direction. Critical negative pressures were obtained on the windward part of the roof. The mean and minimum pressure coefficients on the roof surface varied between -0.9 and -0.3 and between -1.0 and -0.70 for 0° wind direction with 1 mm spoiler aperture (Figure 7a). For 0° wind direction and the roof without spoilers, mean pressures varied between -1.30 and -0.30 and minimum pressure coefficients were between -1.50 and -0.8 (Figure 7b). These results showed that the spoilers decreased the suction loads on the windward roof region at the rate of 30% for wind direction of 0°.

Figures 8 shows the variation of local mean and minimum pressure coefficients on roof surfaces as contour at the wind direction of 90° for the roof with 1 mm spoiler aperture and without spoilers, respectively. Suction effects on the windward side of the roof were more critical than the leeward part of the roof surface. For 90° wind direction with 1 mm spoiler aperture, while the mean and the minimum pressure coefficients were -0.65 and -1.0 on the windward surface of the roof, they were -0.60 and -0.86 on the leeward surface of the roof (Figure 8a).

For the case without spoiler, in the same wind direction, as the pressure coefficients were -0.80 and -1.30 for mean and -1.40 and -1.90 for minimum on the windward surface, they were -0.60 and -1.10 for mean and -1.20 and -1.70 for minimum on the leeward surface (Figure 8b). These results also showed that the spoilers decreased the suction loads on the windward roof region at the rate of 50% for wind direction of 90°. Finally, these findings denoted that spoiler elements attenuated the suction effects especially on leading and rearing edges of the roof and formed uniform pressure field along the roof surfaces. In all cases, the spoilers tended to reduce the roof pressure.

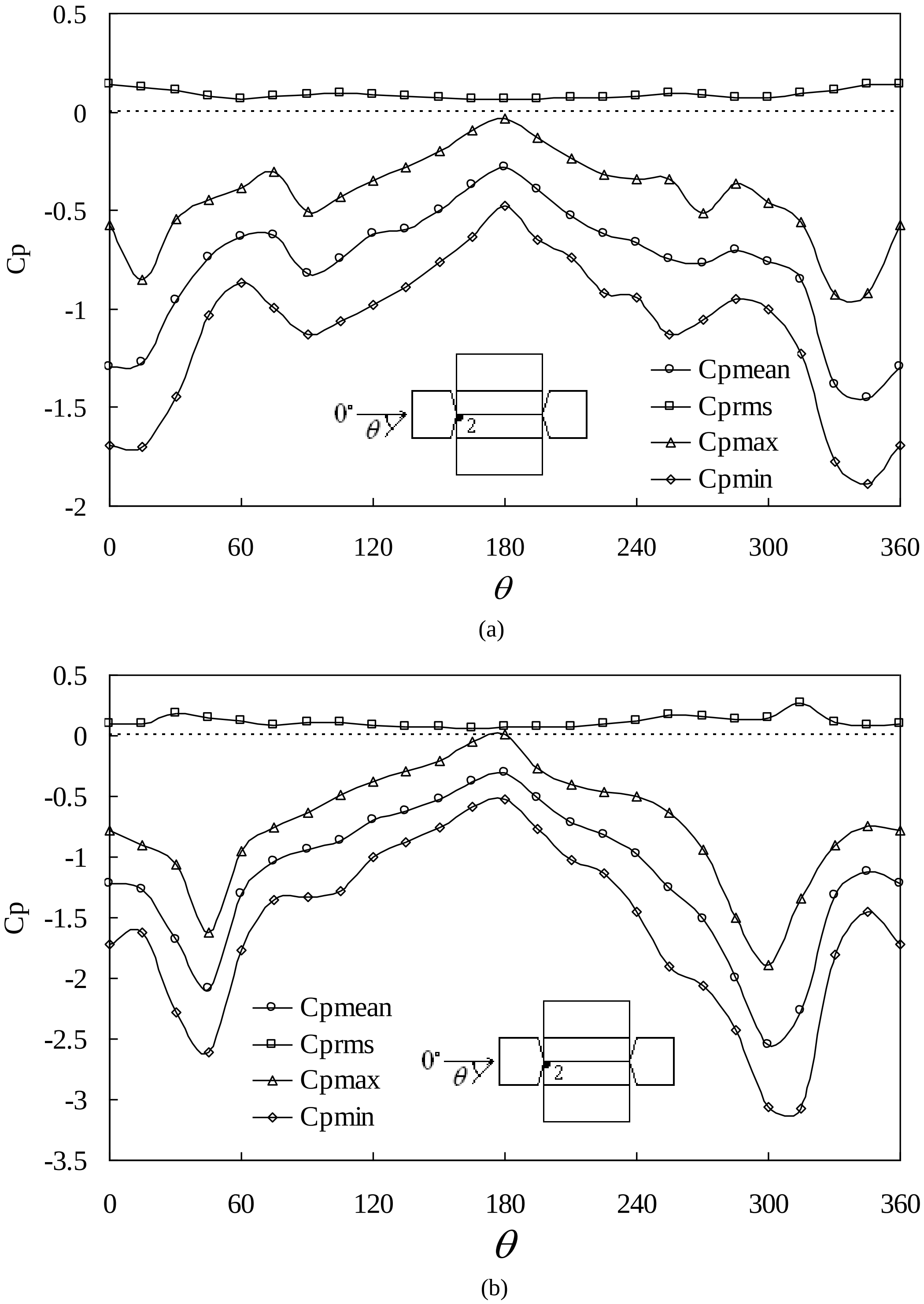


Figure 6. Distribution of the local pressure coefficients with wind direction on the 15° sloped roof ridge corner (a) roof with 1 mm spoiler aperture (b) roof without spoiler

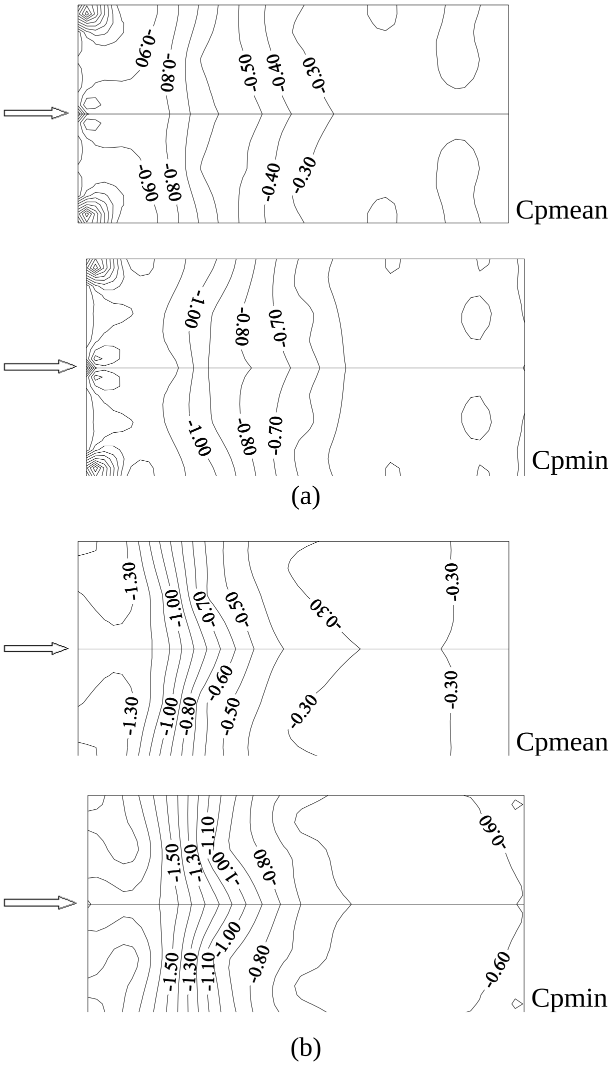


Figure 7. Contour of pressure coefficients on 15° sloped roof surfaces for θ = 0° (a) roof with 1 mm spoiler aperture (b) roof without spoiler

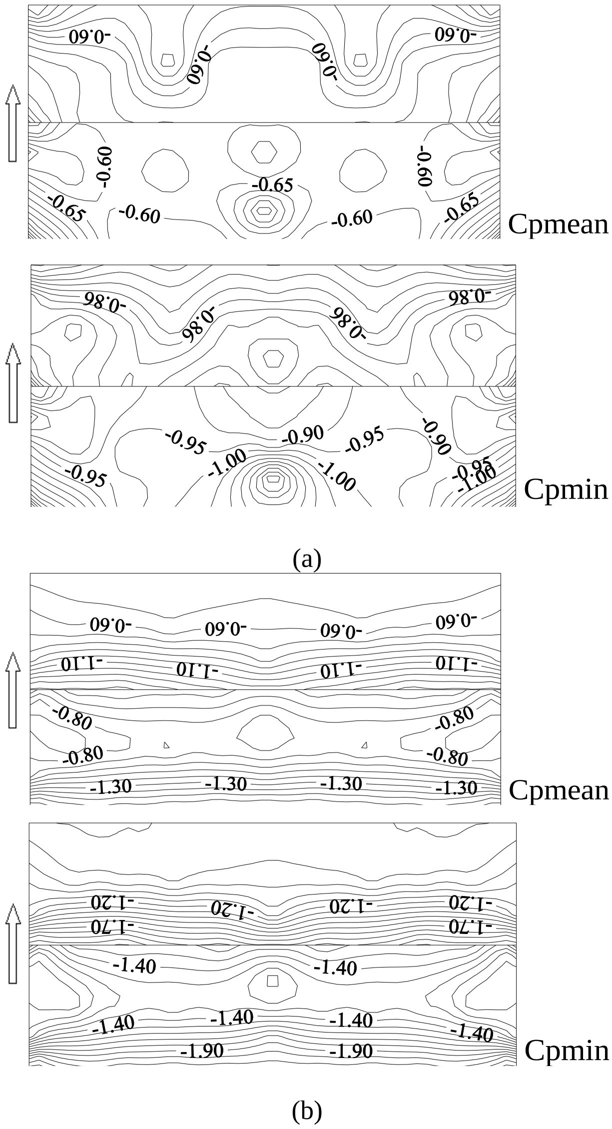


Figure 8. Contour of pressure coefficients on 15° sloped roof surfaces for θ = 90° (a) roof with 1 mm spoiler aperture (b) roof without spoiler

CONCLUSION

In this study, the effect of spoilers placed on the critical regions of 15° sloped gable roof of a building model on pressure distributions were experimentally investigated. Mean and minimum pressure distributions due to wind on the roof were obtained for different spoiler apertures. Flow separated from leading edge of roof attached on the windward side of the roof and re-separated from roof ridge. The largest negative pressures occurred in the separated flow regions. Pressure coefficients were negative on the all of the roof and reverse flow regions occurred on the front part of the windward roof and leeward roof. The highest suction load on the roof corner occurred at the wind angle of 75°. The most critical minimum pressure coefficient for all of the measurements was -3.07 near the windward roof ridge corner at the wind angle of 315° for without spoiler case. Minimum values of fluctuating pressures denoting the magnitude of suction effect were 25% more critical than the mean values. The pressure distributions on the roof were significantly influenced by the spoiler aperture. Spoiler elements placed along the roof ridge and roof edges displayed noteworthy effects in the decreasing of suction loads on roof surfaces. Hence, they can be used to reduce critical suction loads on the roofs as a new novel technique. Suction effect decreased with decreasing spoiler aperture. Spoilers located with 1 mm aperture on the 15° sloped roof model attenuated the suction loads on both leading edges of the roof and on roof ridge up to 50%. This reduction was because of the fact that spoilers tend to prevent flow separation on the roof surfaces. The width and aperture of spoiler elements corresponded to 60 cm and 6 cm in the full–scale building since 1 mm aperture between roof surfaces and spoiler elements equaled to 1/65 of building model height. For further studies on this area, full–scale measurements can be performed for comparison of results between model and full-scale. Additionally, the testing of different arrangements can give more useful results.

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