Wind and Structures, Vol. 6, No. 2 (2003) 91-106
DOI: http://dx.doi.org/10.12989/was.2003.6.2.091

Wind tunnel modeling of roof pressure and turbulence effects on the TTU test building

Bogusz Bienkiewicz†

Wind Engineering and Fluids Laboratory, Department of Civil Engineering Colorado State University, Fort Collins, CO 80523, USA

Hee J. Ham‡

Division of Architecture, Kangwon National University, Chuncheon 200-701, Korea
(Received February 5, 2000, Accepted August 30, 2002)

Abstract. The paper presents the results of 1:50 geometrical scale laboratory modeling of wind-induced point pressure on the roof of the Texas Tech University (TTU) test building. The nominal (prevalent at the TTU site) wind and two bounding (low and high turbulence) flows were simulated in a boundary-layer wind tunnel at Colorado State University. The results showed significant increase in the pressure peak and standard deviation with an increase in the flow turbulence. It was concluded that the roof mid-plane pressure sensitivity to the turbulence intensity was the cause of the previously reported field-laboratory mismatch of the fluctuating pressure, for wind normal and 30°-off normal to the building ridge. In addition, it was concluded that the cornering wind mismatch in the roof corner/edge regions could not be solely attributed to the wind-azimuth-independent discrepancy between the turbulence intensity of the approach field and laboratory flows.

Key words: wind tunnel modeling; wind turbulence, low-rise buildings; flat roofs; incident wind angles; suctions; pressure fluctuations.

1. Introduction

One of the objectives of the collaborative research of the Colorado State University/Texas Tech University Cooperative Program in Wind Engineering (CPWE) was to assess the existing and develop new techniques for physical modeling in wind tunnels of wind loading on low-rise structures. Research effort focused on this objective and carried out at Colorado State University (CSU) included: evaluation of turbulent boundary-layer wind modeled using "standard" wind-tunnel techniques, development of new flow modeling devices for studies of wind effects on low-rise buildings, measurement of point and area-averaged external building pressure, evaluation of building internal pressure, and others. Geometrical scales employed in this effort ranged from 1:100 through 1:25. The modeled target approach flow was the wind prevalent at the Texas Tech University (TTU) field site, denoted herein as the nominal flow. Wind-induced pressure was

† Professor
‡ Assistant Professor, Formerly at Wind Engineering and Fluids Laboratory, Colorado State University

measured on models of the TTU test building and other generic low-rise buildings.

Over the years, a number of wind tunnel studies of the TTU building were undertaken at various laboratories (Tieleman *et al*. 1996, Lin *et al.* 1995, Xu 1995, Rofail 1994, Jamieson and Carpenter 1993, Okada and Ha 1992, Surry 1991, and others). Overall, the researchers reported a good agreement between the laboratory and field wind pressure induced on the exterior surface of the TTU building. For the cornering approach wind, however, it was found that laboratory peak suctions in roof corner/edge areas were lower than those measured during field observations. This laboratory-field discrepancy was attributed to a number of factors: inadequate laboratory modeling of turbulence characteristics of the approach wind (lateral and vertical turbulence intensity, integral scale of turbulence, small-scale turbulence), Reynolds number effects, instrumentation limitations (frequency response of the pressure measurement system, size of pressure taps), and others. Although a number of studies were carried out, the issue of the laboratory-field mismatch remains unresolved and it continues to be a subject of ongoing research and discussion in the wind engineering community (e.g., Cook 2002, and Wu *et al*. 2001, 2002).

This paper presents the results of a laboratory modeling of wind-induced (external, point) pressure on the roof of the TTU test building, carried out at CSU at a geometrical scale of 1:50. The main findings of this investigation were presented during the 10th International Conference on Wind Engineering (Bienkiewicz and Ham 1999). Recent discussion on the topic of adequacy and limitations of wind tunnel modeling of wind effects on low-rise buildings (Cook 2002, Wu *et al*. 2001, 2002, and others) as well as continued interest of wind engineering community in comparisons of field, laboratory and numerical simulations (of wind loading on TTU test building) motivated the authors to revise and expand the material included in Bienkiewicz and Ham (1999). The outcome of this effort is presented herein.

The paper is organized as follows. First, wind tunnel configurations employed to simulate the three considered approach flows are described. Next, the mean and turbulent characteristics of the flows are presented. Finally, the wind-induced external point pressure measured in the mid-plane and corner regions of the roof of the model of the TTU building are discussed and compared with field results. Observations drawn from this analysis are summarized in the concluding section of the paper.

2. Experimental technique

2.1. Wind tunnel, building model, instrumentation and data acquisition

Experiments were performed in the Meteorological Wind Tunnel (MWT) at the Wind Engineering and Fluids Laboratory (WEFL, www.winlab.colostate.edu, formerly the Fluid Dynamics and Diffusion Laboratory), at CSU. The wind tunnel is of a re-circulation type and has a diverging 29 m long test section, 2 m in width and 1.8 m in height.

A 1:50 geometrical scale model of the TTU test building was employed in the study. It was furnished with pressure taps, 0.8 mm in diameter. The positions of the selected taps, see Fig. 1, were determined from field information provided by Levitan and Mehta (1992). Herein only roof pressures are discussed.

Mean velocity and turbulence intensity profiles were measured using single and cross hot film probes in conjunction with constant temperature hot-wire anemometers. The reference velocity and static pressure were monitored using a pitot-static tube mounted at the roof height of the building

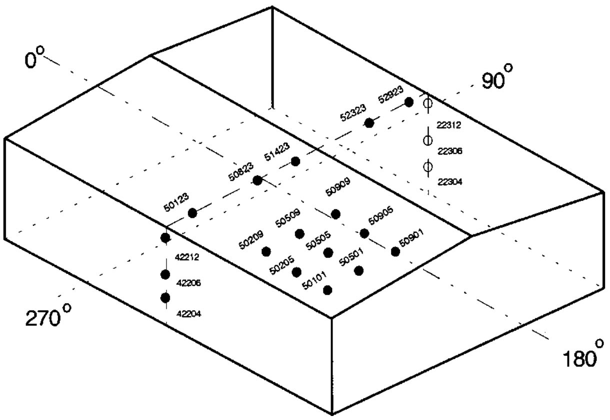

Fig. 1 Location of pressure taps and definition of wind azimuth

model. The pressure was measured using Honeywell Micro Switch pressure transducers connected to pressure taps via short tubing with restrictors. The frequency response of the pressure measurement system had a constant magnitude (within +/- 3% error) and a linear phase for a frequency range spanning from DC through approximately 220 Hz.

The pressure time series was low-pass filtered with a frequency cut-off of 200 Hz and it was acquired at a sampling rate of 1000 samples/second. For each pressure tap, ten records of the pressure data, each consisting of 18,000 data points, were acquired and used in subsequent analysis. The (model-to-prototype) velocity scale was approximately equal to unity. As a result, the time scale was 50:1 and each record of the laboratory data corresponded to a 15-minute long field record. The equivalent field sampling and low-pass filtering frequencies were 20 samples/second and 4 Hz, respectively.

Further information on the building model, instrumentation, data acquisition and processing can be found in Ham and Bienkiewicz (1998) and Ham (1998).

2.2. Simulation of approach flow

Three boundary layer approach flows were developed and employed in modeling of wind-induced point pressure on the TTU building model. The first phase of this effort was focused on simulation of nominal (prevalent at the TTU field site) boundary-layer wind conditions. The target geometrical scale was 1:50. The ultimate goal was to employ the developed nominal flow in measurement of the building roof pressure and to assess the degree of agreement between the laboratory and field results. This effort was a natural extension of earlier studies of the TTU wind flow and building (external) point pressure carried out at CSU. They included a 1:100 geometrical scale investigation reported by Cermak and Cochran (1992), for details see Cochran (1992), and a 1:25 geometrical scale study by Bienkiewicz and Sun (1992), for details see Sun (1993). The geometrical scale of 1:50, selected for the present study, was considered to be a reasonable compromise for the flow blockage and the effects of geometrical details of the turntable and the near-field portion of the floor roughness.

Effort by Ham (1998), also reported by Ham and Bienkiewicz (1998), led to a wind-tunnel set-up, shown in Fig. 2. This arrangement resulted in a turbulent boundary layer flow, denoted herein as CSU-B2, which was in a very good agreement with the nominal field wind. This flow was employed in measurement of external wind pressure on the TTU building model and in a number of related wind tunnel investigations carried out at CSU.

The experimental setup used to generate CSU-B2 flow was subsequently modified. After considerable effort (for details see Ham 1998), two experimental configurations were developed to generate two bounding flows; one of low and one of high level of turbulence. The setup used to simulate the low-turbulence boundary-layer flow (denoted herein as CSU-B1) is shown in Fig. 3.

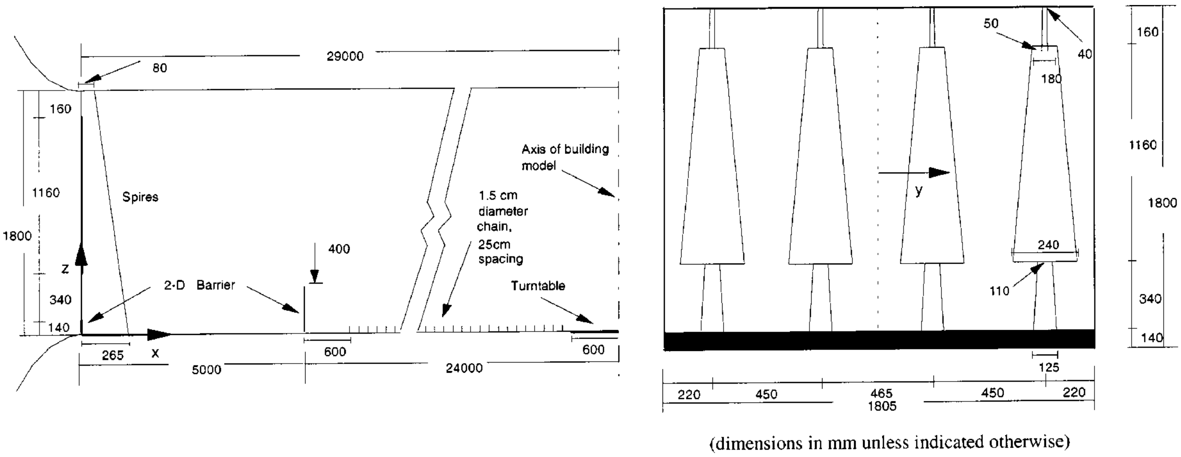

Fig. 2 Setup used to generate nominal TTU flow (CSU-B2)

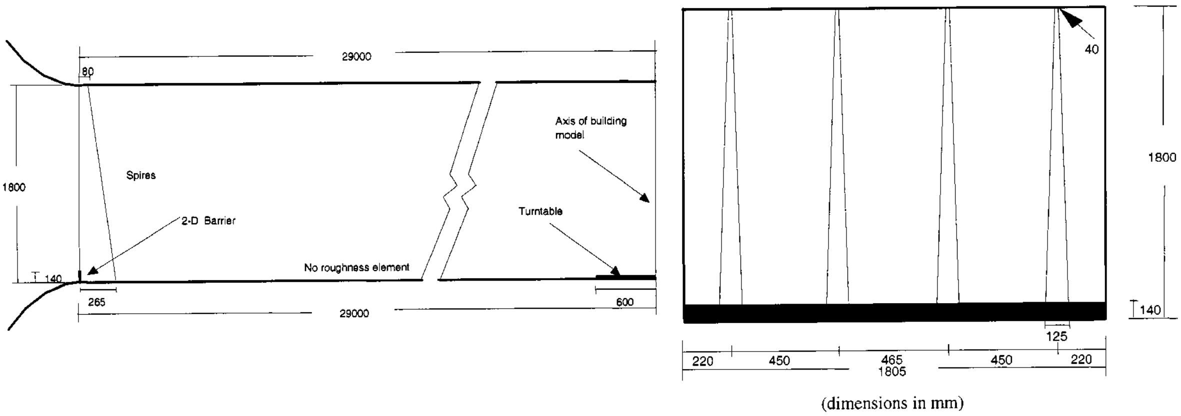

Fig. 3 Setup used to generate low-turbulence flow (CSU-B1)

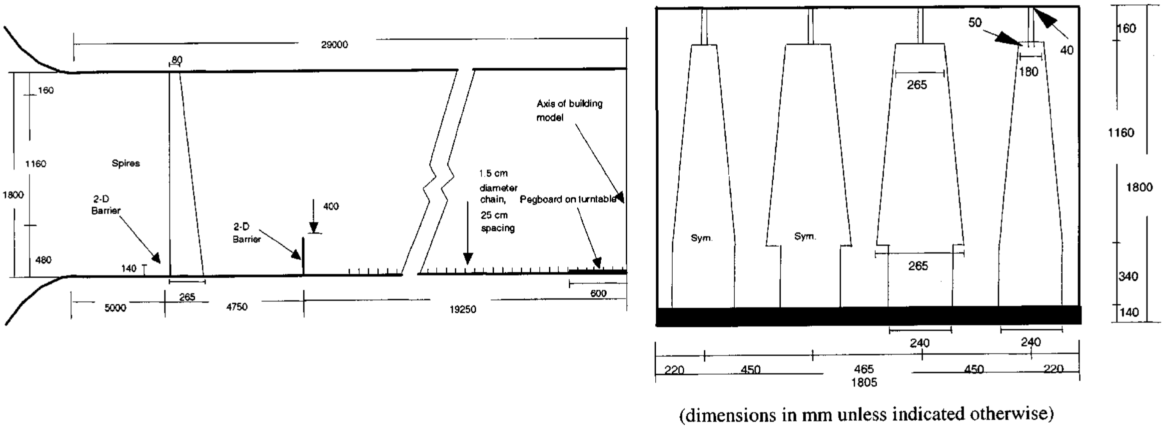

Fig. 4 Setup used to generate high-turbulence flow (CSU-B3)

Details of the arrangement employed to generate the high-turbulence boundary-layer flow (denoted as CSU-B3) are depicted in Fig. 4.

3. Results and discussion

3.1. Approach Flow

The mean velocity and turbulence intensity profiles, as well as power spectra, of the generated flows are shown in Figs. 5 through 9. As is depicted in Fig. 5a, the mean velocity profile of flow CSU-B2 was in a very good agreement with the TTU (nominal) field data reported by Chok (1988). The power-law fit of this profile had an exponent α=0.14. This profile was well bounded by the

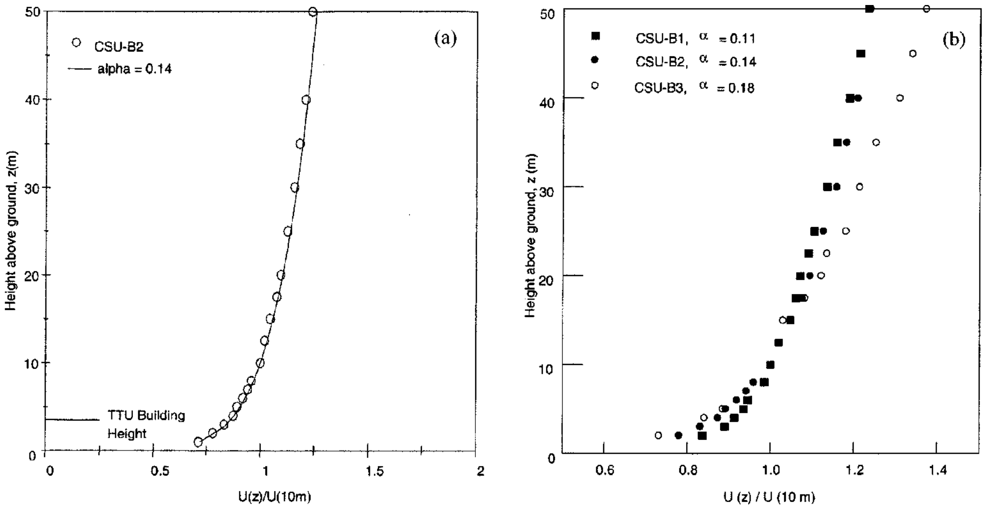

Fig. 5 Normalized mean velocity: (a) field (TTU) and modeled (CSU-B2) nominal flows; (b) low (CSU-B1), nominal (CSU-B2) and high (CSU-B3) turbulence intensity flows

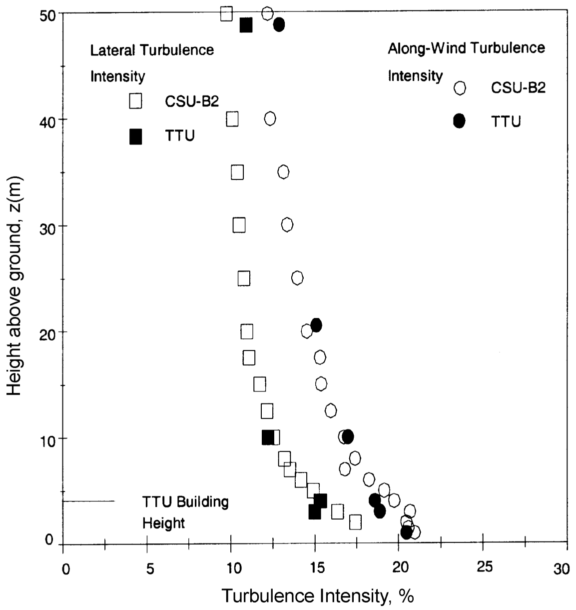

Fig. 6 Field (TTU) and modeled nominal (CSU-B2) along-wind and lateral turbulence intensity

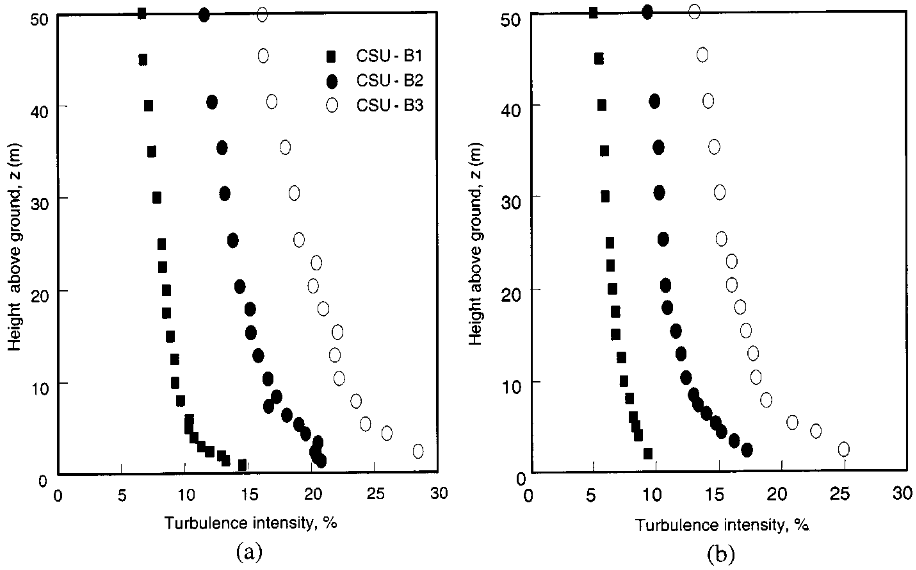

Fig. 7 Modeled along-wind (a) and lateral (b) turbulence intensity

remaining two flows, with α=0.11 and α=0.18, for respectively CSU-B1 and CSU-B3, see Fig. 5b. Fig. 6 shows a very good agreement between the laboratory (CSU-B2) and (nominal) field (Tieleman *et al*. 1996) profiles of the along-wind and lateral turbulence intensities. The turbulence intensity profiles of this flow and the bounding flows (CSU-B1 and CSU-B3) are compared in Fig. 7. It can be seen that the model roof-top intensities ranged from approximately 8% through 25%.

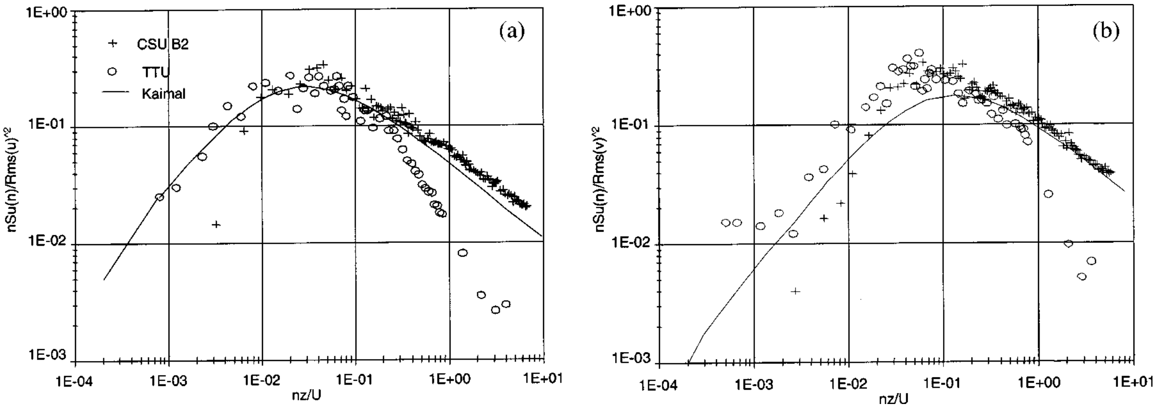

Fig. 8 Field (TTU) and modeled nominal (CSU-B2) along-wind (a) and lateral (b) velocity spectrum (z = 10 m)

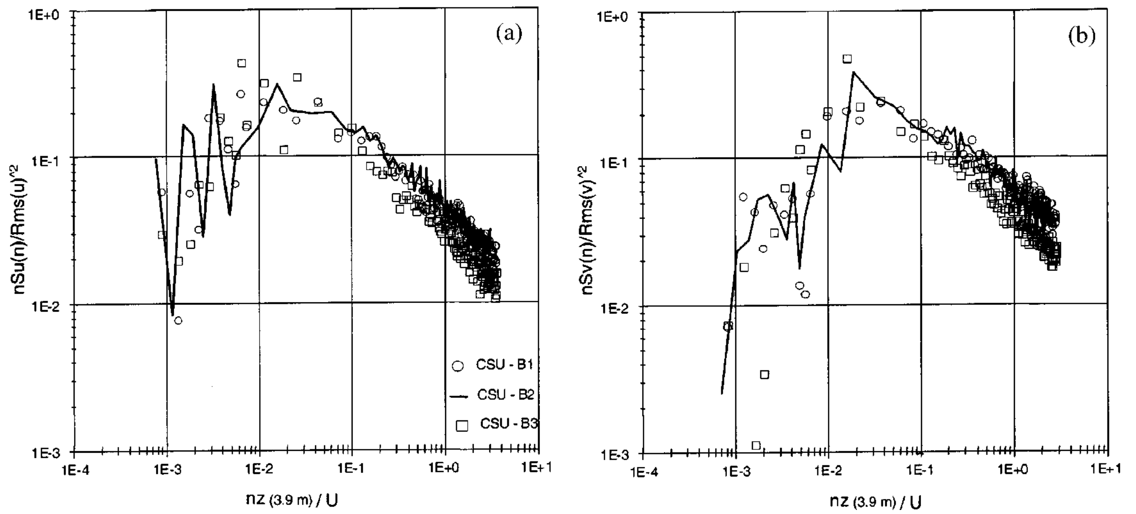

Fig. 9 Spectra of modeled along-wind (a) and lateral (b) velocity component (z=3.9 m)

The power spectra of the along-wind and lateral velocity fluctuations are depicted in Figs. 8 and 9. A good agreement between the laboratory (CSU-B2) and field spectra, evaluated at a reference (prototype) elevation of 10 m (Tieleman *et al.* 1996), is exhibited in Fig. 8. It is apparent that the field spectra are attenuated for the reduced frequency nz/U>0.3, due to the drop-off in the frequency response of instrumentation used to measure time series of the (field) wind velocity. The spectra of the three laboratory flows, evaluated at the TTU building height (the prototype elevation of approximately 3.9 m), are compared in Fig. 9.

3.2. Building pressure

The wind-induced point pressure (the pressure coefficient obtained using the approach flow dynamic pressure at the building roof height) on the exterior surface of the roof of the TTU

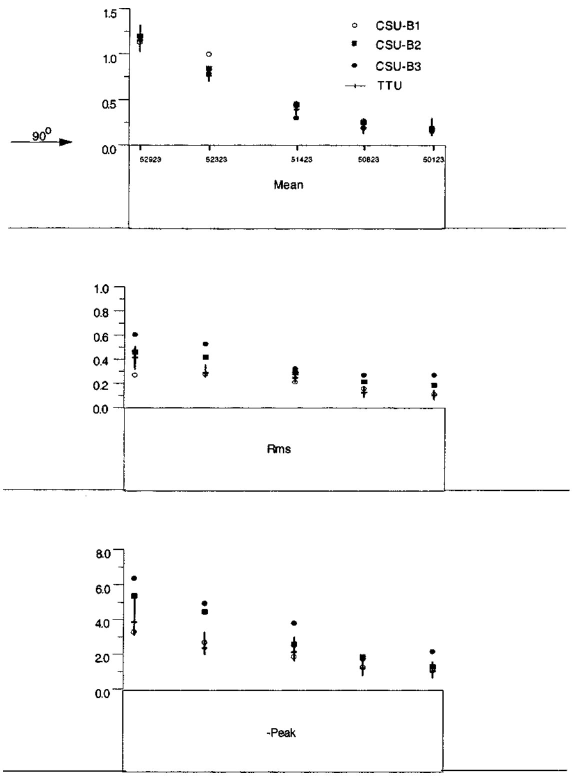

Fig. 10 Effects of turbulence on mid-plane roof pressure, wind azimuth 90°

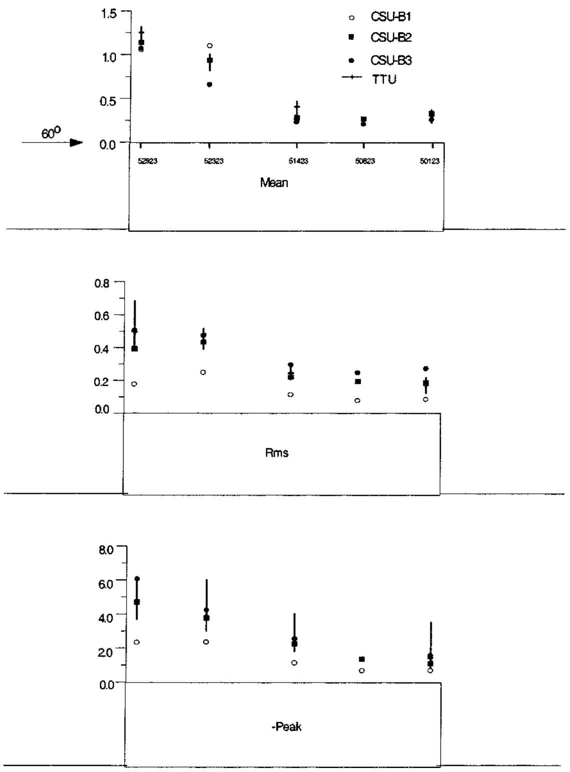

Fig. 11 Effects of turbulence on mid-plane roof pressure, wind azimuth 60°

building is presented in Figs. 10 through 15. The laboratory results obtained in the three flows are compared with the field data acquired at the TTU site. The roof pressure in the mid-plane of the building and in a corner region is respectively shown in Figs. 10 and 11 and Figs. 12 through 15.

In the discussion that follows, the effects of instrumentation (frequency response, filtering, etc.) and the (data) sampling rate on the compared results are not addressed. They are the subject of an ongoing laboratory effort at CSU. The results of this investigation will be reported in the near future.

3.3. Roof mid-plane pressure

The mid-plane roof pressure, Figs. 10 and 11, is presented for two wind azimuths (90° and 60°), considered also by Surry (1991). The results obtained for wind normal to the longer side of the building (wind azimuth of 90°) are depicted in Fig. 10. A comparison of the mean pressure shows a very good agreement between the laboratory measurements acquired in CSU-B2 flow and the field data used by Surry (1991). The pressure standard deviation (rms of fluctuations) and peak suctions acquired in CSU-B2 flow are overall in the upper portion of the scatter in the field data, except for pressure tap 52323 where the laboratory suction exceeds the field scatter. The results in this figure also exhibit the anticipated influence of turbulence on roof pressure. The most pronounced effect is

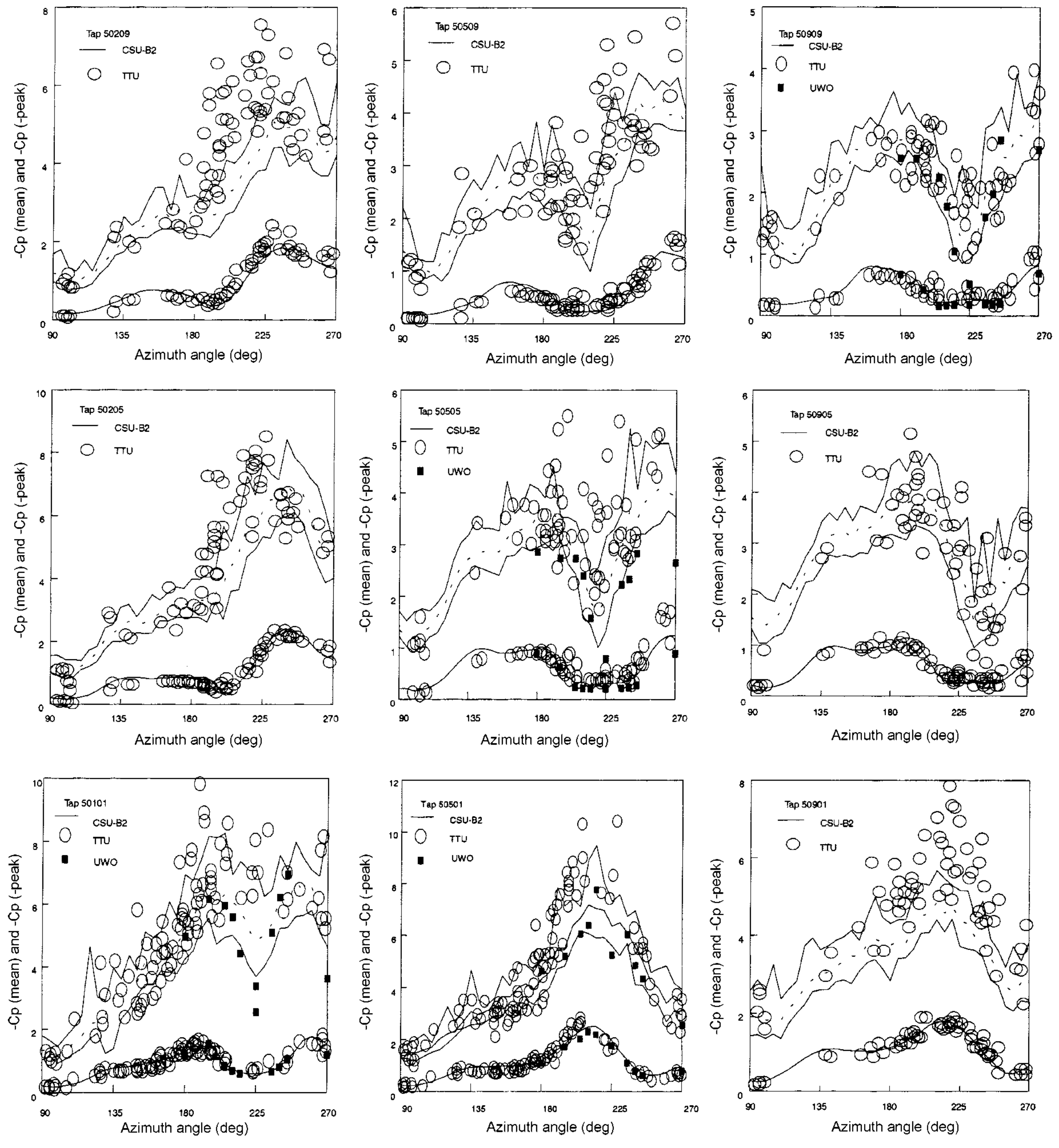

Fig. 12 Mean and peak roof pressure in nominal flow (CSU-B2)

the degree of an increase in pressure fluctuations (as manifested by the rms and peak pressure) with an increase in the turbulence intensity of the approach flow.

The data obtained for wind azimuth of 60°, Fig. 11, exhibit the effects of turbulence intensity similar to those observed for wind azimuth of 90°, Fig. 10. However, a comparison of Figs. 10 and 11 shows a better agreement between the laboratory and field rms and peak suctions for wind

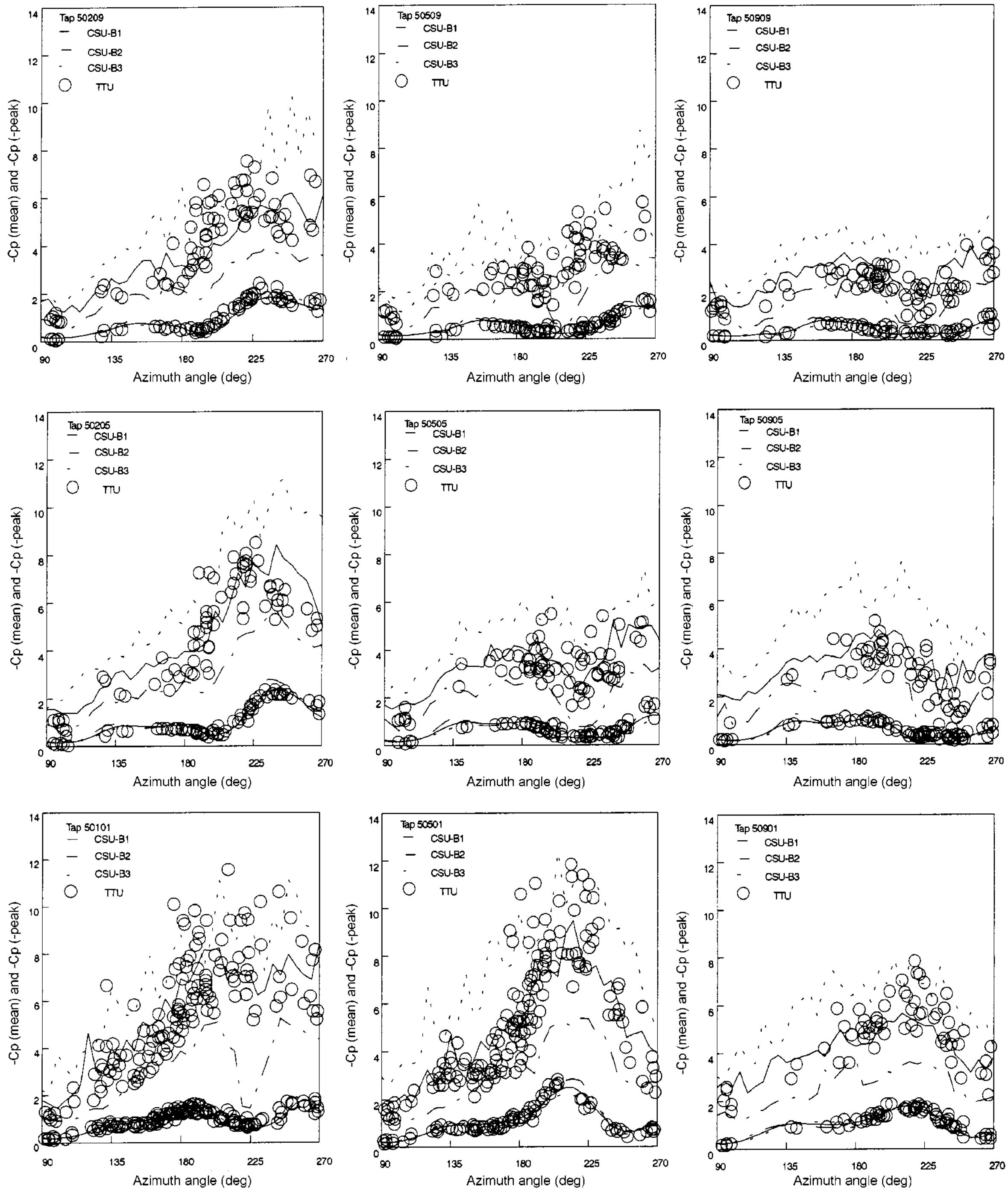

Fig. 13 Effects of turbulence on mean and peak roof pressure

azimuth of 60°.

It is interesting to note that Surry (1991) carried out a similar comparison. He used the same field

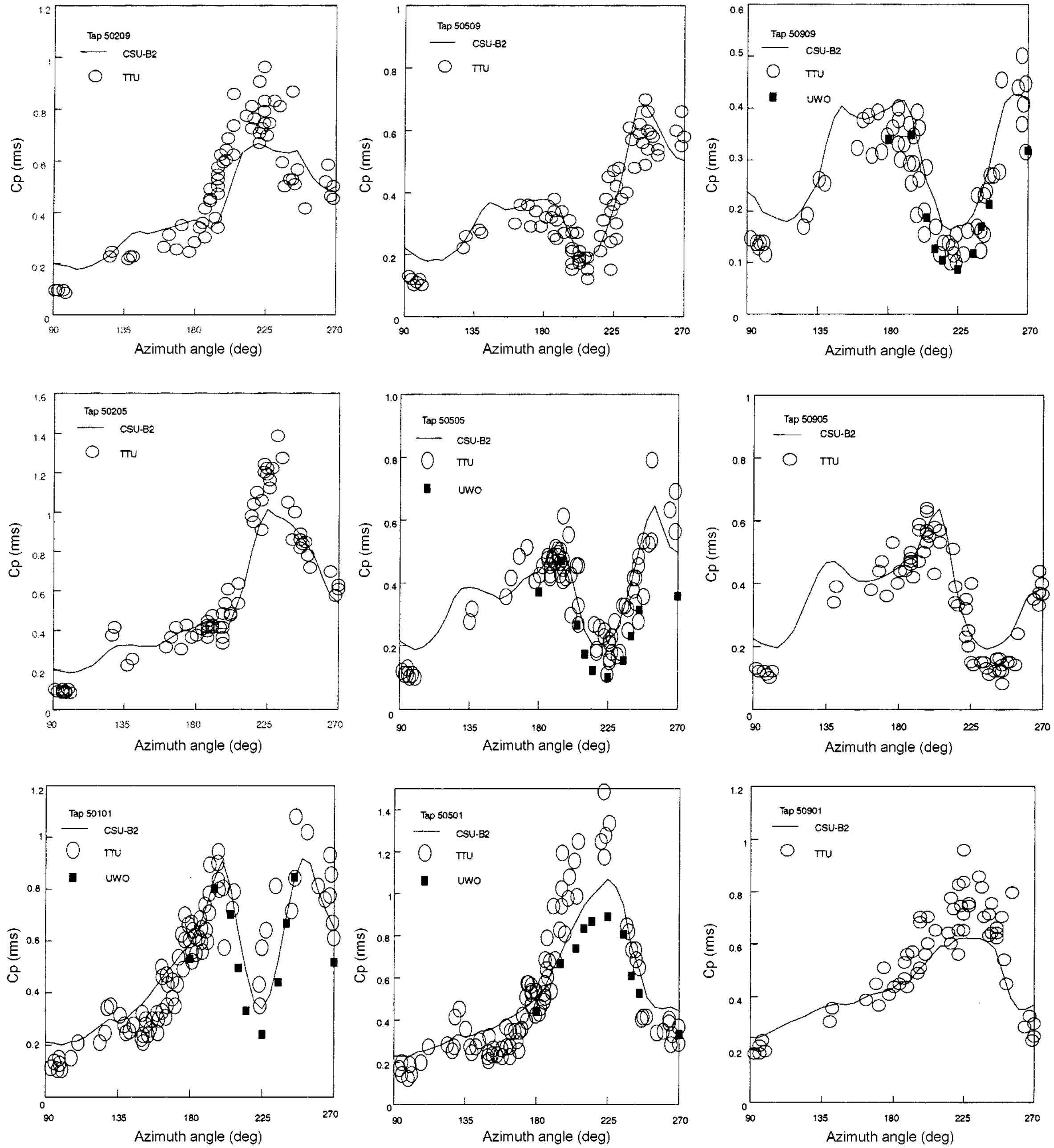

Fig. 14 Standard deviation of roof pressure in nominal flow (CSU-B2)

data and considered the two azimuths discussed above. However, in contrast to the present assessment (of the laboratory-field comparison) he found a better agreement (between the compared data) for the wind azimuth of 90° and a substantial disagreement for the peak suctions for wind azimuth of 60°, Fig. 6 in Surry (1991).

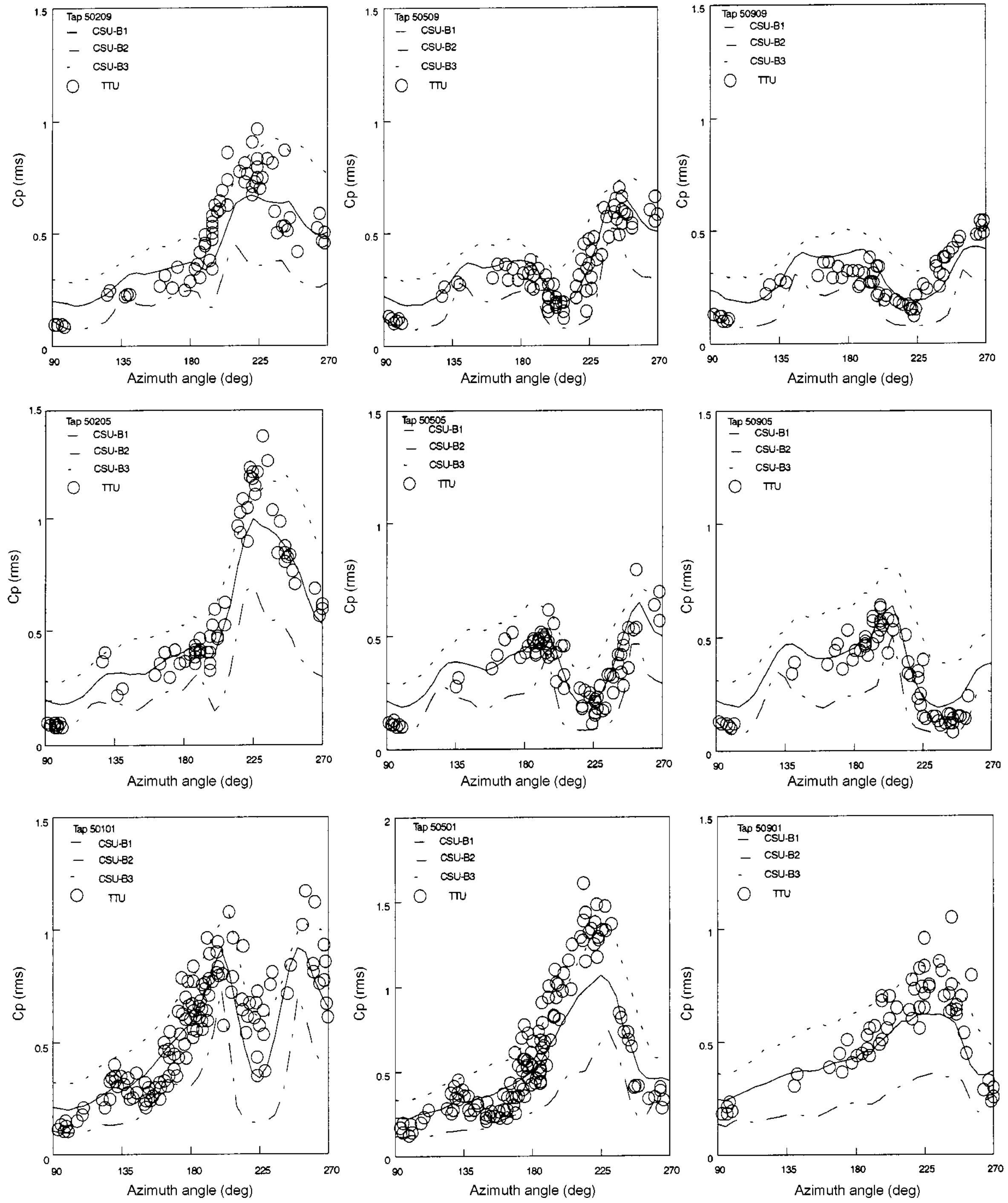

Fig. 15 Effects of turbulence on standard deviation of roof pressure

Explanation of the above contradictory findings can be inferred from the field results published by Levitan *et al*. (1991). It appears that the field roof pressure used by Surry (Figs. 5 and 6 in Surry 1991) is the same as that discussed by Levitan *et al*. (Figs. 3 and 4 in Levitan *et al*. 1991). It follows from Table 1, in Levitan *et al*. (1991), that the (presumably along-wind) turbulence intensity at the TTU building height was overall lower for the wind azimuth (referred to in Levitan *et al*. 1991 as the mean angle-of-attack) of 90^o than that for the wind azimuth of 60^o. A comparison of the turbulence intensity profiles of the approach flows (Fig. 6 herein, Fig. 2 in Surry 1991 and Table 1 in Levitan *et al*. 1991) shows that the rooftop turbulence intensity reported by Surry (1991) was lower than that of the present study and it was overall closer to the field value in Levitan *et al*. (1991), for the wind azimuth of 90^o. This observation justifies a better agreement between the field pressure and laboratory simulation reported by Surry (1991) (for the azimuth of 90^o) than that presented herein. A similar comparison for the wind azimuth of 60^o shows that the field rooftop turbulence intensity in Levitan *et al*. (1991) was significantly higher than that reported by Surry (1991) and closer to the value of the nominal flow (CSU-B2, Fig. 6) used in the present study. As a result, a better agreement between the field data and the fluctuating pressure of this study, for the azimuth of 60^o, is not unexpected.

3.4. Roof corner pressure

The roof corner pressure in Figs. 12 through 15 is presented for nine taps (indicated in Fig. 1) and the wind azimuth ranging from 90^o through 270^o, with an increment of 5^o. Plots in Figs. 12 and 13 compare the laboratory and field mean and peak suctions and show the effects of turbulence on the laboratory data. Figs. 14 and 15 provide similar information on the pressure rms.

The field data included in Figs. 12 through 15 originated from two sources. The field pressure for taps 50101 and 50501 was taken from Tieleman *et al*. (1996). It was restricted to roof pressure records associated with the approach flow of the lateral turbulence intensity not exceeding 20%, as discussed in Tieleman *et al*. (1996). The field data for the remaining roof corner taps (50901, 50205, 50505, 50905, 50209, 50509, and 50909) was taken from Mehta *et al*. (1992), where no restriction was placed on the level of turbulence of the approach flow. In addition, the laboratory data acquired at the University of Western Ontario (UWO), reported by Lin *et al*. (1995), is included in Figs. 12 and 14, for four taps (50101, 50501, 50505, and 50909).

The results in Fig. 12 show an overall very good agreement between the laboratory and field mean and peak roof corner suctions. However, a close examination of the data at taps near the roof edges reveals a measurable discrepancy between the (laboratory and field) peak pressures, for the cornering wind azimuth range. Continuous lines indicate the highest and lowest peaks (for each wind azimuth) out of ten largest suctions, determined from ten segments of the pressure time series. The dashed line represents the average of the ten considered peaks. As mentioned earlier, each segment of the laboratory time series corresponded to a field record length of 15 minutes. It can be seen in Fig. 12 that the peaks of the field roof suctions near roof edges appear to be centered about the largest of the laboratory peaks. An initial interpretation of this observation was that the field peaks could be associated with wind conditions of the turbulence intensity higher than that of the TTU nominal wind, modeled by the CSU-B2 flow. To validate this hypothesis, the effects of turbulence intensity on the roof corner peak pressure were investigated next. The results of this effort are summarized in Fig. 13.

Each peak of the laboratory suction pressure depicted in Fig. 13 is the largest out of ten peak suctions obtained from ten segments of the laboratory data. It can be seen that the peak pressures are strongly influenced by the turbulence intensity of the approach flow. They increase with the intensity for all the tested wind azimuths. The effects of turbulence also are exhibited by the mean pressure, however to a much smaller degree.

As can be seen in Fig. 13, the field peak suctions are bracketed by laboratory peak pressures obtained in the bounding flows, CSU-B1 and CSU-B3. This includes taps near the roof edges and the cornering wind azimuths, where the laboratory peak suctions, measured in the nominal flow CSU-B2, were found to be smaller than their field counterparts.

A laboratory-field comparison of the rms of pressure (fluctuations) is depicted in Figs. 14 and 15. A very good agreement between the CSU-B2 and field data, see Fig. 14, is observed for most of the taps and wind directions. However, a discrepancy between these results can be seen as the approach flow reaches the cornering wind azimuth of approximately 225^o. For this range of the approach flow azimuth, the laboratory rms pressure is lower than that exhibited by the field data. This discrepancy is significantly reduced when the turbulence intensity of the approach flow is increased (through replacement of CSU-B2 by CSU-B3 flow), as is illustrated in Fig. 15. However, such a modification of the flow leads to significant mismatch between the laboratory and field pressure for non-cornering wind azimuths. The effects of lowering the flow turbulence intensity also are illustrated, Figs. 13 and 15.

It follows from the above that the laboratory-field mismatch of the fluctuating pressure cannot be solely attributed to the wind-azimuth-independent discrepancy in the level of the turbulence intensity of the approach flow.

4. Conclusions

The findings of this study can be summarized as follows:

(1) An overall good agreement was found between the field roof pressure and laboratory measurements taken in the modeled nominal approach flow (CSU-B2).

(2) The agreement for the mean pressure was excellent for all the tested roof locations and wind azimuths.

(3) At locations in the roof mid-plane, the degree of the agreement for fluctuating pressure depended on wind azimuth (WA) and it ranged from good ($WA=90^o$) to very good ($WA=60^o$). A close examination of the field data revealed that the disagreement in the compared data resulted from mismatch between the turbulence intensity of the approach field and modeled flows.

(4) In the roof corner region, the degree of agreement of the pressure was very good for most of the tested locations and wind azimuths. However, for cornering wind ($WA \approx 225^o$) the laboratory fluctuating pressure in nominal approach flow (CSU-B2) was lower than its field counterpart.

(5) The effects of turbulence on the roof pressure exhibited the expected trends: an increase in pressure fluctuations with an increase in the turbulence intensity of the approach flow, with relatively small changes in the mean pressure.

(6) For cornering wind, the laboratory pressure fluctuations (both the peak and rms) were brought to a better agreement with the field data, at locations near the roof edges, when the approach flow turbulence intensity was increased above the level attributed to the nominal TTU wind.

However, this modification led to deterioration in the agreement for the remaining wind azimuths and roof locations. As a result, it was concluded that the field-laboratory mismatch of the fluctuating pressure, observed for the modeled nominal flow (CSU-B2), could not be solely attributed to the wind-azimuth-independent discrepancy between the turbulence intensity of the approach field and laboratory flows.

(7) More research is desirable to further investigate laboratory (wind-tunnel) modeling of wind-induced roof suctions. This effort would be greatly facilitated by enhanced statistical description of the variability of the approach field wind and the associated wind-induced surface pressure on the building.

Acknowledgements

This work was performed as a part of the research effort of the CSU/TTU Cooperative Program in Wind Engineering, supported by the National Science Foundation, through engineering grant CMS-9411147.

References

Bienkiewicz, B. and Ham, H. J. (1999), “A 1:50 scale wind-tunnel study of wind pressure on TTU building”, in: A. Larsen, G.L. Larose, F.M. Livesey (Eds.), *Proceedings of the 10th International Conference on Wind Engineering*, 1755-1762.

Bienkiewicz, B. and Sun, Y. (1992), “Local wind loading on the roof of a low-rise building”, *J. Wind Eng. Ind. Aerodyn.* **45,** 11-24.

Cermak, J. E. and Cochran, L. S. (1992), “Physical modeling of atmospheric surface layer”, *J. Wind Eng. Ind. Aerodyn.* **41-44**, 935-946.

Cochran, L. S. (1992), “Wind-tunnel modeling of low-rise structures”, Ph. D. Dissertation, Department of Civil Engineering, Colorado State University, Fort Collins, Colorado.

Chok, C. V. (1988), “Wind parameters of Texas Tech University field site”, M. S. Thesis, Department of Civil Engineering, Texas Tech University, Lubbock, Texas.

Cook, N. (2002), “Discussion on “Influence of incident wind turbulence on pressure fluctuations near flat-roof corners” by F. Wu, P.P. Sarkar, K.C. Mehta, Z. Zhao”, *J. Wind Eng. Ind. Aerodyn.* **90**, 127-130.

Ham, H. J. (1998), “Turbulence effects on wind-induced building pressure”, Ph. D. Dissertation, Department of Civil Engineering, Colorado State University, Fort Collins, Colorado.

Ham, H. J. and Bienkiewicz, B. (1998), “Wind tunnel simulation of TTU flow and building roof pressure”, *J. Wind Eng. Ind. Aerodyn.* **77 & 78**, 119-133.

Jamieson, N. J. and Carpenter, P. (1993), “Wind tunnel pressure measurements on the Texas Tech building at scale of 1:25 and comparison with full-scale”, *Proc. 7USNCWE*, University of California at Los Angeles, 303-312.

Levitan, M. L. and Mehta, K. C. (1992), “Texas Tech field experiments for wind loads part 1: building and pressure measuring system”, *J. Wind Eng. Ind. Aerodyn.* **41-44**, 1565-1576.

Levitan, M. L., Mehta, K. C., Vann, W. P. and Holmes, J. D. (1991), “Field measurements of pressures on the Texas Tech Building”, *J. Wind Eng. Ind. Aerodyn.* **38,** 227-234.

Lin, J.-X., Surry, D. and Tieleman, H. W. (1995), “The distribution of pressure near roof corners of flat roof low buildings”, *J. Wind Eng. Ind. Aerodyn.* **56**, 235-265.

Mehta, K. C., Levitan, M. L., Iverson, R. E. and McDonald, J. R. (1992), “Roof corner pressure measured in the field on a low building”, *J. Wind Eng. Ind. Aerodyn.* **41-44**, 181-192.

Okada, H. and Ha, Y.-C. (1992), “Comparison of wind tunnel and full-scale measurement tests on the Texas Tech Building”, *J. Wind Eng. Ind. Aerodyn.* **41-44**, 1601-1612.

Rofail, A. W. (1994), “Full-scale/model-scale comparisons of wind pressures on the TTU building”, *Proc.*

9ICWE, New Delhi, India, Wiley Eastern Ltd., 1055-1066.

Sun, Y. (1993), “Wind loading on loose-laid roofing paver systems”, Ph. D. Dissertation, Department of Civil Engineering, Colorado State University, Fort Collins, Colorado.

Surry, D. (1991), “Pressure measurements on the Texas Tech building: Wind tunnel measurements and comparisons with full scale”, *J. Wind Eng. Ind. Aerodyn.* **38**, 235-247.

Tieleman, H. W., Surry, D. and Mehta, K. C. (1996), “Full/model scale comparison of surface pressures on the Texas Tech experimental building”, *J. Wind Eng. Ind. Aerodyn.* **61**, 1-23.

Wu, F., Sarkar, P. P., Mehta, K. C. and Zhao, Z. (2001), “Influence of incident wind turbulence on pressure fluctuations near flat-roof corner”, *J. Wind Eng. Ind. Aerodyn.* **89**, 403-420.

Wu, F., Sarkar, P. P., Mehta, K. C. and Zhao, Z. (2002), “Discussion, Authors' response”, *J. Wind Eng. Ind. Aerodyn.* **90**, 131-133.

Xu, Y. L. (1995), “Model- and full-scale comparison of fatigue-related characteristics of wind pressures on the Texas Tech Building”, *J. Wind Eng. Ind. Aerodyn.* **58**, 147-173.

AK